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Nuclear Waste Policy Act
(Section 113)

Consultation Draft

Site Characterization Plan

Reference Repository Location, Hanford Site, Washington

Volume 1

January 1988

U.S. Department of Energy
Office of Civilian Radioactive Waste Management
Washington, DC 20585

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CONSULTATION DRAFT SITE CHARACTERIZATION PLAN

PREFACE

This consultation draft of the site characterization plan (SCP/CD) is being submitted by the Department of Energy (DOE) to the States, affected Indian Tribes, and the Nuclear Regulatory Commission (NRC) as part of the process for the preparation and issuance of the site characterization plan (SCP) required by the Nuclear Waste Policy Act and by the NRC in 10 CFR Part 60. The DOE expects that consultation with the States, affected Indian Tribes, and the NRC will greatly assist the preparation of an SCP representing a site-characterization program that will achieve the DOE's technical and programmatic objectives by being technically sound, timely, and cost effective. In addition, the consultation process is expected to enhance the process for review and comment by the public that will follow the formal issuance of the SCP.

Several observations about this consultation draft should be made to ensure that it is used appropriately. The Act, in Section 113(b), requires that the DOE develop an SCP that is only a general plan for site characterization. This plan is to include a description of the site and is to be accompanied by certain information about the waste package and a conceptual repository design. Essentially the same requirements are specified by the NRC in 10 CFR 60.17. The Act also specifies that the site-characterization activities are to be only the activities that the Secretary of Energy considers necessary to provide data for evaluating the suitability of the site and for compliance (in part) with the National Environmental Policy Act. Although only a general plan is called for, the DOE has, as a matter of policy, prepared a comprehensive and detailed SCP/CD that includes available geotechnical information about the site, a description of the conceptual design of the repository, a description of the waste package, and a detailed discussion of the plans for characterizing the site. The purpose of preparing such a comprehensive and detailed plan is to facilitate the review of the planned site-characterization program by the States and affected Indian Tribes and to obtain from the NRC staff input as to whether the program covered by the plan can be expected to be sufficient for eventual licensing. The comprehensive content and the level of detail reflect earlier consultations with the NRC staff as well as the States and affected Indian Tribes.

The program described in the SCP/CD places primary emphasis on the technical sufficiency of the proposed investigations to ensure that all the potentially needed information will be obtained. The information needed is defined as the geotechnical information necessary to demonstrate the suitability of the site for a repository; to design the repository and the waste package; to select, on the basis of a comparative evaluation, a site for a repository; and to obtain from the NRC an authorization to construct the repository. The DOE has concluded that the compendium of tests, analyses, and activities identified in the SCP/CD is likely to generate all the information needed for siting, design, and licensing. Much less emphasis, however, has been placed on determining the need for each element in the program and for

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ensuring that there are no unnecessary and redundant activities. As a result, the DOE considers that the SCP/CD is comprehensive and sufficient, but it may not yet represent the most efficient or cost-effective program for site characterization. Accordingly, during the consultation period, the DOE will carefully evaluate the program described in this SCP/CD, revise it as necessary and appropriate, and document the changes in the SCP. The DOE intends to ensure that each of the tests, analyses, and activities in the site-characterization program is necessary and is included in the plan; that unnecessary or redundant tests, analyses, and activities are not conducted; and that the program is based on sound management and fiscal prudence.

The extensive experience gained in this and other programs--including field investigations, underground testing, laboratory studies, design activities, and analyses--causes the DOE to recognize that the development of the SCP and the site-characterization program are evolutionary and iterative processes requiring flexibility in planning. They may be changed in response to comments about plans, to reflect new information from testing and analyses, or in response to comments about test results once testing is begun. Any changes that are identified as necessary will be documented in the semiannual progress reports that will be made available for review by all parties.

It should also be noted that the issue-resolution strategies and performance allocations in the SCP/CD are preliminary, and the tentative goals identified in Chapter 8 are not criteria that must be met for regulatory compliance. Agreements between the DOE and NRC staffs clearly recognize and accept that these goals are useful for establishing a testing program, but are not necessary for regulatory compliance. As site characterization progresses and more information is acquired, the goals will probably be changed, with some goals being tightened and others relaxed. In the meantime, during the consultation process, these tentative goals are expected to provide an important focus for comments and discussions on performance allocation, goals, and the testing program.

The SCP/CD does not present complete information on the sequencing of activities, the priorities assigned to activities, or a complete schedule for the site-characterization program. Such information is only now being developed through the preparation of detailed study plans for studies and tests to be performed during site characterization. These study plans will be made available before the start of new onsite activities, in accordance with previous agreements with the States, the affected Indian Tribes, and the NRC staff. As the study plans are completed, the DOE will be able to establish sequencing and priorities for the activities found to constitute an adequate and necessary site-characterization program. This will allow a schedule for the entire program to be developed and included in Section 8.5 of the SCP.

As already mentioned, this SCP/CD is being issued to facilitate a consultation process that is expected to enhance the quality of the SCP. This consultation will occur through interactions at the workshops that will be held after the release of this document and through comments received later on. The DOE believes that the benefits of the consultation process would be maximized if the interactions focused on several key questions. For the NRC

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staff, the key question is as follows: does the SCP/CD provide confidence that the DOE has adequately identified the issues and the kinds of information the NRC will need in its licensing decisions? The key question for the States and the affected Indian Tribes is how well their specific concerns have been identified and addressed. In addition, since Chapter 8 describes the site-characterization program, focus on this chapter is critical.

The DOE has chosen this SCP/CD as its primary instrument for consultations that will assist in defining in the SCP a technically sound and fiscally prudent site-characterization program that will generate the information necessary for siting, designing, and licensing a geologic repository that will protect the health and safety of the public.

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SITE CHARACTERIZATION PLAN

Introduction

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INTRODUCTION

The Hanford Site in the State of Washington contains one of three candidate sites for the first geologic repository for radioactive waste. On May 28, 1986, it was recommended by the Secretary of Energy and approved by the President for detailed study in a program of site characterization. This site characterization plan (SCP) has been prepared by the U.S. Department of Energy (DOE) in accordance with the requirements of Section 113(B) of the Nuclear Waste Policy Act of 1982 (NWPA, 1983) to summarize the information collected about the geologic conditions* at the Basalt Waste Isolation Project (BWIP) site; to describe the conceptual designs for the repository and the waste package; and to present the plans for obtaining the geologic information necessary to demonstrate the suitability of the BWIP site for a repository, to design the repository and the waste package, to prepare an environmental impact statement, and to obtain from the U.S. Nuclear Regulatory Commission (NRC) an authorization to construct the repository.

This introductory chapter begins with a brief section on the process for siting and developing a repository, followed by a discussion of the pertinent legislation and regulations. A description of site characterization is presented next; it describes the facilities to be constructed for the site characterization program and explains the principal activities to be conducted during the program. Finally, the purpose, content, organizing principles, and organization of this SCP are outlined, and compliance with applicable regulations is discussed. The technical and programmatic terms that are used in this introduction and the SCP itself are defined in the glossary.

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THE PROCESS OF REPOSITORY DEVELOPMENT

This section summarizes the process of repository siting, construction, operation, closure, and decommissioning. The discussion includes the types of waste to be received at the repository and the principal interactions with the NRC.

The siting of a repository

As part of its program for the management of civilian radioactive waste, the DOE is conducting studies directed at finding a first-repository site that will provide reasonable assurance that the public and the environment will be

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*In this introduction, the term "geologic conditions" encompasses the geoengineering, hydrologic, geologic, geochemical, climatological, and meteorological conditions at the site, and the term "geologic information" is used in a general sense to refer to all the information that will be obtained from the site characterization program described in this plan.

adequately protected from the hazards posed by spent nuclear fuel and high-level waste*. The process for the siting program is specified by the Nuclear Waste Policy Act.

Several of the steps in the process required by the Nuclear Waste Policy Act have been completed, the three most recent being the following:

1. The Secretary of Energy has nominated five sites as suitable for characterization and issued environmental assessments to accompany each nomination.

2. The Secretary has recommended three of the nominated sites for characterization as candidate sites for the first repository, and the President has approved the recommendation. The three sites are the Yucca Mountain site in tuff in the State of Nevada, the Deaf Smith County site in salt in the State of Texas, and the BWIP site in basalt in the State of Washington.

3. The Secretary has made the preliminary determination that the recommended candidate sites are suitable for development as repositories.

The next step is to conduct site characterization at the three candidate sites approved by the President. Site characterization is a program of studies directed at collecting the geologic information necessary to demonstrate the suitability of a site for development as a repository, to design the repository and the waste package, to prepare an environmental impact statement, and to obtain a construction authorization from the NRC. Details on the site characterization program will be provided later in this introduction.

After completing site characterization and related activities required by the Nuclear Waste Policy Act, the Secretary of Energy is to recommend to the President the first site to be developed as a repository. This recommendation is to be accompanied by an environmental impact statement prepared in accordance with Section 114(f) of the Nuclear Waste Policy Act, the requirements of the National Environmental Policy Act (NEPA, 1970), and the DOE guidelines for the implementation of the National Environmental Policy Act. The President of the United States is then to submit the recommendation to the Congress.

If the BWIP site is recommended by the President to the Congress, the State of Washington may submit, within 60 d, a notice of disapproval to the Congress. This disapproval prevents the use of the site for a repository unless the Congress passes a joint resolution of repository-siting approval within the next 90 d of continuous session. If no notice of disapproval

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*For convenience, the term "radioactive waste" or simply "waste" is often used in this document to mean spent nuclear fuel or high-level waste.

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is submitted or if a notice of disapproval is overturned by the joint resolution, the site designation becomes effective. If the notice of disapproval is not overturned, the disapproval stands, and the President must recommend another site not later than 1 yr after the disapproval.

Construction, operation, closure, and decommissioning of a repository

When the site designation becomes effective, the DOE will submit an application to the NRC for authorization to construct the repository. The Nuclear Waste Policy Act requires that this application be submitted not later than 90 d after the effective date of the site designation. The application will contain a description of the site, a description of the design of the repository and the waste package, and an assessment of the performance of the entire mined geologic disposal system (i.e., the site and the natural barriers at the site, the repository, and the waste package) with respect to applicable regulatory performance objectives. The NRC will review the application and decide whether to authorize the construction of the repository. When a construction authorization has been received from the NRC, the construction of the repository will begin.

When the repository is ready for operation, the DOE will submit an updated application to the NRC for a license to receive and possess radioactive material at the site. When this license has been received, the repository will begin to receive and emplace waste.

The Nuclear Waste Policy Act specifies that the waste accepted by the first repository cannot exceed the equivalent of 70,000 metric tons of heavy metal (MTHM) until a second repository becomes operational. Most of this waste (more than 60,000 MTHM) will consist of spent nuclear fuel from commercial power reactors. The remainder will consist of defense high-level waste and a small quantity of commercial high-level waste. Both the defense and the commercial high-level waste will be solidified into borosilicate glass before acceptance by the DOE.

After being filled to capacity, which is expected to take about 25 yr from the start of waste emplacement, the repository will be kept open for a period of time (up to 25 yr) in order to determine that the repository is performing as expected and the emplaced waste need not be retrieved. The DOE will then submit to the NRC an application for a license amendment that will allow it to permanently close the underground facilities of the repository and to decommission the surface facilities. When closure is completed, the DOE will apply for a license amendment to terminate the license.

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REGULATIONS FOR GEOLOGIC DISPOSAL

As directed by the Nuclear Waste Policy Act, geologic repositories are subject to, and guided by, regulations promulgated by the U.S. Environmental Protection Agency (EPA), the NRC, and the DOE. More specifically, the scope and the content of the site characterization program are dictated by the information needed to demonstrate compliance with these regulations for site selection and licensing.

Primary standards and technical criteria

The primary standards for geologic repositories are concerned with protecting the health and safety of the public from the hazards of the waste to be emplaced in the repository; they have been promulgated by the EPA in 40 CFR 191 (EPA, 1986).* These standards specify (1) limits on the radiation exposure of the general public from operations at a repository, (2) a limit on the amount of radioactivity that may enter the environment for 10,000 yr after disposal, (3) limits on the radiation dose that can be delivered to any member of the public for 1,000 yr after disposal, and (4) requirements for the protection of groundwater.

The EPA standards are implemented and enforced by the NRC regulations in 10 CFR 60 (NRC, 1987a). These regulations consist of (1) procedures for the licensing of geologic repositories and (2) technical criteria to be used in the evaluation of license applications under those procedural rules. The procedural portion of 10 CFR 60 provides specific requirements for a site characterization program and the associated site characterization plan. In addition to requiring that the EPA standards be met, the technical criteria of 10 CFR 60 provide a number of additional requirements:

- Performance objectives (criteria)
- The NRC radiation-protection standards contained in 10 CFR 20 (NRC, 1987c)

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*The U.S. Court of Appeals for the First Circuit has vacated and remanded to the EPA for further proceedings the environmental standards for disposal of spent fuel, high-level waste and transuranic waste (Subpart B of 40 CFR Part 191). Some of the plans described in this SCP were specifically designed to furnish data needed for demonstrating compliance with those standards as promulgated by the EPA in 1985. The basic information needed to demonstrate compliance with any disposal standards eventually promulgated by the EPA is expected to remain substantially the same, and therefore the approach to testing set forth in this SCP is expected to remain substantially the same. Nevertheless, any changes that may be made by the EPA to its standards will be evaluated by the DOE to ensure that the planned testing program will be adequate.

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- Design criteria for the surface and underground facilities of the repository

- Three separate performance objectives for each of the three subsystems of the geologic disposal system: a minimum lifetime for the waste package; a limit on the release rate from the engineered barriers of the repository; and, for the natural system at the site, a minimum time of groundwater travel from the disturbed zone to the accessible environment.

U.S. Department of Energy siting guidelines

As required by the Nuclear Waste Policy Act, the DOE has developed guidelines for nominating and recommending sites for characterization and selecting sites for the development of repositories. Promulgated as 10 CFR 960 (DOE, 1987b), they are referred to here as the "siting guidelines." The siting guidelines are based on the EPA and the NRC regulations.

The siting guidelines are divided into implementation guidelines, postclosure guidelines, and preclosure guidelines. The implementation guidelines are not directly used in the evaluation of sites; their purpose is to specify how the postclosure and preclosure guidelines are to be applied in site screening and selection. The postclosure guidelines govern the siting considerations that deal with the long-term performance of a repository (i.e., performance after waste emplacement and repository closure). The preclosure guidelines govern the siting considerations that deal with the siting, construction, operation, and closure of the repository.

Both the postclosure and preclosure guidelines are divided into system and technical guidelines. The postclosure system guideline defines general requirements for the performance of the entire geologic disposal system after closure. The postclosure technical guidelines specify requirements for one or more elements of the system--the physical properties and phenomena at the site. The preclosure system guidelines address three different systems involving (1) preclosure radiological safety; (2) environment, socioeconomics, and transportation; and (3) the ease and cost of repository siting, construction, operation, and closure. Each of the preclosure system guidelines is associated with a set of technical guidelines specifying requirements on various components of the system (e.g., population density and distribution, meteorology, surface characteristics).

Both the postclosure and the preclosure technical guidelines specify conditions that would disqualify or qualify sites, and they also specify conditions that would be considered favorable or potentially adverse.

Any disqualifying condition constitutes sufficient evidence to conclude, without further consideration, that the site is disqualified, and the presence or absence of almost all of these conditions may be verifiable without extensive data gathering or complex analysis. Indeed, 10 of the 17 disqualifying

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conditions can be applied in the first phase of the site-selection process. In the case of the qualifying conditions, on the other hand, no single condition is sufficient to qualify a site. In order to be qualified, a site must meet all of the qualifying conditions, and failure to meet any one of these conditions will disqualify the site. Failure to meet a qualifying condition can usually be determined only after site characterization and the concurrent investigations of environmental and socioeconomic conditions take place.

The favorable and potentially adverse conditions can be used to predict the suitability of a site before detailed studies have been performed. They provide preliminary indications of system performance. Favorable conditions need not exist at a given site for the site to meet the qualifying condition, but their existence leads to an expectation that subsequent evaluations will enhance confidence in the site's suitability. Similarly, the purpose of determining whether any potentially adverse conditions exist at a site is to provide an early indication of conditions that must be examined carefully before judging the acceptability of that site. Such examinations must evaluate the effects of other, possibly compensatory, conditions present at a site.

The favorable and potentially adverse conditions are intended to be used primarily in the screening phase of site selection, during the search for potentially acceptable sites. However, they were considered in the preliminary evaluations against the siting guidelines that are reported in the Environmental Assessment (DOE, 1986) and were also applied in the decision-aiding methodology that was used in identifying sites to be recommended for characterization.

Most of the evaluations in the Environmental Assessment led to preliminary findings, which are defined as lower-level findings in Appendix III of the siting guidelines. The identification of the favorable and potentially adverse conditions as present or not present was based on the data available at the time of the evaluation or conservative assumptions when the data were inadequate. A favorable condition was claimed to be present only if the existing data clearly supported that conclusion. Similarly, a potentially adverse condition was stated to be present unless the existing data and conservative assumptions clearly supported a conclusion that it is not present.

Final evaluations will be performed after site characterization is completed. These final evaluations will be used to make the higher level findings necessary to demonstrate compliance with the system guidelines and each technical guideline; they will also be used in the comparative evaluation that will be performed to identify which of the characterized sites is to be recommended for the development of a repository. In the case of the technical guidelines, these evaluations will be made against both the disqualifying and the qualifying conditions. To ensure that the investigation of the qualifying conditions is complete, the favorable and potentially adverse conditions will be considered with regard to this contribution to the site's overall performance. No findings as to their presence or absence will be needed, because sufficient data will be available for direct evaluations against the qualifying conditions of the system and the technical guidelines.

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SITE CHARACTERIZATION

Before any site can be judged suitable for development as a repository, it will be necessary to demonstrate that the long-term performance of the site is likely to meet or exceed the established standards. In order to do this, extensive geologic data describing the site must be collected and analyzed in a program of site characterization. Such a program is required by the Nuclear Waste Policy Act, 10 CFR 60, and the siting guidelines. In addition, designs of the repository and the waste package must be developed along with models that will provide reliable numerical predictions of the performance of the total disposal system.

Section 2(21)(B) of the Nuclear Waste Policy Act defines site characterization as follows:

> ...activities, whether in the laboratory or in the field, undertaken to establish the geologic condition and the ranges of parameters of a candidate site relevant to the location of a repository, including borings, surface excavations, excavations of exploratory shafts, limited subsurface excavations and borings, and in situ testing needed to evaluate the suitability of a candidate site for the location of a repository, but not including preliminary borings and geophysical testing needed to assess whether site characterization should be undertaken.

The activities planned for site characterization consist primarily of surface-based field studies, the construction of the Exploratory Shaft Facility, and the tests conducted in that facility. A variety of design and modeling activities are also planned. They will use the results of the studies and tests in analyses required for the resolution of design and performance issues. The studies and the related design and modeling activities, as described in Chapter 8 (Section 8.3), make up the overall site characterization program.

The field studies will be directed at obtaining information on the geologic, hydrologic, geochemical, climatologic, and geoengineering characteristics of the site and the surrounding area through exploratory drilling and testing, the testing of rock and water samples, geophysical surveys, and mapping.

To provide access for detailed study of the potential host rock as well as the overlying strata, the DOE will construct the Exploratory Shaft Facility. The Exploratory Shaft Facility will consist of (1) two exploratory shafts that will provide for access to the host rock, the transport of people and equipment, and ventilation; (2) underground testing areas; and (3) surface facilities needed to support construction and testing.

The exploratory shafts will be sunk to the level where the underground facilities of a repository would be built. At this level they will be connected to one another and to underground testing areas. The shafts and the

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underground testing areas will be used to conduct tests and make observations and measurements of site conditions. The tests will be started during the construction of the exploratory shafts and will be continued in the Exploratory Shaft Facility.

In conducting the site characterization program, care will be taken to minimize adverse environmental and socioeconomic impacts. As reported in the Environmental Assessment (DOE, 1986), no significant adverse impacts are expected to result from site characterization. Nonetheless, the DOE will monitor site characterization activities that might have significant environmental and socioeconomic impacts and, to the extent practicable, implement mitigation measures if necessary. Plans to monitor and mitigate those impacts have been developed in consultation with the State of Washington and the affected Indian Tribes. Those plans are not part of this document; they will be prepared and issued separately.

If the BWIP site in the State of Washington is not selected, a specific plan for decontaminating and decommissioning the site will be developed.

The environmental and socioeconomic effects of the geologic repository will be addressed in an environmental impact statement, to be issued after site characterization. Before beginning to prepare the environmental impact statement, the DOE will hold scoping hearings to provide the public an opportunity to present issues to be considered in the environmental impact statement. Concurrently with site characterization and in support of the environmental impact statement, the DOE will conduct a site investigation program to collect nongeologic information important in determining the suitability of the site and in licensing the repository. Included in this program will be studies of environmental conditions (e.g., air and water quality, terrestrial and aquatic ecosystems, and noise); archaeological, cultural, and historical resources; and the social and economic conditions in the area that could be affected by the repository. The environmental and socioeconomic studies to be conducted will be described in other planning documents.

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THE SITE CHARACTERIZATION PLAN

Before beginning to sink the exploratory shafts, the DOE is required by Section 113(B) of the Nuclear Waste Policy Act to prepare a site characterization plan. This plan is to be submitted to the NRC, the Governor and legislature of the State of Washington, and the governing bodies of the affected Indian Tribes; it is also to be made available to the public. Furthermore, the Nuclear Waste Policy Act requires the DOE to hold public hearings in the vicinity of the BWIP site to inform the residents of the area of the site characterization plan and to receive their comments.

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Purpose and objectives

The basic purpose of this SCP is threefold:

1. To describe the site, the preliminary designs of a repository and a waste package appropriate to the site, and the waste-emplacement environment in sufficient detail to clearly understand the basis for the planned site characterization program.

2. To identify the uncertainties and limitations on the site- and design-related information developed during site screening, to identify the issues to be resolved during site characterization and the information needed to resolve the issues, and to present the strategy for resolving the issues, including the site-suitability findings required by the siting guidelines.

3. To describe general plans for the work, including performance confirmation, needed to (a) resolve outstanding issues, (b) reduce uncertainties in the data, and (c) make site-suitability findings in terms of the siting guidelines.

In this context, "issues" are defined as questions related to the performance of the geologic disposal system that must be resolved to demonstrate compliance with applicable Federal regulations. The issues, which have been organized into a hierarchy, and the strategies for their resolution are discussed later in this section.

The SCP provides the NRC, the State of Washington, affected Indian Tribes, and the public with a vehicle for early input on the DOE's data-gathering and development work to avoid postponing issues to the point where modifications would entail major delays in, or disruptions of, the program. Early review of the site characterization plans presented in the SCP will provide an opportunity for the NRC to comment on whether the DOE's proposed program is likely to generate the data necessary for an application to obtain a construction authorization for the repository.

The issues hierarchy and the issue resolution strategy

The issues that must be resolved to demonstrate the compliance of the disposal system with the applicable Federal regulations have been organized into a hierarchy, and this hierarchy served as one of the basic organizing principles for the site characterization program. The second principle is a strategy for resolving each issue. Understanding these principles is helpful in following the discussions in the rest of this document.

The issues hierarchy is a multitiered framework that lays out what must be known before a site can be selected and licensed. In providing this information, each tier contains progressively more detail than the tier above it. On the first, or highest, tier are the four key issues. Stated as

questions, they are derived from the system guidelines in the DOE siting guidelines; they therefore embody the principal requirements established by the regulations governing repositories. Affirmative answers to the key issues will be necessary if a site is to be selected and licensed.

Each of the key issues is followed, in the second tier, by three groups of issues related to performance and design. Also stated as questions, these issues expand on the requirement stated in the key issue they represent. When each group of issues was constructed, an effort was made to include in the group all the questions that must be answered to resolve the key issue.

The third tier consists of "information needs." Unlike the key issues and issues, the information needs are stated as requirements for technical information, rather than as questions. In identifying the information needs, the DOE attempted to list all the information necessary for resolving the issues. In principle, acquiring all the information called for at the third tier of the issues hierarchy will allow all the issues to be resolved through analyses and evaluations that use the information. If the issues are resolved affirmatively, the key issues will also have been resolved.

The issues hierarchy is useful in site characterization because it furnishes a framework for developing the test program and explaining why the test program is adequate and necessary. In simple terms, the test program will be adequate if it adequately addresses all the information needs in the third tier of the issues hierarchy. The necessity for any particular planned test can be established by determining its role in satisfying an information need. For these reasons, the issues hierarchy is used as an organizing principle for Chapter 8 of this plan, which describes the site characterization program.

To use the issues hierarchy effectively, the DOE has adopted a formal strategy for resolving issues. This strategy, discussed in detail in Chapter 8 (Section 8.2), guides the development of specific plans for resolving each issue and provides the rationale for the associated site characterization activities.

The strategy begins with the identification of regulatory requirements, the development of the issues hierarchy from these requirements, and the preparation of a detailed description of the proposed geologic disposal system. The next part is a process called "performance allocation." It leads to detailed specifications of the information needed to resolve each issue and hence to plans for the investigations and studies that will produce the needed information. The issue resolution strategy then proceeds with the investigations and with analyses of their results until it is possible to show that the information needs have been satisfied. The collected information is used in a concluding set of analyses to resolve the issues, and the resolution is documented.

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Scope

In accordance with Section 112(b)(2) of the Nuclear Waste Policy Act, a site-nomination hearing was held in the State of Washington in March 1983. The purpose of this hearing was to receive comments and recommendations with respect to the issues that should be addressed in the Environmental Assessment and the SCP.

The comments received from the public, the State, and affected Indian Tribes were considered during the preparation of the Environmental Assessment (DOE, 1986) and the SCP. The comments that are addressed in the SCP are tabulated in Section 8.2.1.7. Table 8.2.1.5 correlates technical concerns addressed in the SCP, including those raised at the public hearings, with specific SCP sections where pertinent discussions are presented.

Regulatory requirements for the content of the Site Characterization Plan

The requirements of the Nuclear Waste Policy Act

Section 113(b)(1)(A) of the Nuclear Waste Policy Act requires that the DOE prepare a general plan for site characterization activities. The plan is to include the following:

1. A description of the candidate site.
2. The extent of planned excavations during site characterization.
3. Plans for any onsite testing with radioactive or nonradioactive material.
4. Plans for any activities that may affect the capability of the candidate site to isolate the waste.
5. Plans to control any adverse, safety-related impacts from site-characterization activities.
6. Plans for the decontamination and decommissioning of the candidate site and for the mitigation of any significant adverse environmental impacts caused by site characterization activities if the site is determined to be unsuitable for a repository.
7. Criteria to be used to determine the suitability of the candidate site for the location of a repository, developed pursuant to Section 112(a).
8. Any other information required by the NRC.

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In addition, Section 113(b)(1)(B) requires a description of the waste package, the relationship between the waste package and the site, and waste package activities being conducted by the DOE. Section 113(b)(1)(C) requires a conceptual repository design for the site.

Items 1 and 6 in the list above are self-explanatory, but items 2, 3, 4, 5, and 7 may require some explanation and are briefly discussed below. Item 8 is included in the subsequent discussion of NRC requirements.

The extent of planned excavations (item 2 in the list above) is of interest for several reasons. First, some of the excavations at the site (i.e., the exploratory shafts) will extend to the depth of the repository and, if not constructed properly, may adversely affect the waste-isolation potential of the site. Second, of the activities carried out during site characterization, the construction of shafts has the greatest potential for environmental impacts. In addition, the extent of planned excavations is related to the information about the host rock that can be collected in the Exploratory Shaft Facility.

The use of radioactive materials (item 3) is of concern because of the potential for releases to the environment. The DOE may use radioactive tracer materials with short half-lives ranging from several hours to tens of days in some of the geochemical characterization (Section 8.3.1.4.4). A small quantity of a radioactive marker with a half-life of less than 10 d may be used during the construction of the exploratory shafts in the placement of chemical seal rings. Some activities will use well-logging tools that contain radioactive materials and are commonly used in geologic and hydrologic exploration.

Plans for any investigation activities that may affect the waste-isolation capability of the site (item 4) are of concern because, if the waste-isolation capability is unduly compromised, the site may be found to be unsuitable for a repository. Item 5 in the list above, which asks for plans to control adverse safety-related impacts, is related to this requirement. The NRC has interpreted this to mean (10 CFR 60.17(a)(2)(iv)) adverse impacts that are related to safety during the preclosure period of repository operations and to waste isolation after the closure of the repository.

The requirement for criteria to determine site suitability (item 7) refers to the siting guidelines developed by the DOE pursuant to Section 112 of the Nuclear Waste Policy Act and promulgated as 10 CFR 960. One of the objectives of site characterization is to collect the data necessary to demonstrate that the site meets the guidelines.

U.S. Nuclear Regulatory Commission requirements

Specifications for the content of the SCP are also presented in 10 CFR 60.17. These specifications are essentially the same as those of the Act. However, as allowed by Section 113(b)(1)A)(v) of the Nuclear Waste

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Policy Act (item 8 in the list above), the NRC has specified in 10 CFR 60.17 the additional requirements given below.

1. In describing the candidate site, the SCP is to include information on the quality assurance programs that were applied to the collection, recording, and retention of the information used in preparing the description (10 CFR 60.17(a)(1)).

2. The SCP is to present plans for the application of quality assurance to data collection, recording, and retention during site characterization (10 CFR 60.17(a)(2)(v)).

3. The description of plans for the use of radioactive materials is to include the use of radioactive tracers.

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Regulatory Guide 4.17

To facilitate compliance with the requirements for the SCP, the NRC has prepared Regulatory Guide 4.17, Standard Format and Content of Site Characterization Plans for High-Level-Waste Geologic Repositories (NRC, 1985). The guide suggests the types of information to be provided in the SCP and establishes a uniform format for presenting the information. The DOE considered this guidance in developing the annotated outline for site characterization plans (DOE, 1987a), which has been reviewed by, and concurred in, by the NRC staff, who agreed that it was acceptable for the preparation of site characterization plans.

Organization of the Site Characterization Plan and compliance with regulatory requirements

In preparing the SCP, the DOE made every effort to comply with the content requirements of the Nuclear Waste Policy Act and 10 CFR 60. The discussion that follows explains how the SCP is organized and how it meets these regulatory requirements discussed above. Table 1 presents the regulatory requirements and shows which sections of the SCP provide compliance with each particular requirement.

In preparing this SCP, the DOE has also made every effort to provide the detailed information that is identified in NRC Regulatory Guide 4.17 and that has been requested by NRC staff in a number of DOE-NRC meetings. As a result, this SCP provides considerably more information than the "general plan" required by the Nuclear Waste Policy Act and by 10 CFR 60. The additional information has been provided to allow for a comprehensive review of the DOE's site characterization program by the NRC, the State of Washington, the affected Indian Tribes, and the public.

Table 1. Compliance of the Site Characterization Plan with regulatory requirements

	Requirement	Section of the Nuclear Waste Policy Act	Paragraph in 10 CFR 60	Section in Site Characterization Plan
1.	Description of the candidate site	113(b)(1)(A)(i)	60.17(a)(1)	Chapters 1-5
2.	Information on quality assurance programs that have been applied to the collection, recording, and retention of information used in preparing the description of the site	--	60.17(a)(1)	8.6.4.1
3.	Description of site characterization activities, including:	113(b)(1)(A)(ii)	60.17(a)(2)	8.3, 8.4
3a.	Description of the extent of planned excavations	113(b)(1)(A)(ii)	60.17(a)(2)(i)	8.4.2
3b.	Plans for any onsite testing with radioactive material and nonradioactive material	113(b)(1)(A)(ii)	60.17(a)(2)(ii)	8.3.1,[a] 8.4.2, 8.7.1
3c.	Plans for investigations that may affect the waste-isolation capability of the site	113(b)(1)(A)(ii)	60.17(a)(2)(iii)	8.4.2
3d.	Plans to control adverse safety-related impacts	113(b)(1)(A)(ii)	60.17(a)(2)(iv)	8.4.2
3e.	Plans to apply quality assurance to data collection, recording, and retention	--	60.17(a)(2)(v)	8.6.4
4.	Plans for decontamination and decommissioning and the mitigation of significant adverse environmental impacts	113(b)(1)(A)(iii)	60.17(a)(3)	8.7
5.	Criteria to be used to determine site suitability	113(b)(1)(A)(iv)	60.17(a)(4)	(b)
6.	Description of waste package and associated activities	113(b)(1)(B)	60.17(b)	Chapter 7, 8.3.4
7.	Conceptual repository design	113(b)(1)(C)	60.17(c)	Chapter 6

[a]As explained in the text (Section 8.3.1.4.4), the U.S. Department of Energy may use radioactive tracers in its groundwater program.

[b]These criteria in the siting guidelines (10 CFR 960) are incorporated by reference.

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The SCP is divided into two parts: Part A, which provides a description of the site, the waste package, and the design of the repository; and Part B, which presents the DOE's plans for the site characterization program.

Part A consists of an introduction and seven chapters. The introduction describes the geographic setting of the site and discusses sources of information and the history of site investigations. Chapters 1 through 5 discuss the available information on the geologic conditions at the site. Their purpose is to comply with the requirements of Section 113(b)(1)(A)(i) and (v) of the Nuclear Waste Policy Act and 10 CFR 60.17(a)(1).*

The last two chapters in Part A are concerned with the conceptual design of the repository (Chapter 6) and the waste package (Chapter 7). Their purpose is to comply with the requirements of Section 113(b)(1)(B) and (C) of the Nuclear Waste Policy Act and 10 CFR 60.17(b). Each begins with an introduction that explains the purpose of the chapter, provides an overview of the current design concepts, and shows which SCP chapters contain the site characteristics data on which the design is based and which chapters use or discuss the information presented in Chapter 6 or 7. Like the preceding chapters, Chapters 6 and 7 conclude with a summary section that links the design of the repository and the waste package, respectively, to the issues hierarchy and the site characterization program of Part B by providing a summary of design issues and related information needs. Chapter 6 presents the design basis for the repository, describes the conceptual design, discusses the information needed for the later phases of the design, and summarizes design issues. Chapter 7 describes what is currently known about the host rock in which the waste package will be emplaced, presents the design basis for the waste package, describes the current design and the alternatives that have been or are being considered, and discusses the status of research and development. This chapter also contains a comprehensive discussion of technical concerns that must be addressed during planned waste package development.

In particular, Chapter 1 presents the data collected on the geologic conditions; Chapter 2 discusses the geoengineering properties of the rock units at the site; Chapters 3 and 4 discuss the hydrologic and geochemical conditions, respectively; and Chapter 5 is concerned with climate and meteorology. Each chapter concludes with a summary whose purpose is to link the data and analyses presented with the issues hierarchy and the site characterization program presented in Part B. The summary therefore (1) summarizes the significant results, discussing, as appropriate, performance objectives, conceptual models and boundary conditions, and the quality of the data, including uncertainties; (2) describes how the data are related to the design of the repository and the waste package; and (3) identifies information needs for the issues hierarchy (Part B). In addition, the summaries of Chapters 1 through 5 present a synopsis of the information that is requested by Regulatory Guide 4.17 (NRC, 1985) but has not been shown to be relevant to the BWIP

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*The quality assurance requirements of 10 CFR 60.17 are addressed in Chapter 8 (Section 8.6) of the SCP).

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site. The uncertainties in the data presented in these chapters were used to identify the information needed to resolve the issues and to develop the plans presented in Part B.

Part B, which consists of only one chapter (Chapter 8), describes the site characterization program. Its purpose is to comply with the requirements of Sections 113(b)(1)(A)(ii), (iii), and (iv) and Section 113(b)(1)(B) of the Nuclear Waste Policy Act; with 10 CFR 60.17(a)(2), (3), (4), and (5); and with the quality assurance requirements of 10 CFR 60.17(a)(1) (see Table 1).

Part B begins with an introduction that provides an overview of the approach used in planning the site characterization program. The introduction is followed by the rationale for the site characterization program--namely, the issues hierarchy and the issue resolution strategy (Section 8.1). The next two sections are the most important parts of Part B. Section 8.2 presents the site-specific issues hierarchy and the strategy for resolving each issue. Section 8.3 describes the investigations planned for the site, the repository, the seal system, the waste package, and the performance-assessment program; the purpose of the latter is to determine whether the performance of the disposal system meets the requirements of the applicable Federal regulations. Section 8.4 describes the site-preparation activities associated with surface-based testing, the construction of the surface and underground facilities related to the exploratory shafts, and the testing to be performed in the exploratory shafts and underground drifts. The remainder of Chapter 8 covers milestones, decisions points, and schedules (Section 8.5); quality assurance (Section 8.6); and decontamination and decommissioning (Section 8.7).

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Periodic progress reports

During site characterization at the BWIP site, the DOE will report at least once every 6 mo to the NRC; the Governor and the legislature of the State of Washington; and the Chairmen of the Nez Perce Indian Tribe, the Confederated Tribes of the Umatilla Indian Reservation, and the Yakima Indian Nation. The purpose of these reports is to discuss the nature and extent of site characterization activities, the information developed from such activities, and the progress of waste form and waste package research and development. The reports will include the results of site characterization studies, the identification of new issues, plans for additional studies to resolve new issues, the elimination of planned studies no longer necessary, the identification of decision points reached, changes in strategies, and modifications to schedules when appropriate. The reports will also describe progress in developing the repository design, noting when key design parameters or features that depend on the results of site characterization will be established.

Supporting documents

Many separate documents support the SCP by providing more detailed data about the site and the region, design information, and plans for site characterization activities. Much of the information presented in Chapters 1 through 5 is derived from technical reports prepared specifically for the Basalt Waste Isolation Project, other technical reports describing pertinent investigations at the Hanford Site, professional papers, and various sources in the general technical literature. These documents are cited in the list of references for each chapter and will be supplied to the State of Washington and the NRC for review; they will also be available to the public in the public reading room at the DOE Richland Operations Office.

Chapter 6 of the SCP is supported by the SCP repository conceptual design report (KE/PB, 1987). In addition to presenting the complete conceptual design of the repository, this report includes information about the functions and operations of the repository. Chapter 7 is based on a number of detailed reports about waste-package design and development. Copies of the SCP conceptual design report and the waste-package references will also be provided to the State and the NRC and supplied to the DOE public reading room.

Chapter 8 of the SCP is also supported by various technical documents that describe models, analytical techniques, etc. In addition, study plans will be prepared to provide detailed discussions of the investigations briefly described in Section 8.3. A separate plan will be prepared for the tests and analyses to be performed in each study. These study plans will be reviewed by the NRC and made available to the State of Washington for information. A preliminary schedule of their availability is presented in Section 8.5.

Detailed procedures will be prepared for the tests and analyses described in the study plans. These procedures will be approved and controlled to provide consistent, detailed guidance for performing the test, collecting and recording data, and other activities.

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*A decision on July 17, 1987, by the U.S. Court of Appeals for the First Circuit has required the EPA to reconsider its postclosure standards (Subpart B) in 40 CFR 191. Consequently, the standards in 40 CFR 191 may be subject to revision in the future.

Section 3.6 into a series of conceptual-model frameworks and examines groundwater flow paths, recharge areas, and suspected discharge areas; it concludes with a brief overview of the paleohydrology of the region. Section 3.8 examines the impact of past groundwater withdrawals. Section 3.9 describes the geohydrologic system in the area of the site. Hydraulic relationships between the principal geohydrologic units are discussed in the context of available hydraulic head, hydraulic property, hydrochemical, and geologic evidence. Several conceptualizations depicting groundwater movement are offered. Section 3.10 provides a summary in addition to a brief explanation of how the data presented in Chapter 3 were used in the design of the repository and the waste package.

CHAPTER 4: GEOCHEMISTRY

Chapter 4 describes the geochemical conditions of the site with emphasis on geochemical processes that would occur along groundwater pathways in the natural system, such as radionuclide sorption and desorption, diffusion in the rock matrix, reduction-oxidation reactions, complexation reactions, and the reactions of minerals with groundwater.

Section 4.1 discusses the geochemistry of the host basalt and the surrounding basalt flows, flow tops, and interbeds. It examines chemical, mineralogic, and petrographic data that may influence radionuclide isolation; groundwater geochemistry that can influence radionuclide movement along flow paths; and specific geochemical retardation processes, especially sorption and desorption. Section 4.2 describes the effects of the increased temperature caused by waste emplacement on the geochemical conditions that affect radionuclide isolation. Section 4.3 reviews data derived from natural analog studies and field tests in relation to the expected geochemical environment and geochemical stability of a repository in basalt. Section 4.4 explores the possible effects of human activity and natural changes on the stability of the proposed repository. Section 4.5 provides a summary, identifies information needs, and explains how the data presented in Chapter 4 were used in the design of the repository.

CHAPTER 5: CLIMATOLOGY AND METEOROLOGY

Chapter 5 describes the recent climatology and meteorology of the candidate site and what is known about the past climates of the area.

Section 5.1 discusses the recent meteorological characteristics of the site area, including winds, temperature, precipitation, sky cover and solar radiation, atmospheric pressure, humidity, severe rains, and atmospheric dispersion. Jet stream patterns, topographical features that affect the climate, and the current program for collecting meteorological data are also reviewed. Section 5.3 discusses the paleoclimatology of the site and the Pacific Northwest region and models that can be used to predict future

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climates at the site. Section 5.3 provides a summary, identifies information needs, and explains how the data presented in Chapter 5 were used in the design of the repository.

CHAPTER 6: CONCEPTUAL DESIGN OF A REPOSITORY

Chapter 6 provides an overview of the conceptual repository design (see Fig. 5) described in the SCP conceptual design report (KE/PB, 1987) and discusses how the conceptual design relates to the site characterization program. Sufficient design information is presented in Chapter 6 to ensure that all site data needs are identified.

Section 6.1 summarizes the repository design requirements; the site design data base; analytical tools used for geotechnical design; structures, systems, and components important to safety; and barriers important to waste isolation. Regulatory and DOE requirements, known site characteristics, and major design assumptions are also discussed. Section 6.2 describes previous design activities and explains the current design of the repository, how the repository will be constructed and operated, how radioactive waste will be received and emplaced, and how the closure and sealing of the repository will be carried out. Section 6.3 relates the repository conceptual design to the elements listed in NRC Regulatory Guide 4.17 (NRC, 1987b), identifies the remaining data and information uncertainties related to the design, and explains how these uncertainties may affect the design of the repository. Section 6.4 relates the current design to these design issues and information needs from the issues hierarchy that require site-characterization information. This information is cross referenced to applicable sections of Part B.

CHAPTER 7: WASTE PACKAGE

Chapter 7 discusses the design and development of the waste package. Waste package design and development focuses on functions of waste package components to isolate waste and on chemical and physical processes in the repository environment that influence functional performance.

Section 7.1 describes what is currently understood about the emplacement environment in a basalt repository and how this environment is expected to change after waste emplacement. Section 7.2 discusses the regulatory and design requirements for the waste package, including a quantitative presentation of the design constraints and the current design philosophy. Section 7.3 presents, in detail, the SCP conceptual design for the waste package along with alternative designs. Section 7.4 summarizes the available results of tests and analyses related to the material properties and performance of waste package components (e.g., container corrosion and radionuclide solubility and sorption) in the repository environment. Also presented are quantitative estimates of the performance of the waste package defined by the current conceptual designs. Section 7.5 provides a summary, identifies information needs, and assesses current design issues.

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CONSULTATION DRAFT

SITE CHARACTERIZATION PLAN

PART A: Description of the Mined Geologic Disposal System

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Chapter 7 describes the SCP conceptual design for the waste package. The purpose of the BWIP waste package program is to develop a waste package that meets the performance requirements established in 10 CFR 60 (NRC, 1987a) for the disposal of spent fuel and high-level waste.

The SCP conceptual design currently proposes a waste package that includes (1) the waste itself, either spent fuel or high-level waste; (2) a low-carbon steel container with walls at least 1.4 in. (3.5 cm) thick; (3) preformed packing material of crushed basalt and sodium bentonite; and (4) an outer steel shell. These components will be emplaced in a horizontal borehole.

ORGANIZATION OF PART A

Chapters 1 through 5 present previous findings and data that describe various characteristics of the host rock and its environment. This information is important to understanding the discussions of conceptual repository and waste package designs in Chapters 6 and 7 as well as the planned investigations outlined in Part B.

CHAPTER 1: GEOLOGY

Chapter 1 describes the current knowledge--and uncertainties--about the geologic setting of the reference repository location at the Hanford Site. The types of geologic information required for both preclosure and postclosure periods during which the performance of the location must be assessed are presented in 10 CFR 960 (DOE, 1987).

Section 1.1 introduces the physiographic provinces, topography, common landforms, and geomorphic processes that characterize the site and surrounding region. Section 1.2 describes the lithologic characteristics of rock units, their correlation, and their geologic history, both at regional and site-specific levels of detail. Section 1.3 describes the tectonic setting (including the major structural features), tectonic processes, and Quaternary history. Models used to interpret the structural evolution of the region are also introduced. Section 1.4 discusses the seismologic history and instrumental record and presents regional earthquake distribution patterns and estimates for potential ground motion parameters important to repository design. Section 1.5 examines past regional stability and describes expected long-term tectonic conditions and geologic processes extrapolated for models and disruptive event scenarios. Section 1.6 describes drilling and mining activities in the vicinity of the site, and Section 1.7 describes the mineral and hydrocarbon resources of the region and discusses the likelihood of their future development. Section 1.8 provides a summary, identifies information needs, and explains how the data presented in Chapter 1 were used in the design of the repository.

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performance objectives of 10 CFR 60, the development of construction bid packages for all systems, and the development of final procurement and construction schedules.

The SCP conceptual design phase produced a conceptual design report (KE/PB, 1987) that is summarized in this SCP. This design phase concentrated on design features of the surface repository, underground repository, special waste emplacement envelope, and waste package that require site characterization data. In addition, the SCP conceptual design activities provided input into plans described in Part B to ensure that adequate information will be gathered to complete the remaining design phases. The conceptual designs described in Chapters 6 and 7 satisfy the requirements of the Nuclear Waste Policy Act, Section 113(b)(1)(c)ii, 113(b)(1)(B) (NWPA, 1983).

In establishing basic characteristics and configurations of the repository engineered barriers, the conceptual design presented in Chapter 6 accomplished two purposes:

- Delineation of those structures, systems, and components important to safety and isolation that are necessary to receive, process, transport, and permanently dispose of radioactive waste in an underground facility.

- Identification of information needs relative to both the design data base and the methods available for the engineering design of the repository.

The design elements of the repository (Fig. 5) include the following:

- Surface facilities--The surface facilities include waste handling and processing facilities, shaft surface structures, basalt and wastewater processing, and general support facilities.

- Shafts--Eleven vertical shafts will connect the surface and underground facilities for personnel and material access, waste and rock transport, and ventilation air flow. In addition two exploratory shafts will provide access to an Exploratory Shaft Facility for exploration and testing during site characterization.

- Underground facilities--The underground facilities will be located approximately 916 m (3,000 ft) below the surface and will occupy approximately 8 km^2 (2,000 acres). The facilities include a pillar area, five longitudinal main drifts connecting to main waste emplacement areas (quadrants) on either side of the pillar area, and two ventilation air drifts around the perimeter of the underground facility. The pillar area contains the underground shaft facilities, the Exploratory Shaft Facility, drainage sumps and pumps, and a limited waste emplacement area to accommodate the initial receipts.

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swelling pressure, hydraulic conductivity, and bearing strength, were conducted on packing materials. A natural analog study characterized the potential for long-term stability of copper-based materials in a repository located in basalt.

SCOPE AND STATUS OF DESIGN WORK

Chapters 1 through 5 present previous findings and data concerning the geology, geoengineering, hydrology, geochemistry, and climatology and meteorology of the candidate site. This information is fundamental to understanding the repository and waste package designs described in Chapters 6 and 7 as well as the planned investigations discussed in Part B. As the data base is modified or expanded in the future, concepts found in Chapters 6 and 7 may be refined and changed after this report is released.

The design of the repository and the waste package consists of four distinct phases:

- Conceptual design.
- Advanced conceptual design.
- License application design.
- Final procurement and construction design.

The conceptual design concentrates on the surface and underground system, structure, emplacement, and component designs that require site characterization data and provides the information to ensure that data-gathering plans related to design are adequately included in the SCP. Data-accuracy requirements are established and site-specific licensing issues related to site characterization are identified. This phase is called the SCP conceptual design in this report.

The advanced conceptual design will present the selected design alternatives and refines and fixes the design criteria and concepts to be made final in later design efforts. This design forms the basis for demonstrating project feasibility and estimating life-cycle costs. Preliminary drawings are prepared and a construction schedule developed as required by DOE Order 6410.1 (DOE, 1983).

The license application design will present the resolution of design and licensing issues identified and assessed in earlier design phases and develop the design of the items necessary to demonstrate compliance with the design requirements and performance objectives of 10 CFR 60 (NRC, 1987a).

The final procurement and construction design will develop the final (working) drawings and specifications for procurement and construction. The completion of this design phase will match the completion of the Title II design effort for the entire repository. This design phase will emphasize the completion of design and ancillary support items, final design refinement for the items necessary to demonstrate compliance with the design criteria, and

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tower. In 1982, a network of automated sensors began the measurement of near-surface wind directions and speeds at key locations scattered throughout the region.

Significant climatic changes (related to glacial cycles) have occurred in the Pacific Northwest throughout the Quaternary (the last 1.67 m.y.). Substantial climatic data are available that describe the glacial history of the Pacific Northwest during the Quaternary. The BWIP is continuing the evaluation of these data. Most of the climatic information was obtained from palynological studies. Only a single site east of the Cascade Range (Carp Lake) has yielded information about the climate near the site of the last glaciation.

REPOSITORY INVESTIGATIONS

Past data-gathering activities related directly to the construction and performance of the proposed geologic repository include those discussed above under "Geoengineering investigations."

WASTE PACKAGE INVESTIGATIONS

Existing waste package data were gathered primarily from bench-scale laboratory experiments designed to observe the behavior of the waste package components under the appropriate environmental conditions. Most of the experimental testing was completed under anoxic to reducing hydrothermal conditions similar to those expected after the closure of the repository. Various testing methods were used to determine the following:

- The weight loss of metal coupons as a function of chemical conditions.
- The identity of corrosion products.
- Radionuclide concentrations in solution.
- Changes in groundwater composition.
- Changes in waste package composition.
- Changes in the distribution of radionuclides between the waste package and solution.

Additional experiments were conducted in the presence of steam to measure the corrosion rates of container materials following emplacement but prior to resaturation. Dehydration experiments were completed to measure changes in the composition of bentonite (a waste package and the backfill component) as a function of temperature. Physical property experiments, which measure

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- More than 200 single-hole, small-scale stress tests completed in flow tops and interbeds in some 35 separate boreholes across the Hanford Site.

GEOCHEMICAL INVESTIGATIONS

Both laboratory and field techniques have been used in gathering geochemical data for the candidate site. Mineralogical and petrological data were obtained by analyzing tens of thousands of feet of drill-core samples and samples of outcrops. The concentrations of major elements and selected trace elements in the rock samples were determined by x-ray fluorescence. Neutron-activation analysis was also used for measuring some trace elements. To identify individual primary and secondary phases, electron microprobes, x-ray diffraction, scanning microscopes, and optical microscopes were used.

Groundwater samples from various stratigraphic zones were obtained by pumping from a number of boreholes at the Hanford Site. Some springs were also sampled. The concentrations of inorganic components in these groundwaters were measured by inductively coupled plasma spectroscopy for cations and ion chromatography for anions. Total organic carbon was determined with a total organic carbon analyzer, and dissolved gases were determined with a gas chromatograph. Inorganic carbon was determined by titrimetry.

The distribution of radionuclides between groundwater and mineral phases was measured in the laboratory under conditions that simulate those expected in groundwater flow paths from the repository. Extensive laboratory experiments with radionuclide-groundwater-rock systems were used to obtain radionuclide sorption and desorption information.

Additional data were derived by a variety of approaches. Three methods were used to estimate the reduction-oxidation environment of the natural system. Heat-flow models were used to estimate temperature increases in the natural system due to waste emplacement. Natural analog studies of geochemical processes relevant to repository processes provided another input to characterization of minerals and groundwaters in the natural system.

CLIMATOLOGICAL AND METEOROLOGICAL INVESTIGATIONS

An extensive meteorological measurement program has produced a detailed data base of the recent climate of the Hanford Site region. Formal meteorological measurements in the Hanford Site region began in 1912; the Hanford Meteorology Station and its 122-m (400-ft) instrumented tower began operation in 1945. Atmospheric pressure, precipitation, humidity, sky cover, incoming solar radiation, atmospheric stability, and other parameters are measured at, or observed from, the station. Atmospheric temperature, wind direction, and wind speed are measured at several levels on the instrumented

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HYDROLOGIC INVESTIGATIONS

Information on surface-water and groundwater hydrology for the site and the surrounding region was obtained from several sources of literature and records as well as borehole and surface-based studies conducted for the BWIP in and around the Pasco Basin. Numerous records are kept in open file by State and Federal agencies. In particular, the U.S. Geological Survey (USGS) maintains a computerized file known as the Groundwater Site Inventory Data Base (part of the WATSTORE (a water data storage and retrieval system) data base), which is a systematic digital collection of available data for permitted water wells. For the Hanford Site, records have been maintained since the start of defense-related activities in the 1940s. The records, literature, and BWIP test data have been included in Chapter 3 of the SCP. This information has produced a hydrologic data base that includes the following:

- Regional surface-water data base maintained by the USGS and including approximately 100 gaging stations in eastern Washington and adjacent portions of Oregon and Idaho, hydrometeorological data from some 72 stations, and statistics on more than 400,000 acres of lakes in eastern Washington as well as various reports on water use and flood hazards.

- Regional groundwater data base of approximately 15,000 water wells drilled in 15 Washington State counties within the Columbia Plateau. The data base includes information on water quality, water use, chemical constituents, hydraulic testing, and hydraulic heads. Sources of information include the Washington State Department of Ecology potentiometric networks, the WATSTORE data base of the USGS, and the USGS Regional Aquifer System Analysis Program.

- Groundwater-level measurements made for more than 800 wells completed in the unconfined aquifer within the Pasco Basin. Many of these wells are located at the Hanford Site and have been monitored up to approximately 40 yr.

- Groundwater-levels and hydraulic-test measurements for approximately 200 test intervals in the Columbia River Basalt Group at the Hanford Site.

- Spring inventories, discharge rates, and water chemistry from approximately 150 springs within the Pasco Basin.

- Approximately 40 piezometers, wells, and borehole networks to monitor groundwater levels and (or) fluid pressures within the Columbia River Basalt Group at the Hanford Site. In many of these structures (and a few others) water has been analyzed for geochemistry (major, minor, trace inorganic constituents) as well as radioisotopic content, staple isotopes, total organic carbon, and dissolved gases.

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GEOENGINEERING INVESTIGATIONS

The geoengineering program has evolved since 1977 to provide the data needed to evaluate the feasibility of constructing a repository in the basalt of the Columbia Plateau. Geoengineering data available to date are from the following sources:

- Surface borehole tests.
- Core tests.
- Outcrop mapping.
- Field tests at the Near-Surface Test Facility.
- Case studies on similar rocks (literature).

The borehole data consist of downhole tests (hydraulic fracturing and geophysical tests), whereas core tests include core inspection (logging for joint frequency and fracture infillings) and laboratory tests to determine the thermal and mechanical properties of intact and jointed core samples.

Outcrop mapping provides data on lithologic properties, joint continuity, joint spacings, joint roughness, number of joint sets, and thickness and continuity of intraflow structures.

The Near-Surface Test Facility is located in the northern side of Gable Mountain, a basalt outcrop in the north-central part of the Hanford Site, and consists of three tunnels and three rooms. These tunnels are located in the Pomona flow entablature and are approximately 48 m (150 ft) below the surface. Therefore, the conditions of stress, water, temperature, and rock mass behavior at the Near-Surface Test Facility are not representative of conditions expected at the repository horizon. The Near-Surface Test Facility provided a location to conduct tests in basalt. It was intended to gain a general understanding of basalt rock mass behavior under thermal loading conditions expected in the repository and to develop and demonstrate experimental technology for large-scale rock property measurement. The geoengineering tests that have been completed at the Near-Surface Test Facility include

- Full-Scale Heater Test 1.
- Full-Scale Heater Test 2.
- The jointed block test.
- Stress measurement technique evaluation/development tests.

The first three tests involved both mechanical and thermomechanical components.

Literature studies and visits to underground excavations in similar rock provide valuable information on the expected response of basalt to excavation and thermal loading. No existing excavation is loaded in basalt under similar stress conditions, but quantification of existing excavation experience under high in situ stress fields and in jointed crystalline rock similar to basalt provides valuable information for planning and comparing design alternatives.

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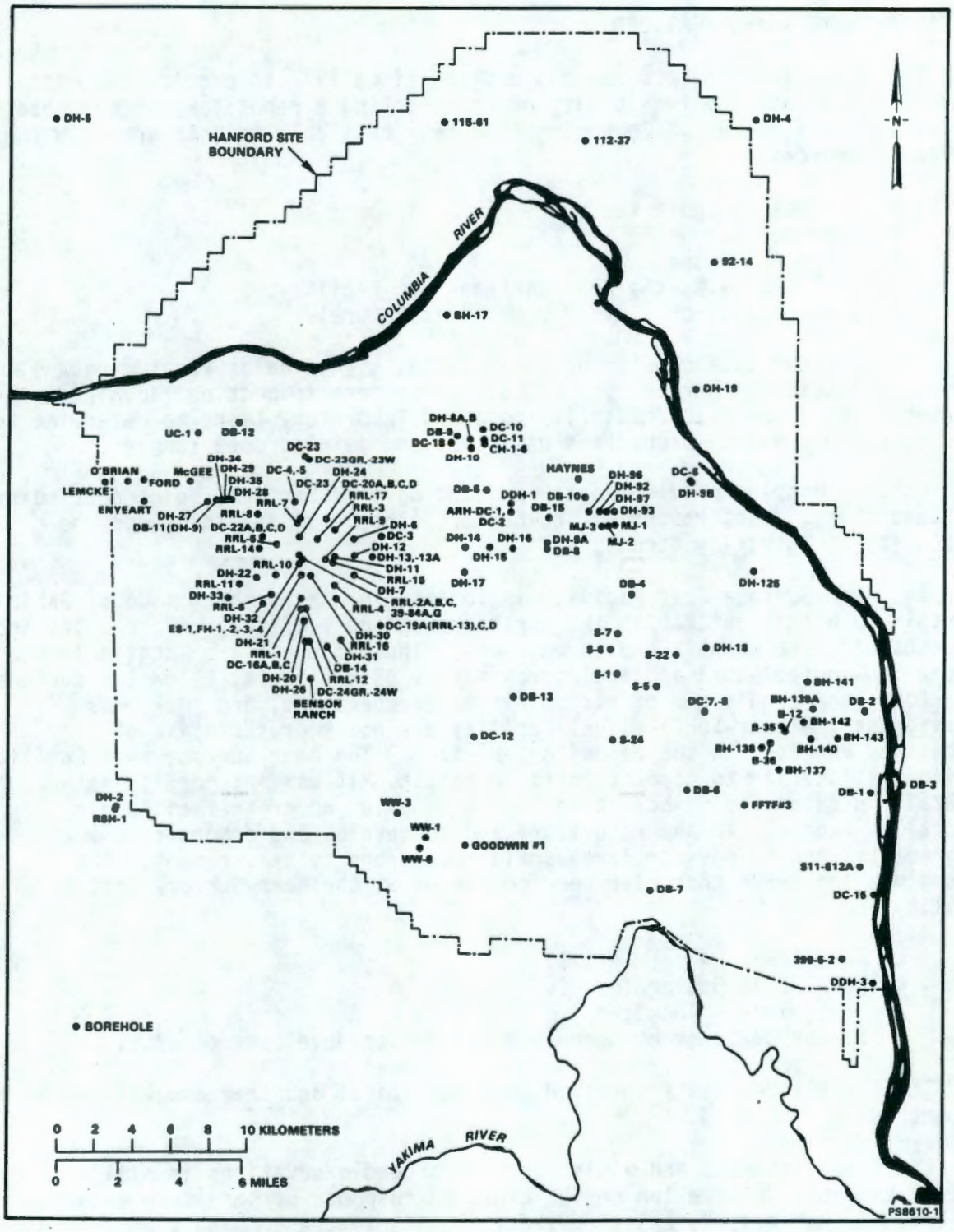

Figure 4. Location map for key boreholes used in Basalt Waste Isolation Project studies.

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These investigations produced a geologic and geophysical data base that includes the following:

- Geologic mapping, including reconnaissance mapping of the Columbia Plateau (163,000 km^2 (62,934 mi^2)) and a detailed compilation map of the Pasco Basin area (5,180 km^2 (2,000 mi^2)).

- Detailed stratigraphic description of over 400 basalt sections on the plateau; many sections in the vicinity of the site contain the Cohassett flow and surrounding units.

- Approximately 12,000 basalt chemistry analyses used to correlate basalt flows.

- Date from approximately 12,000 gravity measurement stations in the Pasco Basin area, with approximately 2,000 of the stations being in and around the not yet defined controlled area study zone.

- Geodetic survey data, based on trilateration and leveling methods, from the Columbia Plateau region and 11 yr of record from about 29 lines in and around the Pasco Basin.

- Remote sensing data of the Columbia Plateau, Pasco Basin, and site from aerial photography and satellite imagery.

- Seismic data from a microearthquake monitoring network operating at the Columbia Plateau since 1969 and nine borehole seismic instruments operating at the site.

- Geophysical survey data that include 1,600 km (1,000 mi) of geophysical lines in the Pasco Basin and over 30 km (20 mi) of seismic refraction lines, approximately 20 km (12 mi) of seismic reflection lines, and 130 km (80 mi) of ground magnetic lines at the site.

- Extensive data from boreholes in the region; data from 2,200 boreholes at the Hanford Site, of which 200 penetrate the first basalt flow; and data from 41 boreholes that penetrate into the basalt sequence at the site (Fig. 4).

This geologic and geophysical information is available in greater detail as separate documents that have previously been released.

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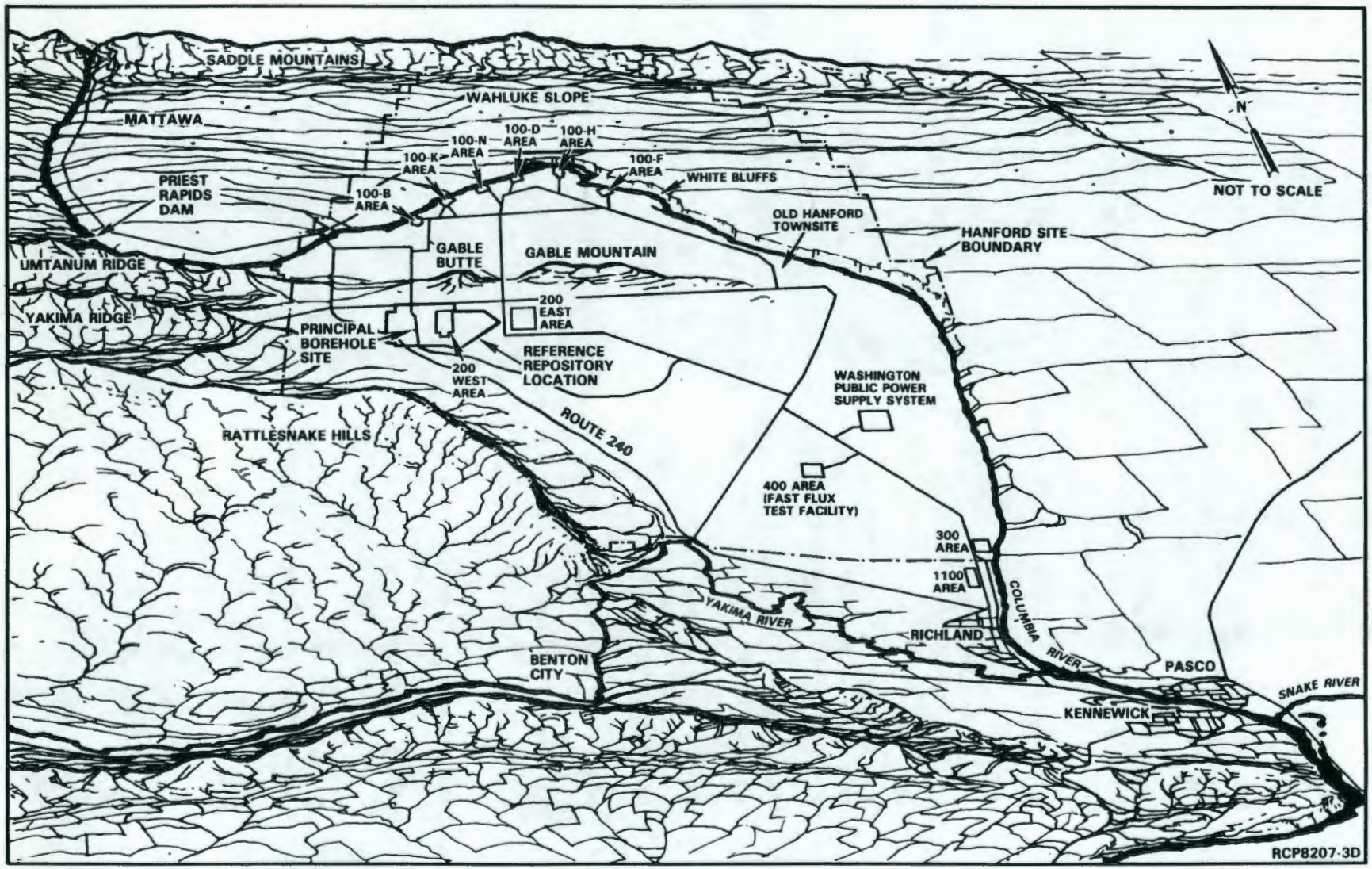

Figure 3. The Hanford Site.

CONSULTATION DRAFT

Some of the geographic attributes of the reference repository location are its isolation from major population centers, arid climate, and availability of abundant freshwater from the Columbia River. There are few competing uses for this land, which has been set aside for nuclear activities. The geographic features, landmarks, and facilities of the Hanford Site are shown in Figure 3.

SOURCES OF INFORMATION AND HISTORY OF SITE INVESTIGATIONS

Part A presents geologic, geomechanical, hydrologic, geochemical, and climatological data on the host rock and its environment. It includes information from the research and exploration activities conducted directly for the BWIP, as well as results of the other studies of the region and the area. The data and interpretations presented in Part A are available in separate documents or data sets.

A substantial portion of the information included in the SCP was presented in the Environmental Assessment (DOE, 1986). Because of new data and refined interpretations, there are some differences between this SCP and the Environmental Assessment; however, in no case have the conclusions presented in the Environmental Assessment been invalidated.

The discussion that follows summarizes past information-gathering activities for each discipline represented in Chapters 1 through 5.

GEOLOGIC INVESTIGATIONS

During the past two decades, many geologic and geophysical investigations have examined the Hanford Site and the surrounding region. These studies have been conducted in support of hydroelectric power development, defense activities, the siting and licensing of commercial nuclear powerplants, and, most recently, hydrocarbon exploration in adjacent areas. The region has also attracted the interest of researchers from the academic community.

Among the commercial-powerplant siting investigations conducted at the Hanford Site, the Skagit/Hanford Nuclear Project (PSPL, 1981) and the Washington Public Power Supply System Nuclear Project WNP-2 (WPPSS, 1981) resulted in comprehensive studies of the geologic characteristics of the region.

Geologic studies initiated for the BWIP in 1977 were designed to aid in the site selection process for the first repository. These investigations started with a review of documents from sources including professional journals, State and Federal programs, graduate student theses, and licensing documents for commercial nuclear powerplants. New field investigations involving geologic mapping, drilling, and geophysical exploration were conducted to fill the gaps in coverage for the area considered for a repository.

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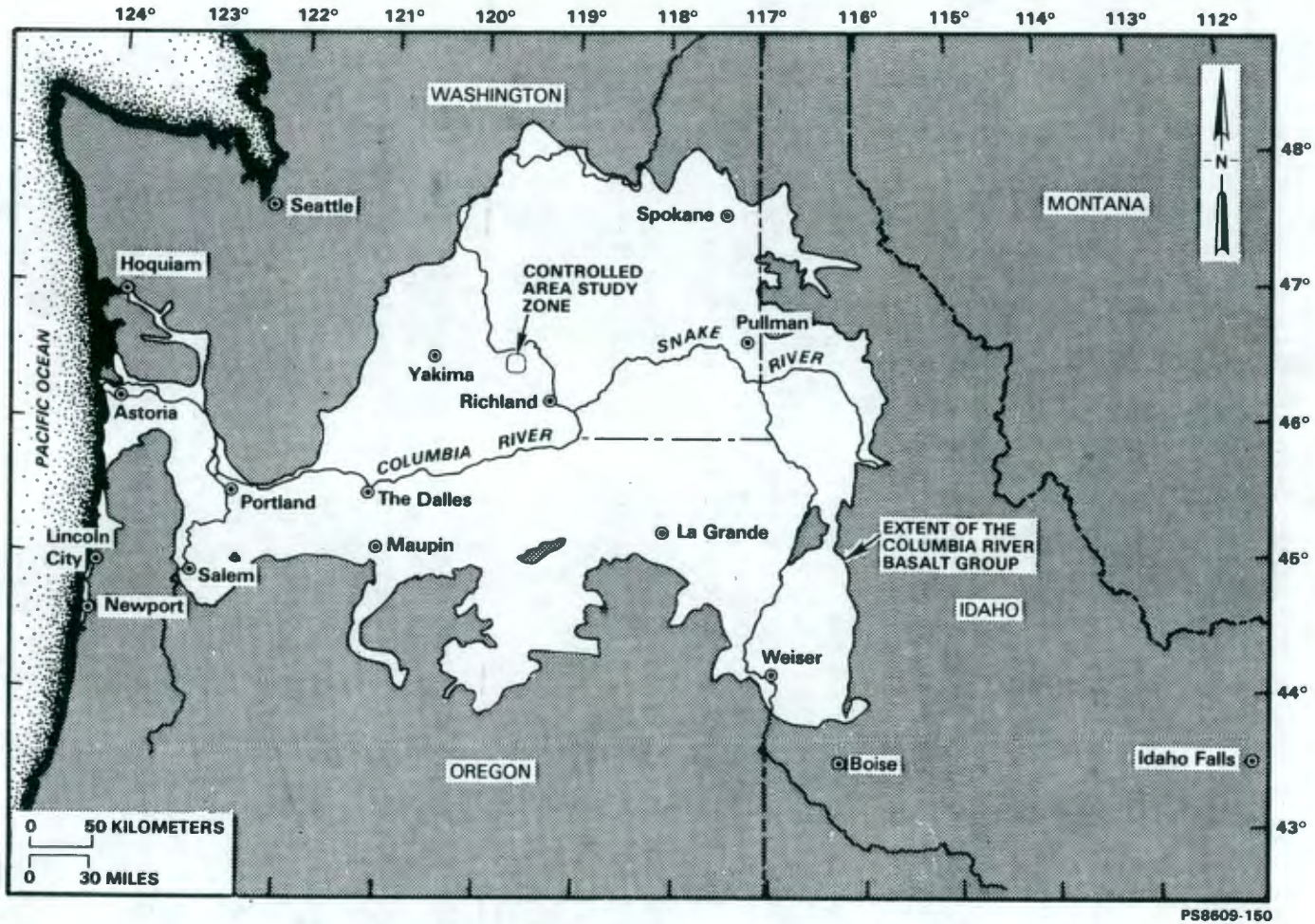

Figure 2. Location map showing areal extent of Columbia River Basalt Group in Washington, Oregon, and Idaho.

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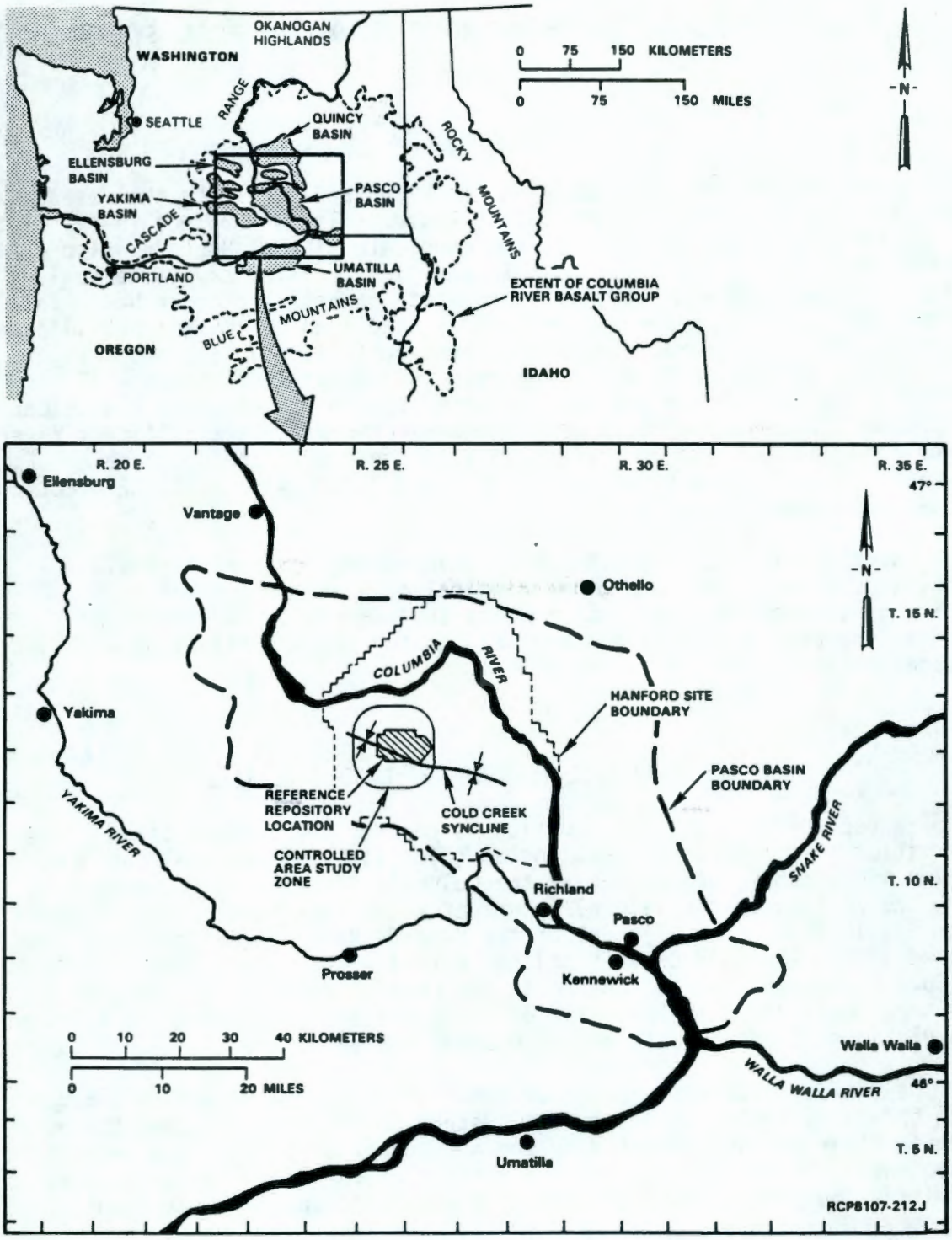

Figure 1. Index map to the Hanford Site, south-central Washington State.

PART A: DESCRIPTION OF THE MINED GEOLOGIC DISPOSAL SYSTEM

INTRODUCTION

Part A of this Site Characterization Plan (SCP) presents the research and exploration data compiled by the Basalt Waste Isolation Project (BWIP) of the U.S. Department of Energy (DOE) on the candidate site at Hanford, also called the reference repository location. In addition, preliminary conceptual designs for the proposed repository and waste package are described. This information should be viewed as an interim step leading to, and providing a basis for, the site characterization investigations, studies, and design activities described in Part B. The results of these activities will determine whether a mined geologic disposal system at the Hanford site can be constructed, operated, closed, and decommissioned without significant adverse effects on public health and safety in accordance with the applicable DOE, U.S. Nuclear Regulatory Commission (NRC), and U.S. Environmental Protection Agency (EPA) regulations.

Chapters 1 through 5 present available geologic, geomechanical, hydrologic, geochemical, and climatological data describing the characteristics of the host rock and its environment. Chapters 6 and 7 describe the preliminary conceptual designs for the repository and the waste package.

GEOGRAPHIC SETTING OF THE CANDIDATE SITE

The reference repository location is part of the Hanford Site, a Federal reservation in south-central Washington (Fig. 1). Its regional geologic setting is commonly referred to as the Columbia Plateau, the boundaries of which are defined by the lateral extent of rocks that make up the Columbia River Basalt Group (Fig. 2) east of the Cascade Range. The candidate site is located within the Cold Creek syncline, a fold within the Yakima Fold Belt. The Cold Creek syncline is located in the central portion of a larger structural unit known as the Pasco Basin. This basin contains the thickest accumulations of basalt within the Columbia Plateau.

The Hanford Site has been under the control of the Federal Government since the early 1940s, when the flat, desert countryside adjacent to the Columbia River was appropriated by the government as part of the war effort. Subsequently, it has been used for a variety of purposes, including defense activities, research, commercial power generation, and waste management.

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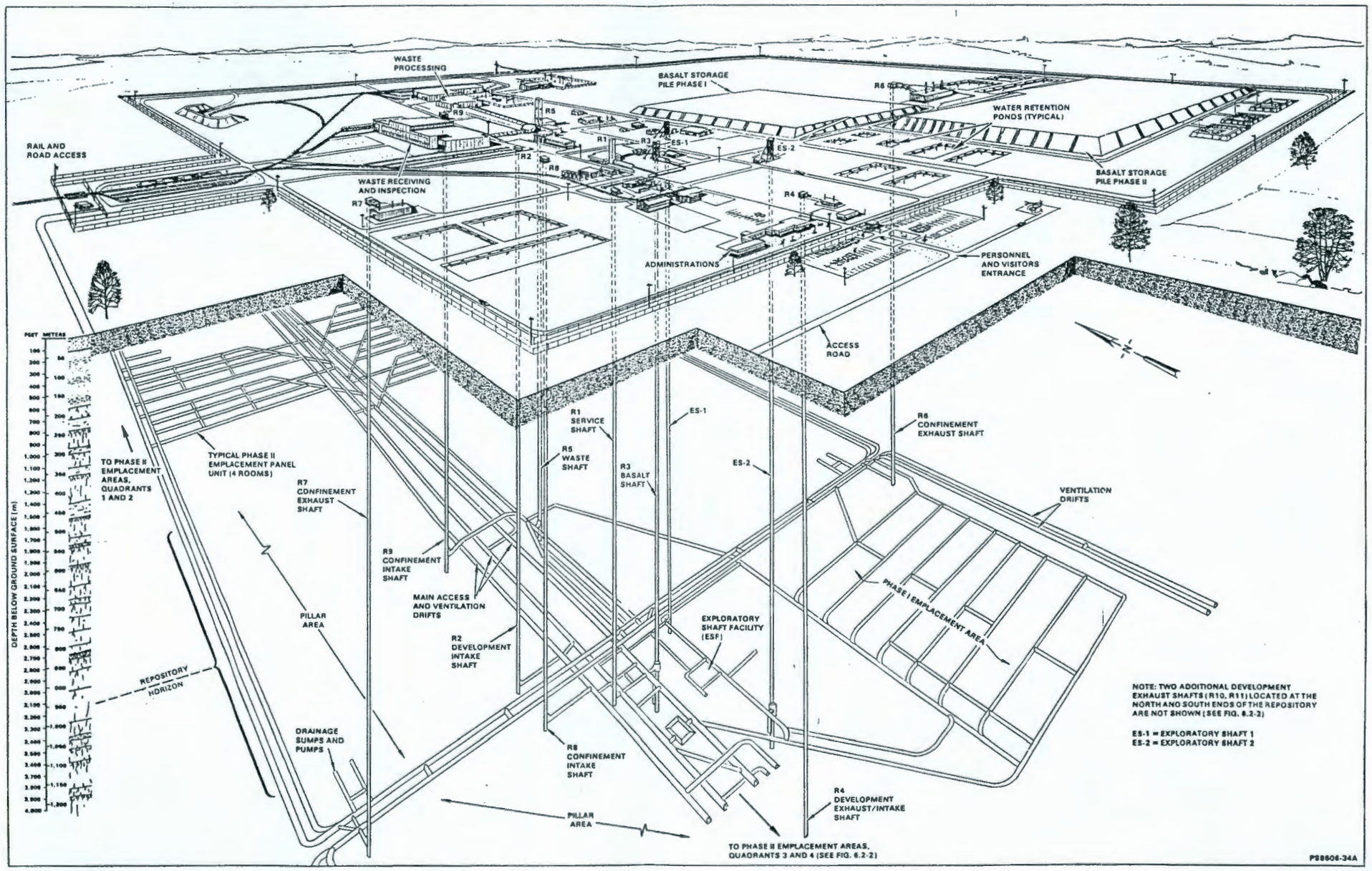

Figure 5. Repository surface facilities, access shafts, and underground facilities.

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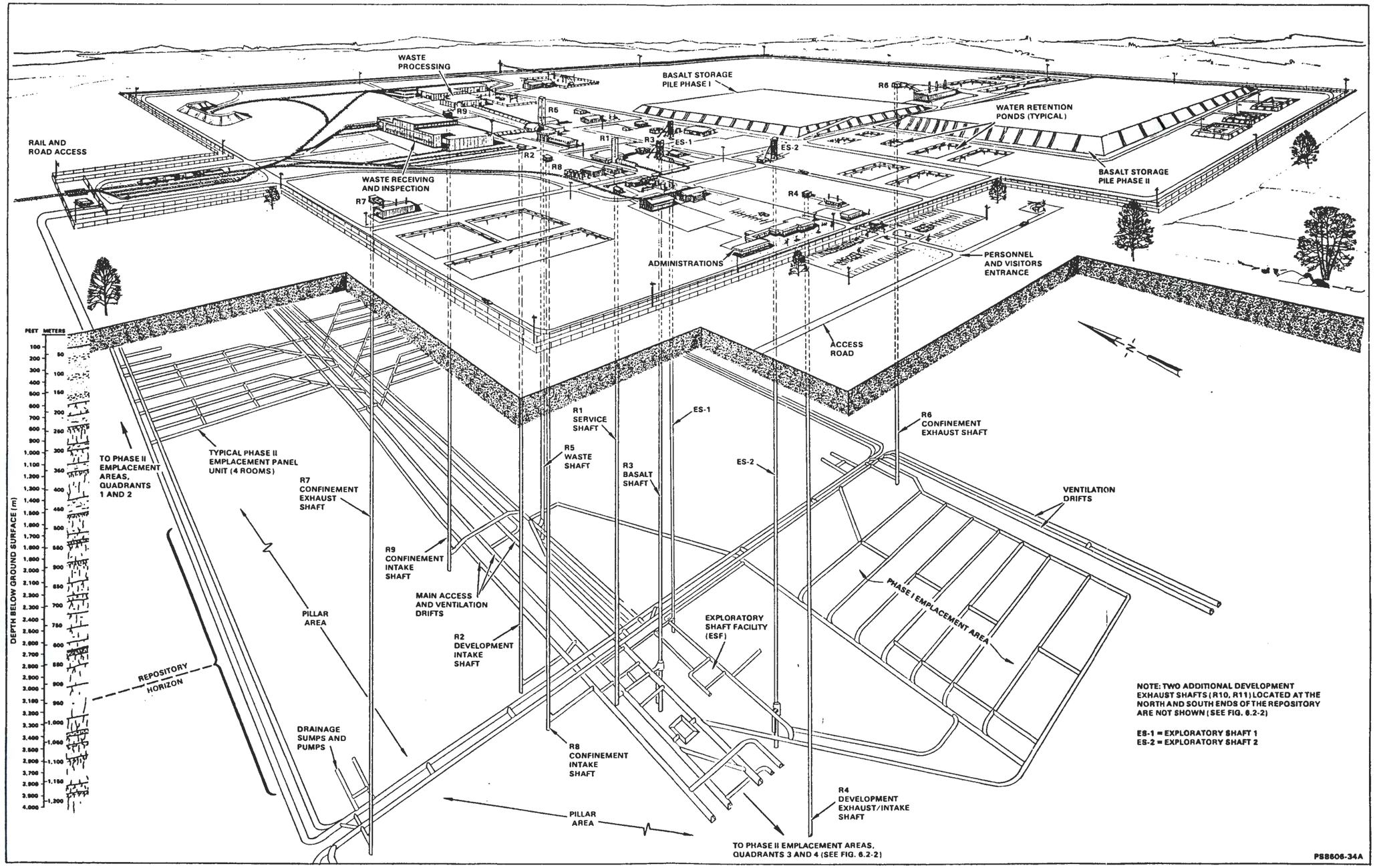

Figure 5. Repository surface facilities, access shafts, and underground facilities.

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SITE CHARACTERIZATION PLAN

Chapter 1.0

Geology

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Chapter 1

GEOLOGY

1.0 INTRODUCTION

This chapter provides a description of the geologic setting of the reference repository location at the Hanford Site, a federally owned nuclear reservation in south-central Washington State. The description is intended to orient the reader as to what is presently known and what is uncertain regarding this geologic setting. The information will aid readers in understanding the relationship between the geologic setting and (1) the proposed design for a repository and (2) the rationale for the site characterization program that is presented in Chapter 8.

The reference repository location at the Hanford Site is located in a geologic setting commonly referred to as the Columbia Plateau (Fig. 1.0-1). The boundaries of this region are defined by the lateral extent of rocks that make up the Columbia River Basalt Group east of the Cascade Range. These flood basalts were extruded through linear fissures between approximately 17 and 6 million years before present (m.y.B.P.). Individual flows contain dense interiors that have sufficient lateral and vertical extent to house a repository. The flow that has been designated as the candidate horizon for a repository is the Cohassett flow, a unit within the Grande Ronde Basalt.

The reference repository location lies within the Cold Creek syncline, a trough-like depression within the Yakima Fold Belt. The strata at the site are essentially flat lying and consist of several deep, thick basalt flows such as the Cohassett flow. The Cold Creek syncline is located in the central portion of a larger structural low known as the Pasco Basin. This topographic and structural basin contains a thick accumulation of basalt and has been in existence as a structural low since at least the earliest extrusion of the basalt flows approximately 17 m.y.B.P.

The remainder of this introductory section contains brief summary remarks on the purpose of geologic investigations in site characterization, the sources for existing data, the plans for acquiring additional data, how the data will be used, and a discussion of data quality and the models that will use geologic information.

PURPOSE OF THE GEOLOGY PROGRAM

Geologic investigations form the foundation for many future decisions to be made regarding the recommendation and possible development of the candidate site at the Hanford Site as a repository. The siting guidelines presented in 10 CFR 960 (DOE, 1987b) are the basis for identifying geologic investigations during the site-selection phases that lead up to recommending a location for

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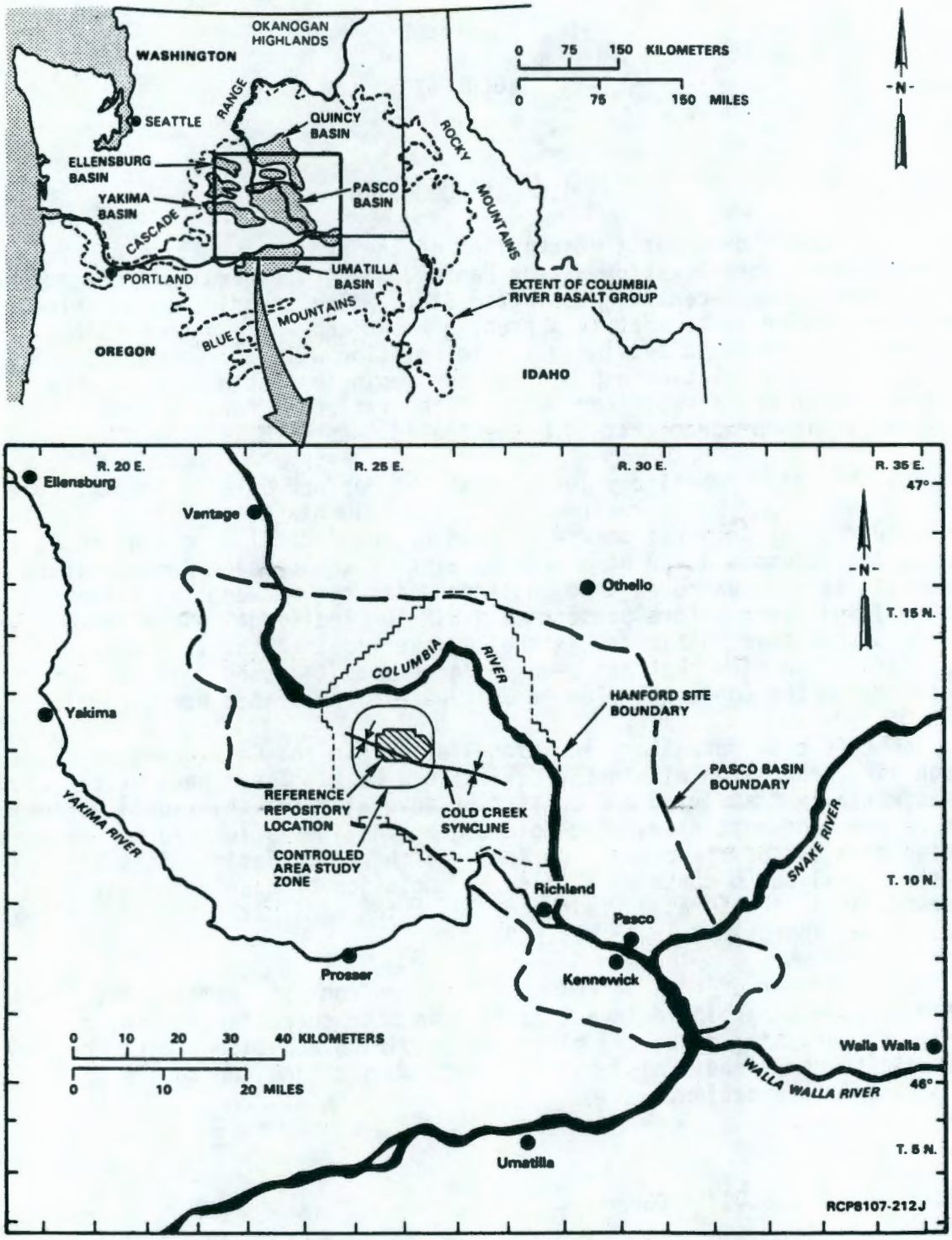

Figure 1.0-1. Index map to the Hanford Site, southeastern Washington State.

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the first repository. This regulation specifies the types of geologic information that are required for both preclosure and postclosure periods during which the performance of the location must be assessed. The geologic studies conducted during site characterization must also be sufficiently comprehensive to provide information to support a license application, using the technical criteria contained in 10 CFR 60 (NRC, 1987).

Geologic investigations play a significant role in the issues resolution strategies that are presented in Section 8.2. They either provide the basic information that is required to resolve an issue or contribute information to other investigations to aid in resolving an issue. The common issues hierarchy that has been adopted for the three candidate sites groups the issues into performance issues, design issues, and characterization issues (DOE, 1987c, pp. 2-3). Geologic investigations contribute to all three groups. Table 8.3.1.2-1 in Chapter 8 provides a summary of the information needs, as developed from the common issues hierarchy, that are provided by geologic investigations.

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SOURCES OF GEOLOGIC DATA

During the past two decades, numerous geologic and geophysical investigations have examined the Hanford Site and the surrounding region. These studies have been in support of hydroelectric power development, nuclear activities associated with defense, siting and licensing of commercial nuclear powerplants, and most recently, hydrocarbon exploration in adjacent areas. The region also has attracted the interest of researchers from the academic community.

Among the commercial powerplant siting and licensing investigations that have been conducted at the Hanford Site, two have resulted in comprehensive reviews of geologic characteristics of the region and specific locations:

- The preliminary safety analysis report for the Skagit/Hanford Nuclear Project (PSPL, 1981, Amend. 23, pp. 2.5-1 to 2.5-34).
- The final safety analysis report for the Washington Public Power Supply System Nuclear Project WNP-2, which is presently operating (WPPSS, 1981, Amend. 18, pp. 2.5-1 to 2.5-231).

These licensing documents have been subjected to numerous reviews by government agencies, including the U.S. Geological Survey (USGS); by private consultants from industry and from the academic community; and by the public--all as part of the U.S. Nuclear Regulatory Commission (NRC) review of the license application.

The geologic studies that were initiated by the Basalt Waste Isolation Project (BWIP) in 1977 were designed to aid the U.S. Department of Energy (DOE) in the site-selection process for the first geologic repository. These investigations started with a review of published work from many sources,

including professional journals, State and Federal programs, graduate theses, and licensing documents for commercial nuclear powerplants. New field investigations involving geologic mapping, drilling, and geophysical exploration were conducted to add to the existing geologic and geophysical data base for the area being considered at the Hanford Site. These investigations were designed to provide the DOE with information that directly applied to site-selection criteria listed in 10 CFR 960, Subparts C and D (DOE, 1987b) or predecessor criteria.

The present data base now includes information in the following forms:

- Geologic maps--various scales, showing surficial deposits, bedrock stratigraphy, and tectonic structures for the Pasco Basin and vicinity.
- Stratigraphic sections--detailed descriptions of basalt sections containing potential candidate horizons at numerous locations.
- Basalt chemistry analyses--approximately 12,000 analyses, which have provided a major advance in correlating basalt flows in the region and in verifying geologic mapping in complex areas.
- Geophysical survey data--gravity, magnetic, seismic reflection, seismic refraction, and magnetotelluric methods.
- Borehole data--stratigraphic, petrologic, mineralogic, structural, and geophysical observations.
- Geodetic survey data--trilateration and leveling methods.
- Remote sensing products--aerial photography and satellite imagery.
- Instrumental records for earthquakes--eastern Washington regional network, Hanford Site surface network, high-resolution borehole subsurface network, instrumentation at repository depths, and strong-motion surface instruments.

This geologic and geophysical information is available in greater detail as separate documents that have previously been released to the public. Among the principal reports that describe the work completed as part of the BWIP are the following: Myers/Price et al. (1979), Myers and Price (1981), DOE (1982), Caggiano and Duncan (1983), Long and WCC (1984), and DOE (1986).

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PLANS FOR OBTAINING ADDITIONAL GEOLOGIC DATA

The additional data-gathering and analysis activities that are required to supplement present geologic information are described in Sections 8.3.1.2 and 8.3.1.6. Detailed descriptions of the planned work are also presented in separate study plan documents. Planned geologic activities have been divided into four primary investigations:

- Stratigraphy and Structure--studies involving stratigraphy, structural geology, intraflow structures, and fracture characteristics.
- Tectonic Events and Processes--studies involving structural geology, deformation, erosion, earthquake seismology, and models for the tectonic setting.
- Mineralogy and Petrology--studies related to characterizing mineral variability and stability.
- Mineral, Hydrocarbon, and Geothermal Resource Potential.

The site characterization activities that are planned as part of the site-selection process contain several aspects that are unique to a geologic repository. These include:

- The need to anticipate geologic processes over a much longer time interval (i.e., 10,000 to 100,000 yr, rather than 50 to 100 yr).
- The subsurface location of the repository at an approximate 950-m (3,100-ft) depth.
- The increased emphasis on rock characteristics as a natural barrier against migration of radionuclides that might be released from engineered barriers.

For these reasons, the investigations to characterize the site for the purpose of selecting a location for a deep geologic repository are more extensive than those required to perform safety analyses for nuclear facilities at the surface. The search for a location to permanently store high-level radioactive wastes is an endeavor not previously undertaken, and the precedents that have been set for allowing the construction and operation of nuclear power reactors may not be comprehensive enough for, or applicable to, licensing a repository.

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USES OF GEOLOGIC DATA

The geologic data contained in Chapter 1, along with new data to be obtained during site characterization, will be used in several ways. First, they will help evaluate the suitability of the candidate site at the Hanford Site relative to the siting guidelines contained in 10 CFR 960 (DOE, 1987b). The criteria contained in this regulation describe the site in terms of "qualifying, favorable, potentially adverse, and disqualifying conditions." The end result of this exercise will be a decision on whether the site meets the minimum requirements set forth in the regulation and, therefore, can be recommended to the President for development as the Nation's first geologic repository. Table 1.0-1 shows the correlation between the subheadings of this chapter and the broad categories of information needs that are contained in the siting guidelines.

Table 1.0-1. Correlation between information presented in this chapter and the U.S. Department of Energy's siting guidelines for nuclear waste repositories (DOE, 1987b)

10 CFR 960: Information Needs for Characteristics, Processes, and Events	Corresponding section of this chapter						
	1.1 Geomor-phology	1.2 Stratigraphy	1.3 Structural Geology/ Tectonics	1.4 Seismology	1.5 Long-term Geologic Stability	1.6 Drilling/ Mining	1.7 Natural Resources
Postclosure guidelines							
Rock Characteristics (960.4-2-3)		X					
Erosion (960.4-2-5)	X				X		
Tectonics (960.4-2-7)			X	X	X		
Natural Resources (960.4-2-8-1)						X	X
Preclosure guidelines							
Rock Characteristics		X					
Tectonics (960.5-2-11)			X	X	X		

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Second, geologic data will provide various parameters to the designers of the repository and waste package. The layout of tunnels will be constrained by the geometry and physical characteristics of the Cohassett flow. The geochemical environment, fracture characteristics of the host rock, and stress regime are all significant factors in the design of the waste canisters and underground excavations. Vibratory ground motion estimates, both for repository depths and the surface, are used in the design of certain facilities that will be associated with the repository.

Third, geologic data will be used in determining how well the repository will perform--in the sense of being able to isolate nuclear waste from the accessible environment. Geologic and geophysical information will be used in nearly all of the modeling associated with this assessment. Example applications include the following:

- Estimating volume and flow rate for groundwater through the host rock in the vicinity of the repository.
- Predicting the transport paths and travel times of radionuclides from the canisters to the accessible environment.
- Predicting the occurrence of future events that would disrupt the engineered containment of nuclear waste or enhance its dispersion to the accessible environment.
- Estimating the dynamic response of engineered facilities to ground motion caused by natural seismicity.

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QUALITY OF GEOLOGIC DATA AND MODELS

Geologic data will be used in a variety of modeling efforts during site characterization. The parameters that describe (1) the physical characteristics of the geologic setting and (2) the processes that are changing those characteristics are useful in models that are applied during the design of repository facilities (see Sections 6.1.2 and 6.1.3) and for performance assessment purposes (see Section 8.3.5). One example of a model that uses the data in this chapter, as well as data to be collected as site characterization continues, is a stratigraphic and structural model for the immediate vicinity of the site. This model, which is essentially a computer data base of observations on the geometry of various stratigraphic units and structures, can be manipulated for both design and performance assessment purposes.

In its present form, the stratigraphic and structural model contains sufficient data to produce generalized structure contour and isopach maps of rock units at the site. However, additional data and more detailed analysis of geophysical surveys are necessary to provide a complete understanding of potential subsurface structures. The model is, therefore, presently limited regarding its usefulness in the design of subsurface excavations and

application in certain performance assessment models, such as groundwater flow simulation (see Sections 3.9.3 and 8.3.1.3). A description of the stratigraphic and structural model, along with the plans for additional data gathering activities, are presented in Section 8.3.1.2.3.3.6.

Geologic data that describe the mineralogy, petrology, and fracture characteristics of basalt flows, in addition to the structural configuration of the rock units, will be used in simulation models for radionuclide flux from various components of the repository system. This modeling activity is described in Sections 8.3.2.5, 8.3.3.5, and 8.3.4.5. The quality of geologic data that are presently available as input to this modeling, and the sophistication of the models themselves, are discussed in those sections.

Predicting future changes to the geologic setting will involve the use of several models that simulate tectonic processes, such as folding, faulting, uplift, and subsidence within the Earth's crust. Much of the data in Chapter 1 will be used to develop hypotheses that explain the mechanisms and rates of occurrence of tectonic processes. Both individual hypotheses and groups of hypotheses will function as models that can be used either for predictions or for providing an understanding of a system. No single simulation of the tectonic setting will be capable of predicting all of the future conditions at the site.

One example of future events that are predicted using modeling methods is the occurrence of earthquake ground motion. The steps leading to the prediction of future earthquake ground motion for which there must be design considerations, involve several models. First, structures or zones that are likely to generate future earthquakes or earthquake swarms are described, including estimates of the largest events that are probable and their rates of occurrence. Second, a model for the attenuation and modification of earthquake waves during their passage from the source areas to the site is either developed or assumed. Third, predictions of the ground motions to be expected at the site are made using the above model, with consideration for certain characteristics of the site (e.g., foundation materials for surface facilities) and the 950-m (3,100-ft) depth for subsurface facilities. A description of the modeling efforts and data requirements for predicting future earthquakes and ground motion at the site is presented in Section 8.3.1.2.

In addition to modeling that will be a part of the repository design and performance assessment processes, numerous hypotheses will be developed during site characterization to portray various aspects of the geologic setting, such as the relationship between folding and faulting within a Yakima fold. These hypotheses will continue to be tested as site characterization proceeds, and they may eventually function as predictive tools. Their special usefulness lies in providing an understanding of the structures and processes that characterize the geologic setting--an understanding that is essential if informed judgments on the suitability of the site are to be made in the future. Without an understanding of the processes that have shaped the geologic setting as it exists presently, there can be little confidence in predicting the future performance of the site as a repository.

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ORGANIZATION OF CHAPTER 1

Chapter 1 provides a description of the geology of the candidate area and site, field and laboratory activities conducted in support of geologic studies, and geologic data acquired from the literature. It also describes models applicable to current and future site characterization activities.

Section 1.1 describes the physiographic provinces, topography, common landforms, and geomorphic processes contained in the geologic setting.

Section 1.2 describes the lithologic characteristics of rock units, their correlations, and their geologic history, both at regional and site-specific levels of detail.

Section 1.3 describes the tectonic setting of the reference repository location, including the major structural features, tectonic processes, and Quaternary history. Models used to interpret the structural evolution of the region are introduced. The structural geology of the reference repository location is described in detail, using surface geologic maps, geophysical survey results, and borehole data. Information on stress regime, rates of deformation, and geothermal regime is also included.

Section 1.4 describes historical earthquakes, the instrumental record, and distribution of earthquakes for the region and the reference repository location. Estimates for ground motion parameters of importance to design and performance assessment, along with a discussion of seismic hazards, are presented.

Section 1.5 examines the long-term regional stability with respect to tectonic and geologic processes. It describes the conditions to be expected during the next 10,000 yr, as extrapolated from models and disruptive event scenarios.

Section 1.6 describes drilling and mining activity in the vicinity of the reference repository location.

Section 1.7 discusses the mineral, hydrocarbon, and geothermal resources of the region and the likelihood of their future development.

Section 1.8 summarizes information from the previous sections that is significant to site characterization objectives, and introduces the issues and planned activities that are described in detail in Chapter 8.

Section 1.9 contains the references.

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1.1 GEOMORPHOLOGY

The following description of the geomorphologic setting is divided into discussions of the physiography of the region, the geomorphic units of the candidate area, and the geomorphic processes that have acted to shape the land surface of the candidate area. The region is represented by the Columbia Intermontane Province, along with the Cascade Range and Northern Rocky Mountains Provinces that border it. The candidate area is contained within the Columbia Basin and Central Highlands subprovinces, an area underlain by the Columbia River Basalt Group and commonly referred to as the Columbia Plateau.

The discussion of regional physiography is included to orient the reader to the large-scale physical characteristics of the geographic location. A description of the intermediate scale geomorphic units is intended to introduce the reader to the geomorphic processes that have acted to shape the land surface that can be seen today, as well as to the structural geology characteristics of the candidate area.

The description of geomorphic processes that have either been active during approximately the last 5 m.y., are active presently, or are likely to be active during the next 10,000 yr, form part of the basis for an assessment of long-term geologic stability of the candidate site (see Section 1.5). Changes in either the types or rates of geomorphic processes could alter the hydrologic system, resulting in a potential impact on the capability of the repository to isolate radioactive wastes.

Changes in geomorphic processes typically follow changes in climate or tectonic activity. Examples of possible future conditions are as follows:

- Fluvial or proglacial aggradation leading to the creation of new landforms (e.g., flood bars or outwash plains) or tectonic movements that divert the Columbia River closer to the reference repository location, and thereby shortening groundwater flow paths.

- Increases in groundwater recharge, either through increased fluvial activity or proglacial floods associated with future climatic changes, which increase flow rates.

- Deep incision of the land surface resulting from a change in base level that is caused by either tectonic uplift or climatic change, which would result in the repository becoming closer to the land surface.

- Fracturing or tectonic movements induced by isostatic adjustment of a continental ice sheet overlying or near the site that could alter the hydrologic regime.

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1.1.1 PHYSIOGRAPHY

This discussion of physiography is based on the classification scheme presented in Thornbury (1965, p. 444). It uses three main subdivisions: province, subprovince, and section. The discussion of physiography is made at the province level. A more detailed description of the topography, landforms, and structural characteristics at the subprovince and section levels is presented in Section 1.1.2.

The candidate area is contained primarily within the Columbia Basin and Central Highlands subprovinces of the Columbia Intermontane Province. Freeman et al. (1945), Thornbury (1965, pp. 442-470), McKee (1972, pp. 174-289), and Alt and Hyndman (1984) present more detailed descriptions of the physiography of the region surrounding the candidate area.

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1.1.1.1 Columbia Intermontane Province

The candidate site at the Hanford Site lies within the Columbia Intermontane Province that is bordered on the north and east by the Rocky Mountains and on the west by the Cascade Range (Fig. 1.1-1). The Basin and Range Province lies to the south. The Columbia Intermontane physiographic province has been a topographic and structural depression since the early Miocene. It is subdivided into smaller physiographic units primarily on the basis of topography, although structural geology has played a role in subdivisions as well.

The dominant geologic characteristics of the Columbia Intermontane Province have resulted from flood basalt volcanism. Flows of the Columbia River Basalt Group were extruded from linear vents in southeastern Washington, northeastern Oregon, and west-central Idaho between about 17 and 6 m.y.B.P. Although most basalt flows lie east of the Cascade Range, some flowed as far west as the Pacific Ocean via the ancestral Columbia River. The ancient basalt surface has subsequently been altered by tectonism, volcanism, weathering, and erosion.

The Columbia Intermontane Province is distinguished by its relatively uniform rock type and undeformed nature, when compared to adjacent provinces that developed under different tectonic and climatic settings. The Columbia Plateau is the portion of the Columbia Intermontane Province that is covered by the Columbia River Basalt Group (Thornbury, 1965, p. 442). This area includes folded and faulted uplands, as well as sediment-filled basins; thus, the term "Columbia Plateau" is a misnomer in that the Columbia River Basalt Group is rarely preserved as an elevated plateau. Although not a formal geologic name, "Columbia Plateau" is used in this report because of its common use in the literature; it is also defined as the geohydrologic setting in the Environmental Assessment (DOE, 1986, pp. 1-17).

The Columbia Intermontane Province is subdivided into four subprovinces: Columbia Basin, Central Highlands, High Lava Plains, and Owyhee Upland (Freeman et al., 1945; Thornbury, 1965, p. 444; see Fig. 1.1-1). The Columbia

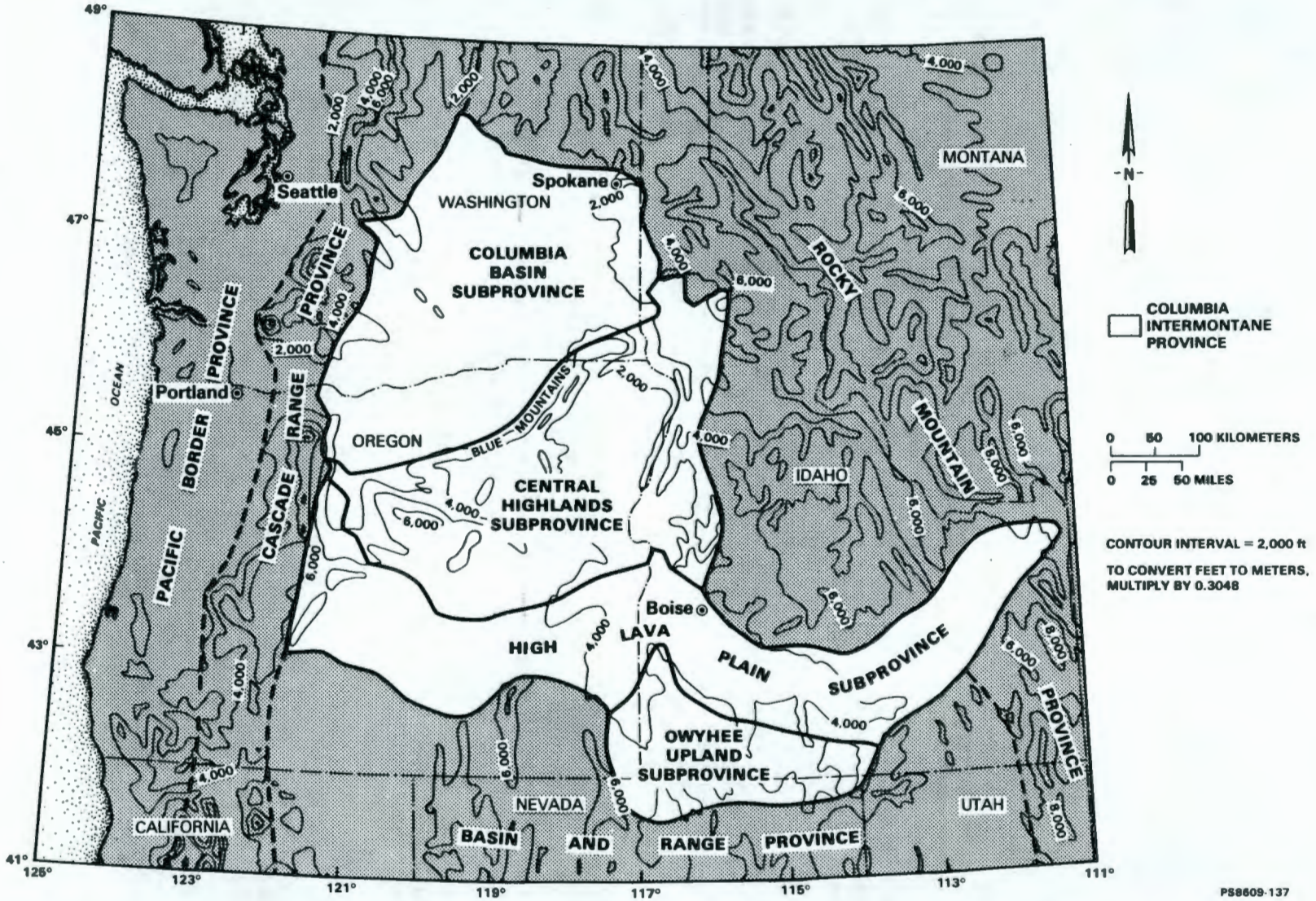

Figure 1.1-1. Divisions of the Columbia Intermontane Province and adjacent provinces (after Freeman et al., 1945, p. 56; Thornbury, 1965, p. 445).

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Basin subprovince, where most of the Columbia River Basalt Group is located, is bounded by the Cascade Range on the west, the northern Rocky Mountains on the north and east, and the Blue Mountains to the south. These mountain ranges developed under different tectonic regimes and at different times. Degradation of these mountain ranges surrounding the subprovince has led to aggradation of relatively thick sequences of volcaniclastic and epiclastic sediments in basins within the Columbia Basin since the early Miocene.

1.1.1.2 Cascade Range Province

The Cascade Range, a relatively narrow, north-south trending mountain chain, lies along the western border of the Columbia Intermontane Province. The relief of this dissected volcanic upland ranges from 4,400 m (14,410 ft) at Mount Rainier to near sea level along the Columbia River Gorge. The Cascade Range formed as a result of back-arc volcanism associated with plate subduction off the Pacific coast (see Section 1.3.2.1.3). Cascade volcanism, which began in the Eocene, continues today as reflected by the recent eruptions of Mount St. Helens. Active geomorphic processes include degradation through fluvial downcutting, mass wasting, and mountain glaciation as well as local aggradation of debris flow, pyroclastic, and airfall deposits associated with recent eruptions of Mount St. Helens. The high relief of the Cascade Range suggests that mountain building, through volcanism and tectonic uplift, is presently occurring at a faster rate than reduction of relief by exogenetic processes.

The arid to semiarid climate over most of the Columbia Basin subprovince is directly related to the "rain shadow" effect of the Cascade Range. These relatively dry conditions are reflected in the central plateau by the chemical precipitation of calcic soils, and these conditions can be traced back at least into the late Miocene (approximately 8.5 m.y.B.P.). Vertebrate fauna in the Ellensburg and Ringold Formations, however, suggest warm and humid conditions have also existed during the late Cenozoic, so that the Cascade Range must have been periodically at lower elevations.

1.1.1.3 Northern Rocky Mountains Province

The northern portion of the Rocky Mountain physiographic province lies along the north and east border of the Columbia Basin subprovince (see Fig. 1.1-1). The Rocky Mountains, ranging from about 750 to 3,800 m (2,500 to 12,500 ft) in elevation, are a broad mountainous mass containing a complex assemblage of rocks. This assemblage consists of Precambrian to Mesozoic sedimentary, metasedimentary, and metavolcanic rocks, along with Mesozoic to early Cenozoic intrusive and extrusive igneous rocks. Like the Cascade Range, the Rocky Mountains are simultaneously undergoing tectonic uplift and degradation through weathering, fluvial, mass wasting, and to a lesser extent, glacial processes.

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1.1.2 GEOMORPHIC UNITS

For the most part, Columbia River basalt is confined to the Columbia Basin and Central Highlands physiographic subprovinces (Fig. 1.1-2). These are subdivided into nine sections primarily on the basis of topography (the terminology is that of Freeman et al., 1945, pp. 60-69). The Central Highlands subprovince generally has higher relief and a more humid climate compared to the arid to semiarid conditions of the Columbia Basin subprovince. A summary of relief, climate, and types of processes and landforms within these units is presented in Table 1.1-1. In general, the same processes that have been active within the Columbia Basin and Central Highlands subprovinces throughout the Quaternary are presently active, with the exception of large-scale flooding and glaciation, both of which ended about 13,000 yr ago.

The following discussion on geomorphic units begins at a regional scale for those units within the Central Highlands and Columbia Basin subprovinces. This is followed by a site-specific discussion of units within and adjacent to the reference repository location.

1.1.2.1 Central Highlands subprovince

The Central Highlands subprovince (see Fig. 1.1-2) is divided into three sections: the Blue Mountains, the Wallowa-Seven Devils, and the Tri-State Upland units (Freeman et al., 1945, pp. 65-69; Thornbury, 1965, pp. 457-459). The Blue Mountains are a broad, generally northeast-trending upwarp of pre-Miocene rocks that are locally capped by Columbia River basalt. They range in elevation from approximately 350 to 3,000 m (1,150 to 9,850 ft) and consist of Upper Paleozoic to Lower Mesozoic accretionary sedimentary and volcanic rocks, Mesozoic intrusives, and early Tertiary volcaniclastic and sedimentary rocks. Tectonic uplift in the Blue Mountains, which has been active throughout late Cenozoic time, continues along east-west trending folds and faults to the southwest and along high-angle, northwest-trending Basin-and-Range type faults south and east of the Columbia Intermontane Province (see Section 1.3.2.2.1.3). Mountain glaciation occurred locally during the Pleistocene; however, today the only active processes are weathering, mass wasting, and stream incision of the highlands and sedimentation in the valleys.

The Wallowa-Seven Devils section, located in the southeastern Central Highlands subprovince, is a mountainous region over 3,000 m (9,850 ft) high in places. An arm of Columbia River basalt, known as the Weiser Embayment, lies within this section. Like the Blue Mountains, the Wallowa-Seven Devils section is undergoing degradation through weathering, stream incision, mass wasting, and mountain glaciation (Farooqui et al., 1981b, pp. 39-48).

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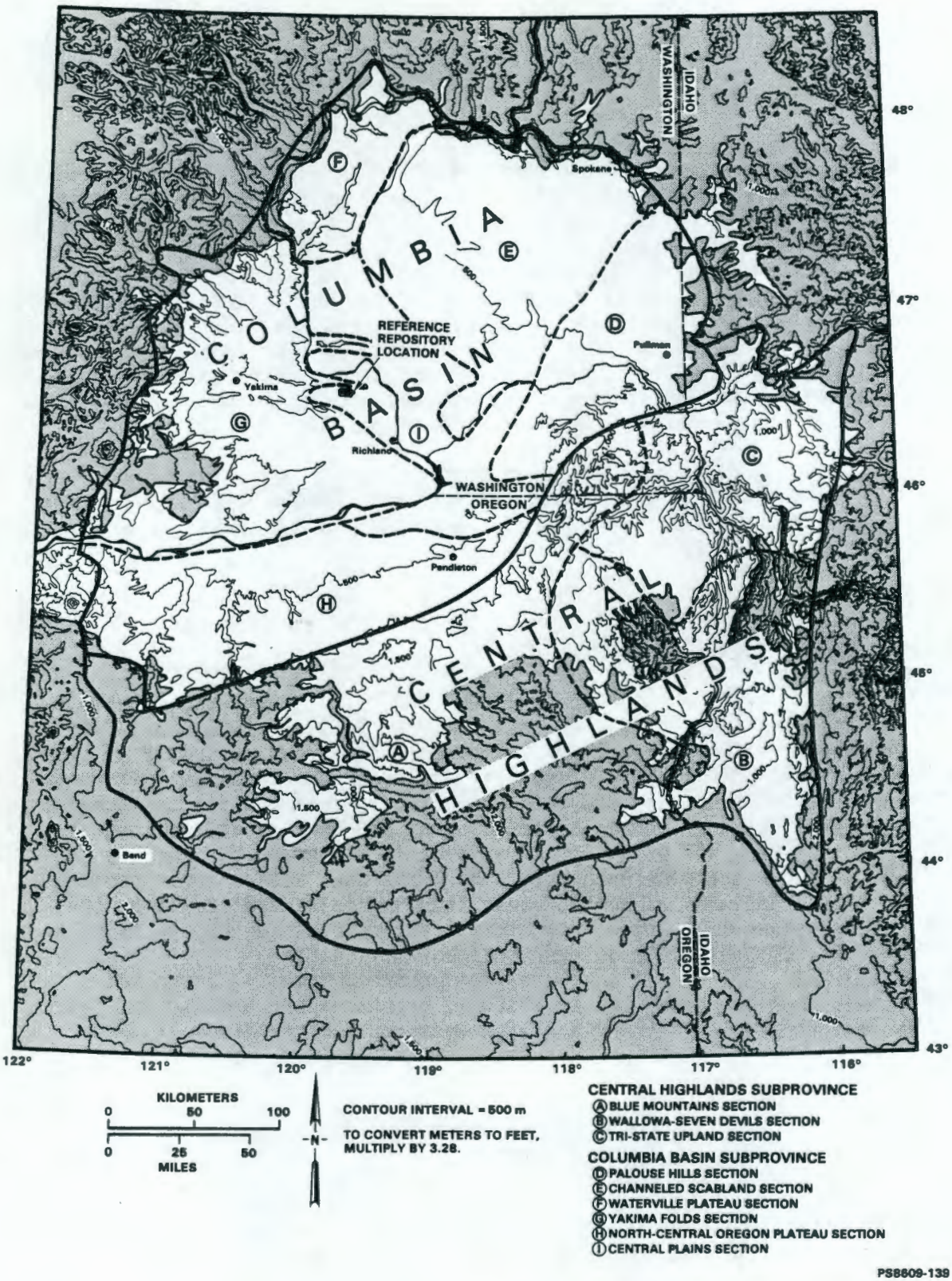

Figure 1.1-2. Geomorphic units within the Central Highlands and Columbia Basin subprovinces that contain the Columbia River Basalt Group (unshaded area; after Thornbury, 1965, p. 445).

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Table 1.1-1. Characteristics of geomorphic units in the Columbia Basin and Central Highlands Subprovinces (sheet 1 of 2)

Physiographic section	Relief, elevation min/max, m(ft)	Present climate	Tectonic setting	Aggradational processes and landforms					Degradational processes and landforms				
				Fluvio-lacustrine	Glacial/ proglacial	Mass wasting	Eolian	Volcan-ism	Weathering	Mass wasting	Fluvial	Glacial/ proglacial	Eolian
Blue Mountains	Low to high, 300/2,750 (984/9,022)	Semiarid to humid	Broad east-west uplift with local synclines and fault-block grabens	Flood plains, alluvial fans, lakes	Moraines[a], outwash[a]	Talus, slopewash	--	Airfall tephra	Chemical ≥ mechanical, nivation	Rockfall, slump, creep, land-slides	Gullies, rills, sheetwash, alluvial terraces	U-shaped valleys,[a] tarns[1]	--
Wallowa-Seven Devils	Moderate to high, 425/3,050 (1,394/10,006)	Semiarid to humid	Highly deformed and uplifted mountain mass	Flood plains, alluvial fans, lakes	Moraines[1], outwash[1]	Talus, slopewash	--	Airfall tephra	Chemical ≥ mechanical, nivation	Rockfall, slump, creep, land-slides	Gullies, rills, sheetwash, alluvial terraces	U-shaped valleys,[a] hanging valleys,[a] tarns[a]	--
Tri-State Upland	Low to high, 250/1,650 (820/5,413)	Arid to humid	Relatively unde-formed basalt upland	Flood plains, alluvial fans	--	Talus, slopewash	--	Airfall tephra	Mechanical ≥ chemical, mima mounds	Rockfall, slump, creep, land-slides	Gullies, rills, sheetwash, alluvial terraces	--	Deflation
North-Central Oregon Plateau	Low to high, 100/1,000 (328/3,281)	Arid to semiarid	Gently north-dipping basalt upland	Flood plains, alluvial fans	--	Talus, slopewash	Loess sheets	Airfall tephra	Mechanical > chemical, mima mounds	Rockfall, slump, creep, land-slides	Gullies, rills, sheetwash, alluvial terraces	--	Deflation
Palouse Hills	Low, 300/750 (984/2,461)	Arid to semiarid	Overlies very gently, west-dipping Palouse slope	--	Flood bars[a]	Slopewash	Loess sheets	Airfall tephra	Mechanical > chemical, nivation	Slump, creep	Gullies, rills, sheetwash	Anasto-mosed channels,[a] streamlined loess hills[a]	Deflation
Channeled Scabland	Low to moderate, 150/750 (492/2,461)	Arid to semiarid	Gently dipping basalt plain to the east, folds and faults to the west	Lakes	Flood bars,[a] giant current ripples[a]	Talus, slopewash	Loess sheets	Airfall tephra	Mechanical > chemical, mima mounds	Rockfall, slump, creep	Gullies, rills, sheetwash	Flood terraces,[a] coulees,[a,b] cataracts,[a] hanging valleys[a]	
Waterville Plateau	Low to moderate, 425/850 (1,394/2,789)	Arid to semiarid	Relatively unde-formed basalt upland	--	Flood bars[a], Moraines,[a] outwash plains,[a] eskers,[a] kames,[a] kettles[a]	Talus, slopewash	Loess sheets	Airfall tephra	Mechanical > chemical	Rockfall, slump, creep	Gullies, rills, sheetwash	Flood terraces[a], coulees[a]	Deflation

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Table 1.1-1. Characteristics of geomorphic units in the Columbia Basin and Central Highlands Subprovinces (sheet 2 of 2)

Physiographic section	Relief min/max elevation, m(ft)	Present climate	Tectonic setting	Aggradational processes and landforms					Degradational processes and landforms				
				Fluvio-lacustrine	Glacial/proglacial	Mass wasting	Eolian	Volcan-ism	Weathering	Mass wasting	Fluvial	Glacial/proglacial	Eolian
Yakima folds	Moderate to high, 300/1,050 (984/3,445)	Arid to semiarid	East-west trending compressional anticlines and faults, volcanism on extreme west	Alluvial fans	--	Talus, slopewash	Loess sheets	Airfall tephra, cinder, cones, lava flows	Mechanical > chemical, mima mounds	Rockfall, slump, creep, land-slides	Gullies, rills, sheetwash		Deflation
Central Plains	Low, 100/300 (328/984)	Arid	East-west trend-ing synclines to level basalt low-lands	Flood-plains, lakes	Flood bars,[a,b] giant cur-rent ripples,[a] berg-mounds,[a] outwash,[a,b]	Slopewash	Loess sheets, sand dunes	Airfall tephra	Mechanical > chemical	Slump, creep, land-slides	Gullies, rills, sheetwash, alluvial terraces	Anasto-mosed channels,[a,b] flood terraces,[a,b] clastic dikes[a]	Dune blowouts; deflation

[a]Inactive process.
[b]Process with potential impact to waste isolation.

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The Tri-State Uplands are a broad upwarp covered with Columbia River basalt. The Snake, Salmon, Clearwater, and Grande Ronde Rivers, along with their tributaries, have incised steep-walled canyons into the upland that are as much as 1,200 m (4,000 ft) deep. The Snake River Canyon in the Tri-State Upland, as well as in the Wallowa-Seven Devils section, was modified by cataclysmic floods that flowed north from pluvial Lake Bonneville during the late Pleistocene (Malde, 1968, pp. 6-7; and Scott et al., 1982, pp. 582-586).

1.1.2.2 Columbia Basin subprovince

Six physiographic sections are recognized within the relatively dry, low-relief Columbia Basin subprovince: Palouse Hills, Channeled Scabland, Waterville Plateau, Yakima Folds, North-Central Oregon Plateau, and Central Plains (see Fig. 1.1-2 and 1.1-3). The reference repository location is situated in the Central Plains section, near its southwestern border with the Yakima folds section.

The Palouse Hills are composed of maturely dissected, low-rolling hills of windblown silt (loess) that may be as much as 90 m (300 ft) thick (Easterbrook and Rahm, 1970, pp. 113-119). They overlie a mostly undissected plateau of Columbia River basalt. Throughout most of the Quaternary and continuing today, southwesterly winds blowing across the Yakima Folds and Central Plains have transported loess toward the Palouse Hills. At one time, loess probably covered a larger area extending to the north and west but was subsequently removed during cataclysmic flooding. Locally, the Palouse Hills are being degraded through nivation and deflation (see Table 1.1-1).

The area scoured by flooding is referred to as the Channeled Scabland. Proglacial floods occurred during the Pleistocene after the failure of ice dams and sudden release of meltwater from lakes north and east of the Columbia Basin subprovince (see Section 1.1.3). These floods left behind an array of unique landforms including anastomosing coulees, potholes, giant current ripples, and gravel bars (Bretz, 1959, pp. 9-17; Easterbrook and Rahm, 1970, pp. 132-141; Baker, 1978, pp. 81-115). Channeled Scabland features extend locally into adjacent morphogenetic regions, including the Waterville Plateau, Palouse Hills, Yakima folds, and Central Plains sections. The principal effect of flooding on the Channeled Scabland was erosion, while in the southwestern Central Plains, the net effect was deposition.

For the most part, landforms along the northern Columbia Basin subprovince are the result of continental glaciation and proglacial cataclysmic flooding. The Okanogan Lobe of the Cordilleran Ice Sheet extended down onto the Waterville Plateau, a relatively flat basalt upland mantled with glacial moraines, kames, eskers, and other ice-contact deposits (Easterbrook, 1979, pp. 183-187). Beyond the ice limit, which is defined by the Withrow Moraine, the basalt is overlain by a thin cover of eolian deposits (Hanson, 1970, p. 113).

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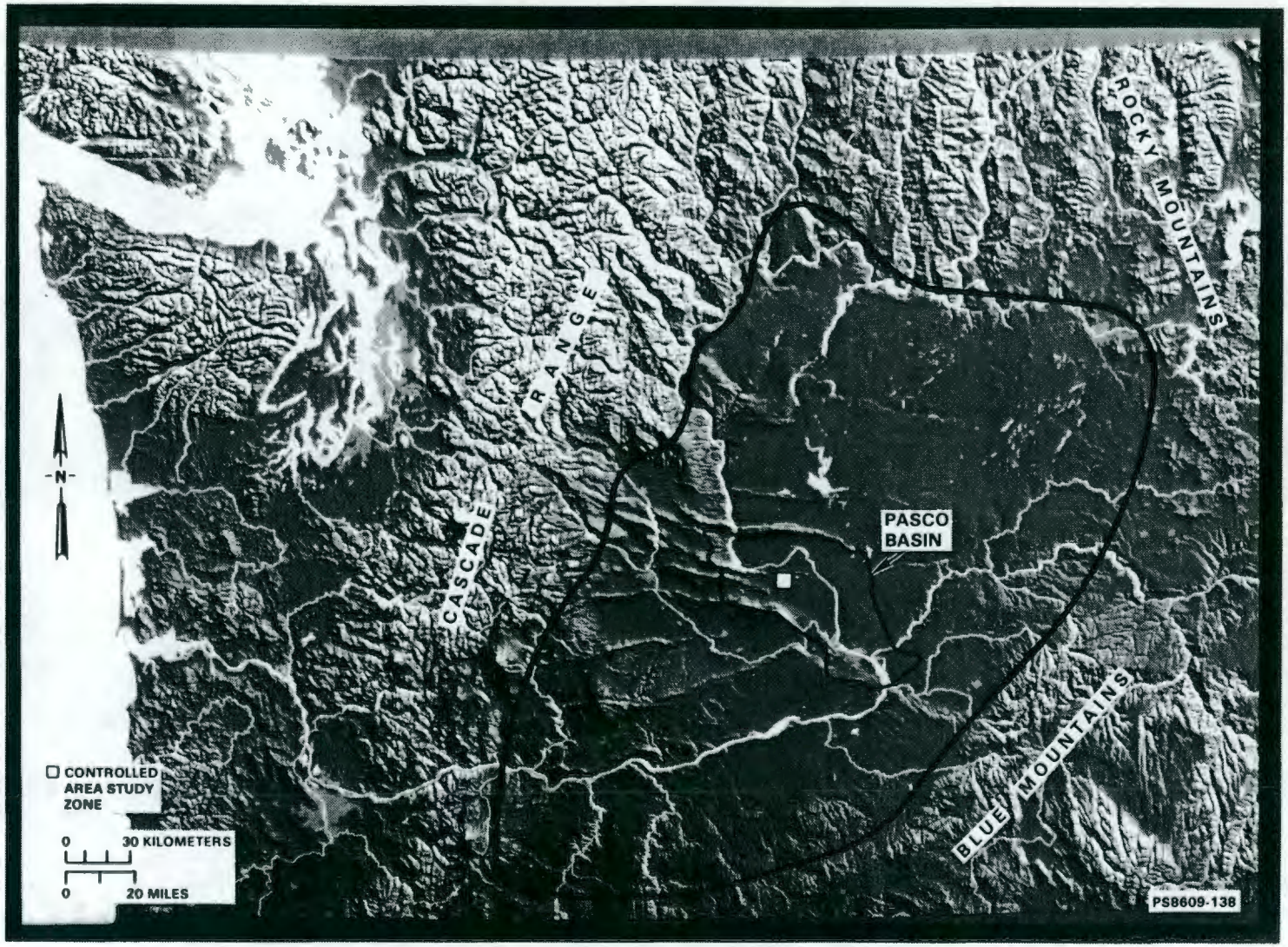

Figure 1.1-3. Computer-enhanced image of the Columbia Basin physiographic subprovince of the Pasco Basin.

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The Yakima folds section, located in the west-central Columbia Basin subprovince, consists of east-west trending, asymmetric anticlinal folds. These folds, up to 2,000 m (6,560 ft) high in the western plateau, plunge eastward where they merge with the low-relief Central Plains (Fig. 1.1-4). Yakima folds appear to be the result of generally north-south tectonic compression that has been active since the middle Miocene (Section 1.3.2.4). Volcanism, as young as Pleistocene in age, is associated with the Simcoe volcanic field along the west-central boundary of the Yakima folds section. The structural and tectonic history of the Yakima folds is discussed in more detail in Section 1.3.2.2.1.3.

The North-Central Oregon Plateau is a moderately dissected plateau that dips gently to the north. It abuts the Blue Mountains to the south and merges with the Yakima folds to the north (Farooqui et al., 1981b, pp. 44-45). Fluvial activity and mass wasting are active processes, along with local deposition of eolian sand and silt. Deep canyons are cut into the plateau by the Deschutes, John Day, and Umatilla Rivers and their tributaries. The Umatilla Basin, a large structural basin, forms the eastern boundary of this section (see Section 1.3.2.2.1, and 1.7.2.1).

The Central Plains include the low-relief areas of the central Columbia Basin subprovince adjacent to and between Yakima folds (see Fig. 1.1-4). Filling of the synclinal valleys by deposits from rivers, lakes, and wind has been synchronous with growth of the adjacent folds through the Neogene. The Central Plains were significantly modified, however, through erosion and deposition by proglacial floods during the Pleistocene. Except for minor fluvial and eolian activity, the Central Plains, as well as the rest of the Columbia Basin subprovince, have remained essentially unchanged since about 13,000 yr ago.

Two major structural basins, the Quincy and Pasco Basins, are contained within the Central Plains section (Thornbury, 1965, p. 446; see Section 1.3.2.2.1). The Pasco Basin (see Fig. 1.1-3) is the structural unit that contains the reference repository location (see Section 1.3.2.2.2).

1.1.2.3 Reference repository location and surrounding area

The area around the reference repository location is subdivided into five geomorphic units on the basis of topography and lithology (Fig. 1.1-5). These units, discussed in the order of generally decreasing elevation, are the (1) Yakima Ridge Upland, (2) Yakima Ridge Piedmont, (3) Cold Creek Bar, (4) Central Hanford Sand Plain, and (5) Cold Creek-Dry Creek Alluvial Plain.

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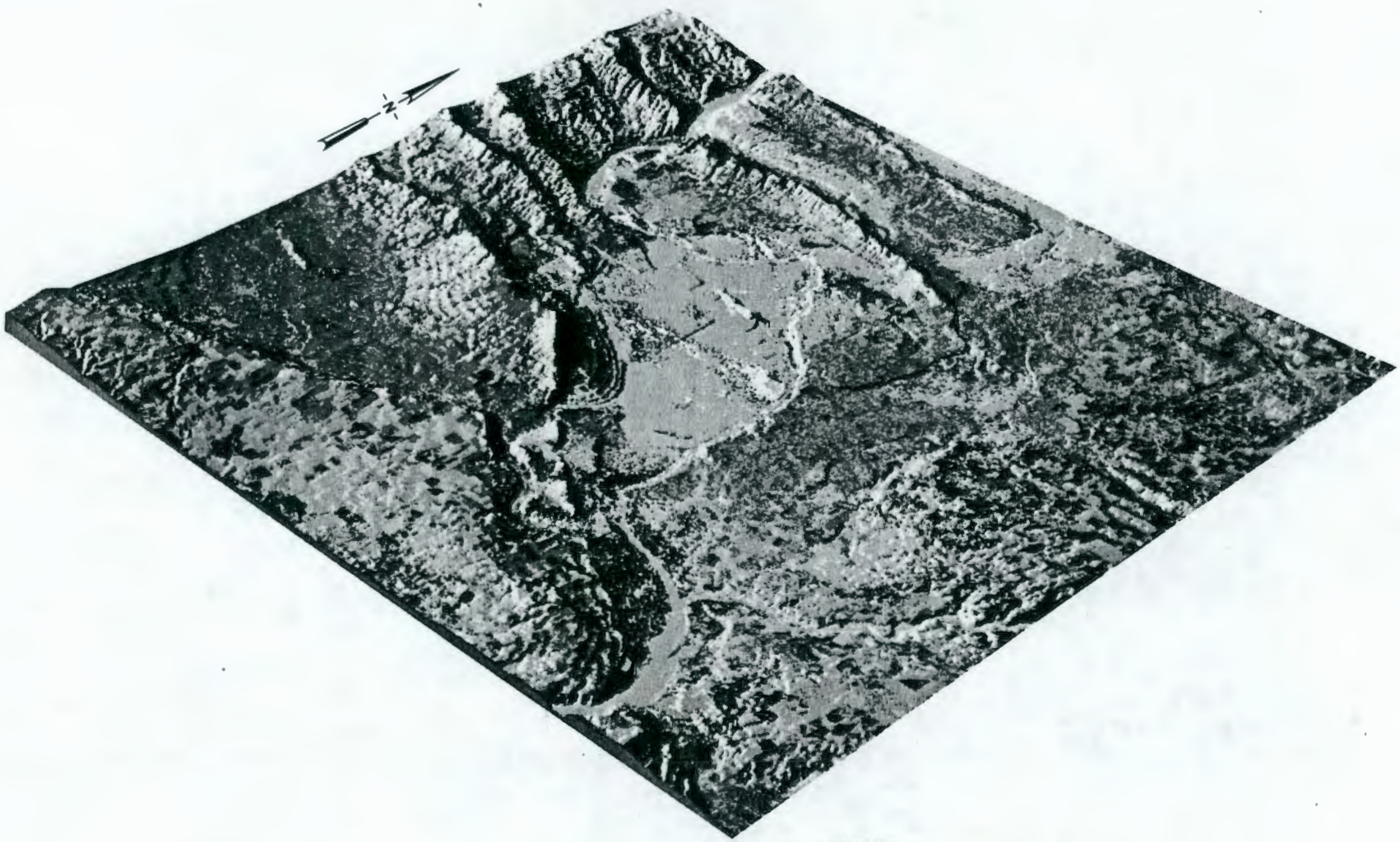

Figure 1.1-4. Computer-enhanced surficial relief map of a portion of the Central Plains and Yakima Folds sections. The Pasco Basin, a structurally defined feature that contains the reference repository location, is roughly coincident with the flat-lying region in the center of the map.

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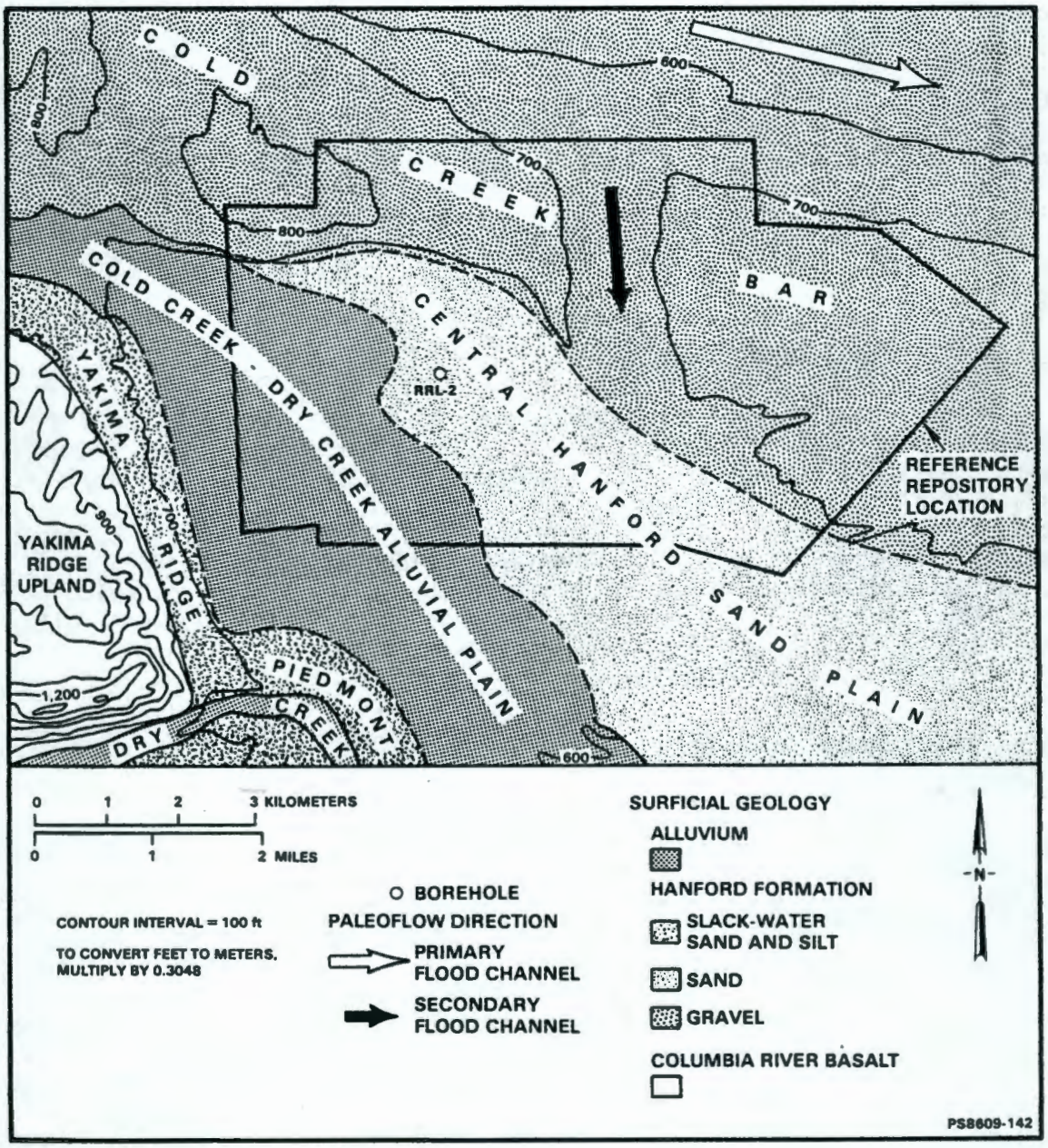

Figure 1.1-5. Surficial geologic and geomorphic map of the reference repository location and vicinity. Borehole RRL-2 is the site proposed for the first exploratory shaft.

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1.1.2.3.1 Yakima Ridge Upland

Yakima Ridge is a northwest-southeast trending anticlinal fold that plunges beneath a cover of surficial sediments near the southwest corner of the reference repository location (see Section 1.3.2.2.2.3). The upland area is often mantled with a thin veneer of loess and colluvium. This upland is the area closest to the reference repository location that is presently being eroded, mainly by stream dissection, headward erosion, and mass wasting. The erosion rate has been slow; it appears that no more than 10 to 15 m (33 to 49 ft) of fluvial incision has occurred since the late Miocene. The maximum relief in the Yakima Ridge Upland near the reference repository location is 290 m (950 ft), and the average slope gradient is approximately 10°.

1.1.2.3.2 Yakima Ridge Piedmont

The Yakima Ridge Piedmont lies between the Central Hanford Sand Plain and the Yakima Ridge Upland (see Fig. 1.1-5). The piedmont surface dips gently to the northeast and is generally defined by the area that is overlain by slackwater flood deposits of the Hanford Formation (see Section 1.2.2.2.2). Loess, slopewash, and ice-rafted bergmound material are also present. Data from the few boreholes located in the Yakima Ridge Piedmont indicate that the suprabasalt sediments thin and pinch out to the southwest toward Yakima Ridge where there appears to be a greater percentage of basaltic slopewash, alluvial fan, and fanglomerate debris eroded from Yakima Ridge.

1.1.2.3.3 Cold Creek Bar

The Cold Creek Bar (Bretz et al., 1956, pp. 1010-1014) formed along the south flank of an anastomosing flood channel system that extends from Sentinel Gap to Wallula Gap (see Fig. 1.1-6). This flood bar appears to represent deposits of multiple floods, based on internal structures. During flooding, it prograded southward to its present position in the Cold Creek Valley, forming a significant topographic barrier with the Columbia River drainage to the north. The northern part of the bar is erosional, having been modified as the last cataclysmic floodwaters receded from the basin. Maximum slopes on this bar face south at approximately 7° (Fig. 1.1-7). Maximum elevation of the bar is about 230 m (755 ft), while the lowest elevation measured in the flood channel to the north is about 200 m (655 ft). The Cold Creek Bar is composed of coarse sand and gravel on the northern and eastern margins and grades laterally into a silty, medium-to-coarse sand toward the southwest.

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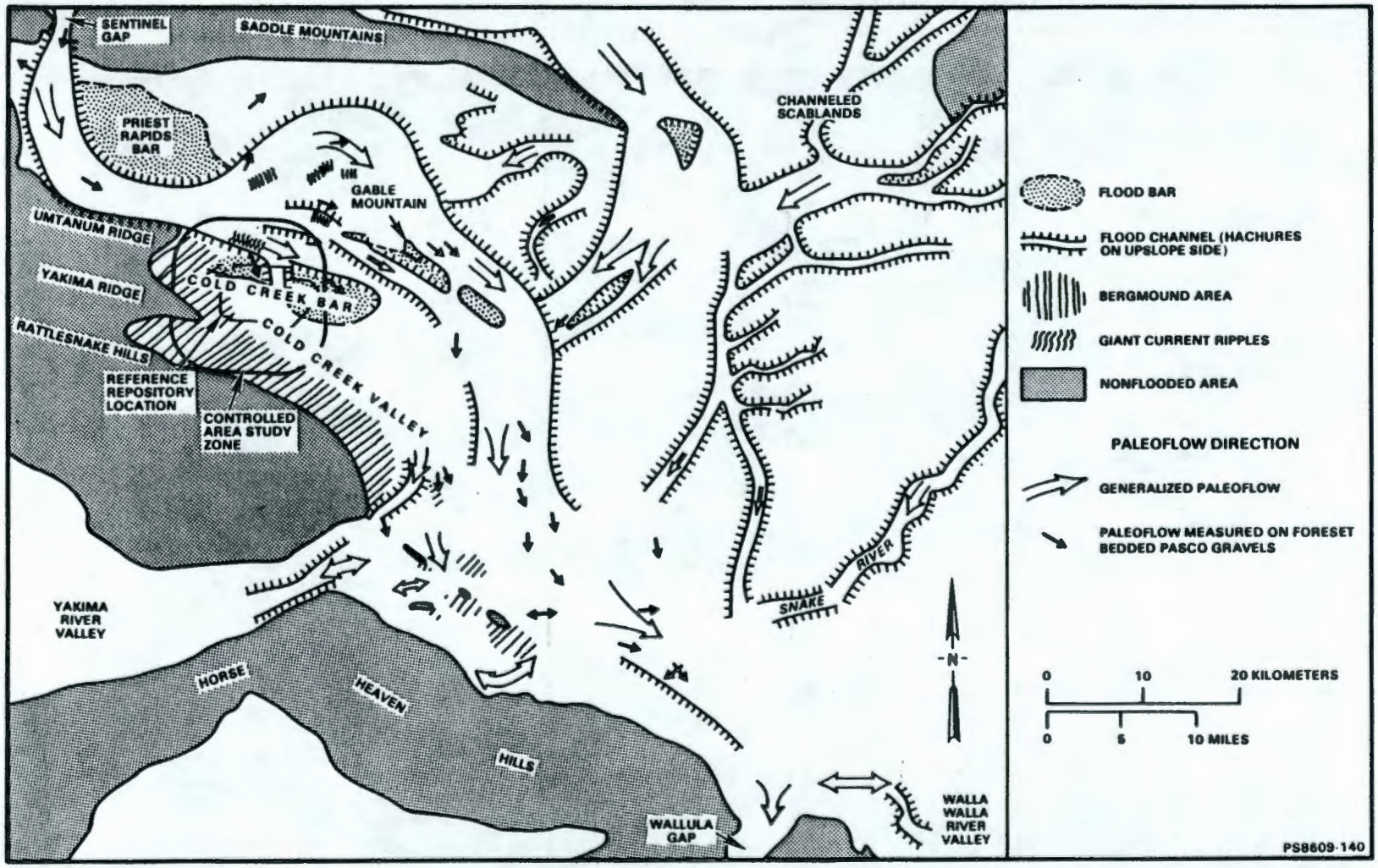

Figure 1.1-6. Paleoflow directions and landforms associated with proglacial cataclysmic flooding in the central Columbia Plateau.

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Figure 1.1-7. View of the reference repository location, looking south from the top of Cold Creek Bar. Central Hanford Sand Plain is in the foreground and Rattlesnake Hills are in the background.

CONSULTATION DRAFT

1.1.2.3.4 Central Hanford Sand Plain

The Central Hanford Sand Plain is composed of laminated sands with minor silts confined to an area south of the Cold Creek Bar (see Fig. 1.1-5). The surface of the plain is relatively smooth and slopes gently toward the center of Cold Creek Valley (see Fig. 1.1-7). Recent alluvium, composed of mostly silt and fine sand deposited in the Cold Creek Valley, is superimposed on the western part of this late-Pleistocene sand plain. Northeast-southwest trending longitudinal sand dunes mantle much of the sand plain. These have formed through the reworking of the loose flood deposits since the Pleistocene.

1.1.2.3.5 Cold Creek-Dry Creek Alluvial Plain

An alluvial plain that developed during the Holocene is the youngest geomorphic unit at the reference repository location (see Fig. 1.1-5). It slopes slightly to the southeast and represents the extent of fluvial activity since the last cataclysmic flood approximately 13,000 yr ago. Inactive parts of the alluvial plain are covered with a thin layer of windblown sand. The exact extent of the alluvial plain is uncertain at this time. Plans for additional studies to map surface deposits are presented in Sections 8.3.1.2.3.3.4 and 8.3.1.2.4.3.1; studies involving flooding potential are found in Section 8.3.1.3.3.3.

1.1.3 GEOMORPHIC PROCESSES

This section summarizes a total of seven geomorphic processes responsible for the present configuration of the Columbia Basin and Central Highlands subprovinces (see Table 1.1-1). Of these processes two are related to endogenetic geologic processes (e.g., volcanism and tectonism) and five are exogenetic (e.g., glacial-proglacial activity, fluvial-lacustrine activity, eolian activity, mass wasting, and weathering). The present rates of aggradational and degradational processes operating near the reference repository location are relatively slow because of the dry climate (WCC, 1980a, pp. 33-38). Changes in climate and the hydrologic effects are discussed further in Chapters 3 and 5. In general, processes active during the Holocene have done little to modify the landscape that was developed during the late Pleistocene. Of the processes discussed in this section, only those related to renewed glacial or proglacial activity are likely to impact the site over the next 100,000 yr (see Section 1.5.3). These include the potentially adverse effects of glacial ice or melt water that lead to changes in the groundwater flow at the site.

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1.1.3.1 Tectonism

Movements of the earth's crust have played a major role in the geomorphologic evolution of the Columbia Intermontane Province since the early Miocene (Fecht et al., 1985, pp. 43-45). Because of its proximity to the reference repository location, tectonic activity within the Yakima Fold Belt is of particular interest in assessing geologic stability. The Yakima folds have developed due to north-south crustal shortening that produced east-west trending ridges. These ridges have been undergoing degradation mainly through weathering, mass wasting, and fluvial processes. Intervening synclinal valleys, on the other hand, have aggraded intermittently with fluvial, proglacial, and eolian deposits since Columbia River Basalt Group time. Average rates of uplift and subsidence on these folds are estimated at less than 40 m/m.y. (less than 130 ft/m.y.) for the middle to late Miocene (Reidel and Fecht, 1981, p. 3-44).

Besides leading to degradation in uplands, tectonic activity over the next 10,000 yr could alter fluvial processes, resulting in (1) changes in watershed drainage pattern, (2) channel aggradation or degradation, (3) changes in channel pattern or sinuosity, (4) channel diversion or avulsion, and (5) flooding due to subsidence (Schumm et al., 1982, pp. 36-52). Detailed discussions of the structural geology and tectonic development of the Columbia Plateau and Yakima Fold Belt are given in Section 1.3.

1.1.3.2 Volcanism

Basaltic volcanism that blanketed parts of the Columbia Intermontane Province in the Miocene has not been a significant geomorphic agent within the Columbia Basin subprovince during the Quaternary (see Section 1.3.2.1). Quaternary volcanism has been limited to the extreme western margin of the Columbia Basin subprovince and is associated with the Cascade Range Province (see Fig. 1.1-1). Lava and pyroclastic flows from future eruptions of Cascade volcanoes could potentially dam the Columbia River Gorge, leading to base-level changes (see plans to address this in Section 8.3.1.2.4.3.1). These changes could possibly leave impacts that extend as far as the Columbia Basin subprovince (see Section 1.5.3). Otherwise, the effects of volcanism over the next 10,000 yr are expected to be limited to the aggradation of periodic layers of airfall tephra.

Airfall tephra from at least three Cascade volcanoes has blanketed the central Columbia Plateau since late Pleistocene time (Shipley and Sarna-Wojcicki, 1983). This tephra includes material from several eruptions of Mount St. Helens prior to the most recent May 1980 eruption. Other volcanoes have erupted less frequently; these include two closely spaced eruptions from Glacier Peak about 11,200 yr ago (Mehringer et al., 1984) and the eruption of Mount Mazama about 6,600 yr ago. In general, tephra layers have not exceeded more than a few centimeters in thickness, except for the eruption of Mount Mazama, where up to 10 cm (3.9 in.) of tephra fell over eastern Washington.

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1.1.3.3 Glacial-proglacial activity

Geologic evidence suggests that glacial activity has been limited to the margins of the Columbia Basin subprovince. This included the Okanogan Lobe of the Cordilleran Ice Sheet, which extended 50 km (31 mi) south of the Columbia River onto the Waterville Plateau (Waitt and Thorson, 1983, pp. 54-55). The maximum extent of the ice is defined by the well developed Withrow Moraine, which lies approximately 110 km (68 mi) north of the Pasco Basin. Mountain glaciers from the Cascade Range extended down the Chelan, Wenatchee, and Kittitas Valleys before terminating along the extreme western margin of the plateau. Mountain glaciation also occurred at higher elevations as cirque or valley glaciers within the Wallowa-Seven Devils, Aldrich, and Strawberry Mountain ranges within the Central Highlands subprovince (Porter et al., 1983, p. 72). Another major glaciation is not expected for approximately 50,000 yr (Craig and Hanson, 1985, p. 4). Although there is no evidence to suggest that continental glaciers have ever occupied the Pasco Basin, it has been estimated that there is a 0.5 probability that ice could cover the Pasco Basin sometime during the next one million years (Bull, 1979, p. IV-2).

Proglacial cataclysmic flooding associated with the sudden release of water from glacial Lake Missoula directly affected much of the Columbia Basin subprovince (Bretz, 1969, p. 505). Cataclysmic floods are responsible for much of the present morphology of the Channeled Scabland and Central Plains. Floodwaters from glacial Lake Missoula flowed down the Columbia River and across the Channeled Scabland before being impounded behind Wallula Gap (see Fig. 1.1-6), which was too restrictive for the volume of water involved. The floodwaters ponded to elevations up to 350 m (1,150 ft), which translates into a water depth of 140 m (460 ft) at the reference repository location. Ponded floodwaters in the Central Plains ebbed after 4 to 5 d (Craig and Hanson, 1985, pp. 102-103); estimates for maximum total flood duration range from 11 d (Craig and Hanson, 1985, p. 103) to 14 d (Baker, 1973, pp. 20-22). These floods produced significant erosion in some parts of the Columbia Basin subprovince, although the net effect within most of the reference repository location was depositional because of the protection provided by Cold Creek Bar (see Fig. 1.1-6 and 1.1-5).

The exact number and timing of proglacial floods is debatable (Baker and Bunker, 1985, pp. 123-124). Recent workers have postulated as few as 2 (Bjornstad, 1980, p. 72; Bunker, 1982, p. 17; WCC, 1981b, pp. 24-32) to as many as 40 (Waitt, 1980, p. 46) separate late-Pleistocene floods. The latter hypothesis suggests that floods occurred at a frequency of one flood every two to six decades toward the end of the Wisconsin Glaciation (Waitt, 1984, p. 57). The timing and frequency of cataclysmic floods are discussed further in Section 1.2.1.3.5.3.

The likelihood of renewed glaciation over the next 100,000 yr is very high; however, the timing, duration, and effects of such a glaciation are uncertain at this time. Extensive modeling of future glaciation and proglacial flooding will be carried out during site characterization (Section 8.3.1.5.2). Preliminary modeling suggests a glacial advance large enough to produce renewed cataclysmic flooding is not expected for about

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another 50,000 yr (Craig and Hanson, 1985, p. 4). Temporary glacial advance and retreat before that time, however, could lead to proglacial changes in landform development and groundwater recharge. The transient nature and short duration of cataclysmic floods suggest that the impact on the recharge of deep confined aquifers would be minor; this is indicated by the relatively shallow depths of flood coulees (approximately 100 m (330 ft)) when compared to the proposed depth of a repository (1,000 m (3,280 ft)).

On the other hand, recharge of the shallow, confined aquifers might be extensive. Of more importance to the groundwater-flow system is the potential for future noncataclysmic, glacially induced increases in discharge to the Columbia River. For example, lower temperatures and changes in rainfall during future glacial periods will alter runoff and vegetation. Plans to address uncertainties and potential impacts of increased proglacial discharge and cataclysmic flooding using paleoclimatic modeling will be discussed in Section 8.3.1.2.4.3.1.

Other possible effects associated with future glacial or proglacial processes include (1) lowered sea levels and (2) increased seismicity and fracturing near the reference repository location due to crustal loading by ponded floodwaters or an ice sheet located within or north of the Pasco Basin. The effects of up to 250 m (820 ft) of sea level change accompanying a new episode of glaciation are discussed in Section 1.1.3.4. While the effects of proglacial floodwaters are short-term and are not expected to induce crustal movements, the isostatic loading and unloading of an ice sheet are uncertain and could produce a proglacial bulge (Bull, 1979, p. IV-5) and (or) alter fracture networks (Hunter, 1983, p. 37) near the site. Plans to address these concerns are presented in Section 8.3.1.2.4.3.1.

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1.1.3.4 Fluvial-lacustrine activity

Fluvial and lacustrine processes associated with the Columbia River system, which includes the ancestral Snake and Yakima Rivers, have been active since the late Miocene (Fecht et al., 1985, pp. 42-45). Clastic sediments of the Ringold Formation represent the deposits of these rivers and lakes in the central Columbia Basin subprovince and indicate that deposition was almost continuous from about 10.5 m.y.B.P. until about 3 m.y.B.P. (Bjornstad, 1985). Since this period, a major change in regional base level has resulted in as much as 150 m (500 ft) of fluvial incision, all of which occurred prior to 900,000 yr ago. The cause of this change in base level is uncertain (Fecht et al., 1985, pp. 37-38); however, only minor downcutting has occurred since and, therefore, a similar degradational event is not expected over the next 100,000 yr. Plans to study further the cause of base-level changes and their tectonic implications are presented in Section 8.3.1.2.4.3.1.

Within the reference repository location, the post-Ringold erosional surface was filled partially with locally derived alluvium prior to, and perhaps between, periods of Pleistocene flooding. However, in most areas of the Columbia Basin subprovince, the record of Pleistocene fluvial activity was

destroyed by cataclysmic floods. The potential for fluvial incision at the reference repository location (190- to 245-m (620- to 800-ft) elevation) is limited to depths at or above the narrow bedrock channel at Wallula Gap (50-m (165-ft) elevation), which constitutes the local base level for the Pasco Basin. During the Holocene, the major rivers appear to have adjusted themselves to local base level at Wallula Gap, except in upland areas where net degradation is probably continuing. Significant incision in the Cold Creek Valley is not expected during the next 10,000 yr, because the surface within the Cold Creek Valley has not been significantly eroded since the last Pleistocene flood, approximately 13,000 yr ago, and because another glaciation is not expected for approximately 50,000 yr.

The most significant changes in base level during the next 100,000 to 1,000,000 yr are most likely to come about through eustatic changes in sea level (Schwartz, 1979, pp. IX-3 to IX-6). Based on Pleistocene sea level fluctuations, regional base level could conceivably drop between 100 m (330 ft) to as much as 250 m (820 ft) below present sea level (WCC, 1980a, p. 52). The Cohassett flow within the reference repository location is generally greater than 580 m (1,900 ft) below sea level (Landon and Bjornstad, 1986, p. A-35). Assuming there is no tectonic uplift, incision from such a drop in sea level could proceed no closer than 330 m (1,080 ft) above a repository in the reference repository location, if the maximum drop in sea level were to occur. However, it is not likely that erosion to this depth would occur in the Pasco Basin, approximately 480 river kilometers (300 river miles) from the present coastline. A change in sea level over this distance would probably result in a temporarily higher river gradient and only minor headward erosion within the Pasco Basin.

The combination of (1) a thick sequence of rock below sea level, and (2) the location of the reference repository location within a basin that has had a long history of subsidence (Caggiano and Duncan, 1983, pp. 8-1 to 8-2) suggests a very low probability of host-rock incision under the present or projected geomorphic, tectonic, or climatic regimes during the next 100,000 yr (Hunter, 1983, pp. 38-40).

The effects of denudation through normal fluvial mass wasting and weathering in upland areas around the Pasco Basin is uncertain but could conceivably result in increased infiltration and recharge of confined aquifers. Thus, the denudation rate is especially important where Grande Ronde Basalt lies at or just below the surface, such as in portion of the upper Cold Creek Valley and Channeled Scabland. Denudation rates are often calculated from the suspended loads of rivers. Probable rates of degradation have been estimated for the Pasco Basin based on rates reported for other river systems; these range from 30 m/m.y. (98 ft/m.y.) (WCC, 1980a, pp. 82-83) to 50 m/m.y. (164 ft/m.y.) (Tubbs, 1979, p. II-3). These estimates are very high, however, when compared to the 10 to 15 m (33 to 45 ft) of downcutting that is measureable on Yakima fold ridges since Elephant Mountain time (10.5 m.y.B.P.). Plans to address rates of denudation and changes in the location of groundwater recharge in upland areas around the Pasco Basin are presented in Section 8.3.1.2.4.3.1.2.

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The course of the Columbia River is presently contained within the Wahluke and Pasco synclines, which are minor depressions within the larger Pasco Basin. There is presently no evidence to suggest that the river has occupied the Cold Creek syncline since the last cataclysmic flood, approximately 13,000 yr B.P. Glacial activity and tectonic movements that may be reasonably anticipated during the next 10,000 yr are unlikely to cause a deviation of the river into the Cold Creek syncline, due to the longer repeat interval of glacial advances (see Section 5.2.1.2.4) and the low rates of tectonic movements (see Section 1.3.2.4).

The probability for a major avulsion of the Columbia River related to aggradation of proglacial streams in the Pasco Basin is uncertain at this time. For this to happen, a rise in base level of 25 m (80 ft) would be required in order to divert the Columbia River from its present position to the saddle between Gable Mountain and Gable Butte into the Cold Creek syncline. The maximum amount of aggradation that could be associated with future glacial advance is not known, but will be addressed in geomorphic studies (Section 8.3.1.2.4.3.1) and climatic modeling performed during site characterization.

The presence of Holocene alluvium over the southwestern part of the reference repository location (see Fig. 1.1-5) indicates the site has been affected by seasonal-type flash flooding of Cold Creek and Dry Creek. However, the exact extent of the floodplain, and thus the likelihood for flooding of surface facilities and transportation routes associated with a repository, are uncertain at this time. Detailed air photo interpretation and geologic mapping are planned for the central Cold Creek syncline to delineate the extent of the Cold Creek-Dry Creek flood plain (Section 8.3.1.2.3.3.4). Flood risk analysis associated with these creeks is discussed in Section 3.2. Additional site characterization activities involving the surface hydrology near the reference repository location are presented in Section 8.3.1.3.

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1.1.3.5 Eolian activity

Wind is an active geomorphic agent, particularly within the arid to semiarid Central Plains. However, wind has done little more than to locally rework and redistribute the uppermost late-Pleistocene flood deposits. Wind-related deposits include loess, dune sand, and sheet sand.

Loess occurs in sheets that mantle much of the upland areas of the Columbia Basin subprovince. Loess deposits in the Pasco Basin are relatively thin (5 to 10 m (16 to 32 ft)). Loess, which accumulates more on the north and east (downwind) facing slopes of ridges, may attain thicknesses of 30 m (100 ft) or more. Many different ages of loess are recognized in the Columbia Basin subprovince, ranging in age from Holocene to perhaps as early as the late Pliocene. Recent loess deposits are generally loose and well sorted, unlike older loess deposits, which are highly weathered, poorly sorted, and often capped or interbedded with resistant layers of pedogenic carbonate or silica.

Dune sand occurs in northeast-trending, longitudinal-shaped dunes in the south-central and eastern parts of the Pasco Basin. They reflect the predominantly southwest direction of strong winds across the basin (Fig. 1.1-8). The slightly different trends of these dunes probably reflect topographic control, perhaps by wind gaps and anticlinal ridges in the path of prevailing winds (ERDA, 1975, p. II.3-B-4).

Degradation by wind is limited to dune "blowouts" and deflation. Dune blowouts sometimes occur where vegetal cover has been destroyed along stabilized dunes, but generally do not penetrate far below the base of the dune field. Deflation to basalt bedrock occurs locally and only along windward slopes of the Yakima fold ridges.

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1.1.3.6 Mass wasting

Mass wasting occurs in moderate- to high-relief areas in the Columbia Basin and Central Highlands subprovinces as slumping, soil creep, rockfall, and landsliding (see Table 1.1-1). Landslides are typically backward-rotated blocks near their sources and often grade into debris flows farther downslope (Fig. 1.1-9). Landslides often occur along the steep northern flanks of ridges in the Yakima folds, such as the Horse Heaven Hills and Rattlesnake Hills (see Fig. 1.1-8). There is no evidence for landsliding within the controlled area study zone.

The Corfu landslide, located on the north side of the Saddle Mountains, is a large compound landslide system consisting of at least 24 separate mass movements that were closely related in space and time (Lewis, 1984). Movement was initiated along steeply dipping interbeds between Columbia River basalt flows when moisture was increased due either to a wetter climate or saturation by cataclysmic floods. Many of the larger, stabilized landslides are probably of late Pleistocene age, but some may be older (Myers/Price et al., 1979, p. III-69).

Recent landslides are common along the White Bluffs and are located between 22 to 27 km (14 and 17 mi) from the site, towards the northeast and east. One of these, the Savage Island landslide (see Fig. 1.1-9), is almost 2 km (1.2 mi) wide. According to a study by Schuster and Hays (1984), these landslides are irrigation-induced and generally have not traveled more than a few hundred meters, nor have the toes of landslides exceeded 30 m (100 ft) in thickness. Other landslides occurred along the White Bluffs prior to irrigation, but probably were related to unstable slopes after saturation and undercutting by Pleistocene proglacial floodwaters.

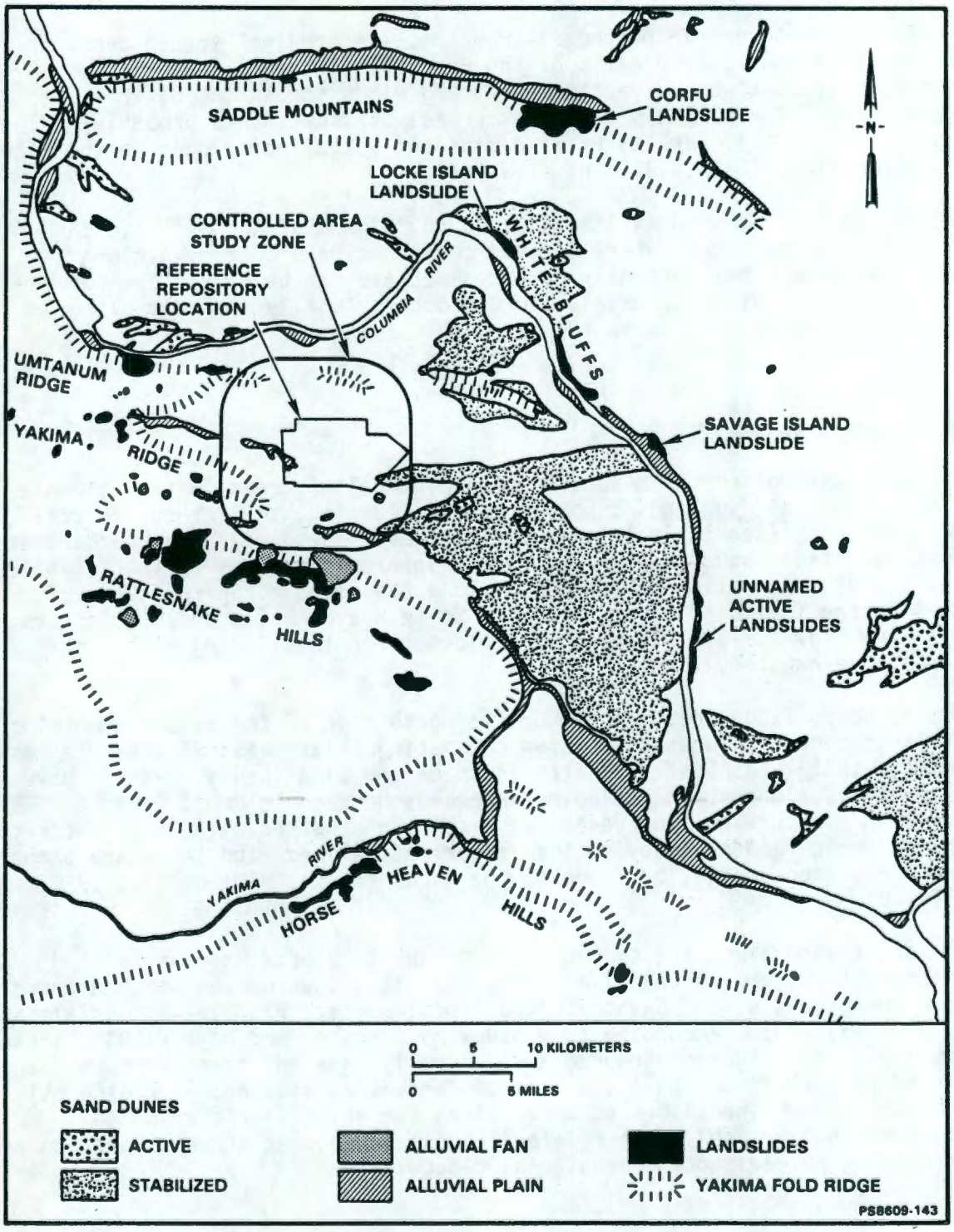

Figure 1.1-8. Late Quaternary landforms within and adjacent to the Pasco Basin (modified from Myers/Price et al., 1979).

Figure 1.1-9. View looking northwest across Savage Island landslide. White Bluffs and the Ringold Formation plateau are on the right, and the Columbia River is in the upper left. Landslide morphology changes from backward-rotated blocks near the scarp (right) to debris flows downslope (left). Gable Mountain is located on the horizon in the upper left portion of the photo.

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1.1.3.7 Weathering

Weathering is primarily a degradational process, accomplished through the in situ chemical and mechanical decomposition of parent material. Generally there is an inverse relationship between chemical (oxidation, hydration, solution) and mechanical (freeze-thaw, unloading, biologic activity) weathering, the rates of which depend on temperature and precipitation (Leopold et al., 1964, pp. 40-46). The highest rates of weathering occur where chemical processes predominate, such as in tropical environments where high temperatures and precipitation prevail. Rates of weathering generally decrease with decreasing temperature and rainfall.

Chemical weathering within the arid to semiarid Columbia Basin subprovince favors the formation of resistant layers of pedogenic calcium carbonate. At least two carbonate-plugged soil horizons, also referred to as caliche or calcrete, are present in the late-Pliocene upper Ringold unit along the White Bluffs. Near the ground surface these soils might locally restrict infiltration or otherwise act as hydrologic barriers in the unconfined aquifer. The deep groundwater flow system would be unaffected, however, unless there existed hydrologic communication between confined and unconfined aquifers. Elsewhere, calcic soils have developed atop the eroded Ringold Formation in the western Pasco Basin (see Section 1.2.1.3.4) and atop early-to middle-Pleistocene eolian and flood deposits throughout the basin.

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1.2 STRATIGRAPHY AND LITHOLOGY

This section summarizes stratigraphic and lithologic data gathered during the site-selection activities. The discussion is divided on the basis of two geographic areas: (1) a general discussion for the Columbia Plateau, with emphasis on the Pasco Basin, where stratigraphic units are discussed at the group, formation, and member level and (2) a more detailed discussion of the stratigraphic units and features of basalt flows and sedimentary units within the controlled area study zone. Much of the discussion of basalt within the controlled area study zone concentrates on the Cohassett flow, which has been identified as the candidate horizon.

Stratigraphic and lithologic studies are diverse and usually serve multiple purposes for the characterization of the region and controlled area study zone. Studies of basement rocks are required to assess sub-basalt resource potential and to obtain parameters for geophysical studies designed to assess structures. Knowledge of the stratigraphy and lithology of the basalts is required to (1) provide a framework on which other geologic and hydrologic studies depend (e.g., structure, tectonics, groundwater flow); (2) identify a repository host rock that is laterally continuous; (3) identify physical properties of the host rock that could influence repository design; (4) identify isolation capabilities of the rock; and (5) provide input parameters to performance assessment modeling. An understanding of the suprabasalt sediments and other late-Cenozoic deposits is needed (1) to determine timing and rates of late-Tertiary and Quaternary tectonic deformation, (2) to provide input data for climatic modeling, and (3) to identify geomorphic processes that have been and are likely to be active.

1.2.1 STRATIGRAPHIC FRAMEWORK OF THE CANDIDATE AREA

This section provides a general description of the stratigraphic units within the Columbia Plateau. The discussion begins with descriptions of the sub-basalt units (Section 1.2.1.1) found along the margin of the plateau and those units that have been penetrated by deep boreholes within the plateau. The units of the Columbia River Basalt Group are discussed in Section 1.2.1.2. Descriptions are given for formal stratigraphic units to the member level. Descriptions of internal features of basalt flows, intraflow structures, and cooling joints are also included. Sedimentary deposits coincident with and overlying the Columbia River Basalt are discussed in Section 1.2.1.3. A more detailed discussion of stratigraphic units as they occur in the controlled area study zone is presented in Section 1.2.2.

1.2.1.1 Sub-basalt rocks

Information on sub-basalt rocks is needed to assess the tectonic development and natural resource potential of the region. Present knowledge

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of these rocks is limited to studies of exposures along the margins of the plateau as well as a few deep boreholes and geophysical surveys within the interior of the plateau (Campbell, 1985).

A variety of rock types of varying ages surround the Columbia Plateau. Along the western margin of the plateau, the basalt flows lie on an irregular surface that resulted from the erosion of a complex terrane of Paleozoic and Mesozoic metamorphic rocks (Misch, 1966), Mesozoic to early-Tertiary sedimentary rocks (Armstrong, 1978), and early-Tertiary intrusive and volcanic rocks (Gresens et al., 1977). To the north, basalt is underlain by pre-Cambrian metamorphic and sedimentary rocks, Paleozoic metasedimentary and volcaniclastic sedimentary rocks, Mesozoic marine lavas and sedimentary rocks, and Mesozoic to early-Tertiary granitic rocks (Fox and Beck, 1985, pp. 323-341). Along the eastern margin of the plateau, basalt rests on Precambrian metasedimentary rocks (Hooper and Webster, 1982) and Mesozoic intrusive and volcanic rocks (Brooks and Vallier, 1978; and Brooks, 1979). To the south, basalt overlies Paleozoic sedimentary rocks (Vallier et al., 1977); Mesozoic volcanic, metamorphic, and intrusive rocks (Brooks and Vallier, 1978); and early-Tertiary volcanic and sedimentary rocks (Armstrong, 1978).

Several detailed reports are available on the sub-basalt Tertiary sedimentary rocks that border the Columbia Plateau. Reports containing summaries of this stratigraphy, together with extensive reference lists, are given below.

- Northwest margin of the plateau. Eocene or Oligocene fluvial and deltaic sequences of the Wenatchee, Swauk, Chumstick, Rosylyn, Manashtash, Naches, Wildcat Creek, and Spencer Creek Formations (Campbell, 1985; 1986).

- Western margin. South central Washington Eocene and Oligocene volcaniclastic sequence of the Ohanapecosh Formation and Miocene lavas and volcaniclastics of the Fife's Peak and Stevens Ridge Formations (Hammond, 1980; Campbell, 1985).

- Southern margin of plateau in the Blue Mountains, central Oregon. Cretaceous marine strata and Eocene to Oligocene fluvial and volcaniclastic sedimentary units (Fritts and Fisk, 1985a; 1985b; Kleinhaus et al., 1984, pp. 239-257; Fox and Reidel, 1987; Swanson, 1969).

- Northern margin of plateau - Methow and Republic Grabens. Summaries of the marine Cretaceous stratigraphy and early Tertiary sedimentary units for the Methow Graben (Barksdale, 1975) provide summaries of the early Tertiary volcaniclastic and fluvial units in the Republic Graben (Gaylord, 1986; Meussing, 1962).

The sub-basalt units present along the margin of the Columbia Plateau are inferred to be present in large areas of the Columbia Basin and represent possible correlative sequences of sedimentary and volcaniclastic rock beneath the Columbia River basalt. These units are further discussed in Section 1.7.2 of this chapter and plans for further work are described in Section 8.3.1.6.

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No sub-basalt rocks are exposed within the central interior of the Columbia Plateau, including the Pasco Basin. Therefore, the only direct information on sub-basalt stratigraphy is from deep hydrocarbon exploration boreholes. Deep boreholes in the western Columbia Plateau show that Columbia River basalt is underlain in places by lower-Tertiary sedimentary rocks similar to those exposed along the western margin of the plateau (Campbell, 1985, Fig. 4; see Section 1.7.2). Two of three deep boreholes recently drilled to the west of the Pasco Basin terminated in this lower-Tertiary sequence; a third continued through a sequence interpreted to be Cretaceous marine sedimentary rocks before terminating in crystalline rocks (Campbell, 1985, Fig. 4). Data from a fourth hydrocarbon exploratory well recently completed in the Saddle Mountains, which is most proximal to the controlled area study zone, show that the well penetrated the basalt section at 3,490 m (11,450 ft) and continued into a sedimentary section to a total depth of 5,339 m (17,516 ft).

Magnetotelluric data collected in the central Pasco Basin by the BWIP (Geotronics, 1984; Argonaut, 1980; Senturion, 1979; Z-Axis, 1985) and the USGS (Stanley, 1982) have identified sub-basalt units that apparently correlate with the sedimentary and crystalline rocks reported from the deep boreholes. Additional magnetotelluric data on sub-basalt rocks have been acquired by oil companies, but remain proprietary and are not presently available to the BWIP.

Most recent interpretations of the available data (Berkman et al., 1986) show that the electrically resistive basalt in most portions of the Pasco Basin is in excess of 3,050 m (10,000 ft) thick. An underlying electrically conductive unit, believed to represent a possible Cretaceous to Eocene sedimentary sequence, is estimated to be approximately 6,100 m (20,000 ft) thick. Below this unit, lithologies are uncertain, but evidence suggests another electrically resistive layer interpreted to be basement rock. Seismic refraction studies by Rohay and Malone (1983) report that the basement rock is approximately 10 km (6.2 mi) deep.

Plans to further study the structure, stratigraphy, and hydrocarbon potential of rocks underlying the Columbia River Basalt Group are presented in Sections 8.3.1.2.3.3.4 and 8.3.1.6. These studies include additional magnetotelluric and refraction surveys, in addition to a possible deep sub-basalt borehole within the Pasco Basin.

1.2.1.2 Columbia River Basalt Group

The Columbia River Basalt Group (Fig. 1.2-1) comprises an assemblage of continental flood basalts and consists of a thick sequence of Miocene tholeiitic basalt flows. These flows cover an area of more than 163,000 km^2 (63,000 mi^2) in Washington, Oregon, and Idaho (Fig. 1.2-2a through 1.2-2cc) and have an estimated volume of about 170,600 km^3 (40,800 mi^3) (Tolan et al., 1987). Radiometric age determinations suggest flows of the Columbia River Basalt Group were erupted during a period from approximately 17 to 6 m.y.B.P., with more than 98% by volume being erupted in a 2.5-m.y. period from about 17 to 14.5 m.y.B.P. (Tolan et al., 1987).

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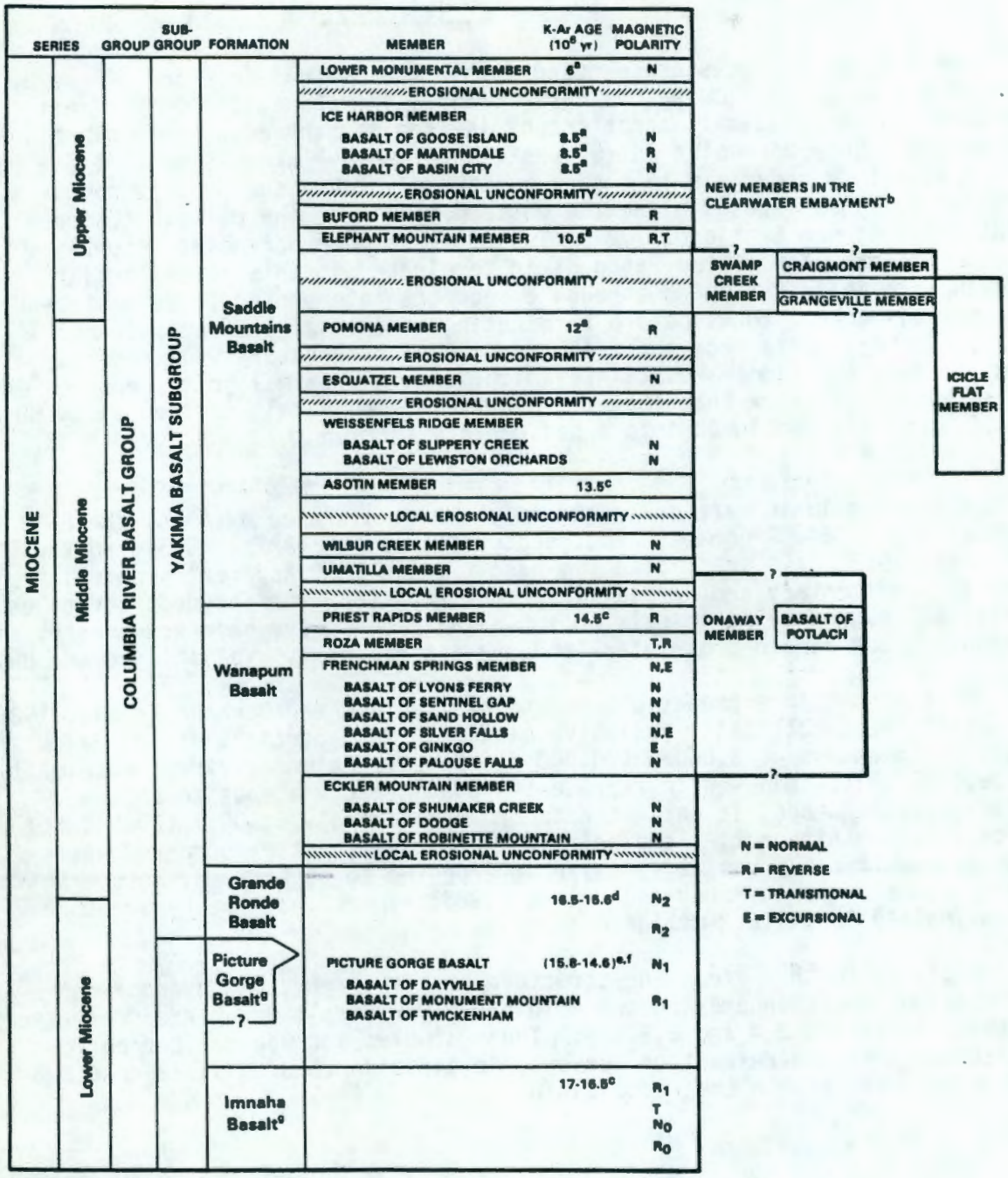

[a] DATA FROM McKEE et al. (1977).
[b] FROM CAMP (1981).
[c] DATA FROM McKEE et al. (1981).
[d] DATA FROM McKEE et al. (1981) AND LONG AND DUNCAN (1982).
[e] DATA MOSTLY FROM WATKINS AND BAKSI (1974).
[f] INFORMATION IN PARENTHESES REFERS TO PICTURE GORGE BASALT.
[g] THE IMNAHA AND PICTURE GORGE BASALTS ARE NOWHERE KNOWN TO BE IN CONTACT.

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Figure 1.2-1. Stratigraphic nomenclature for the Columbia River Basalt Group of the Columbia Plateau (modified from Swanson et al., 1979b; Beeson et al., 1985).

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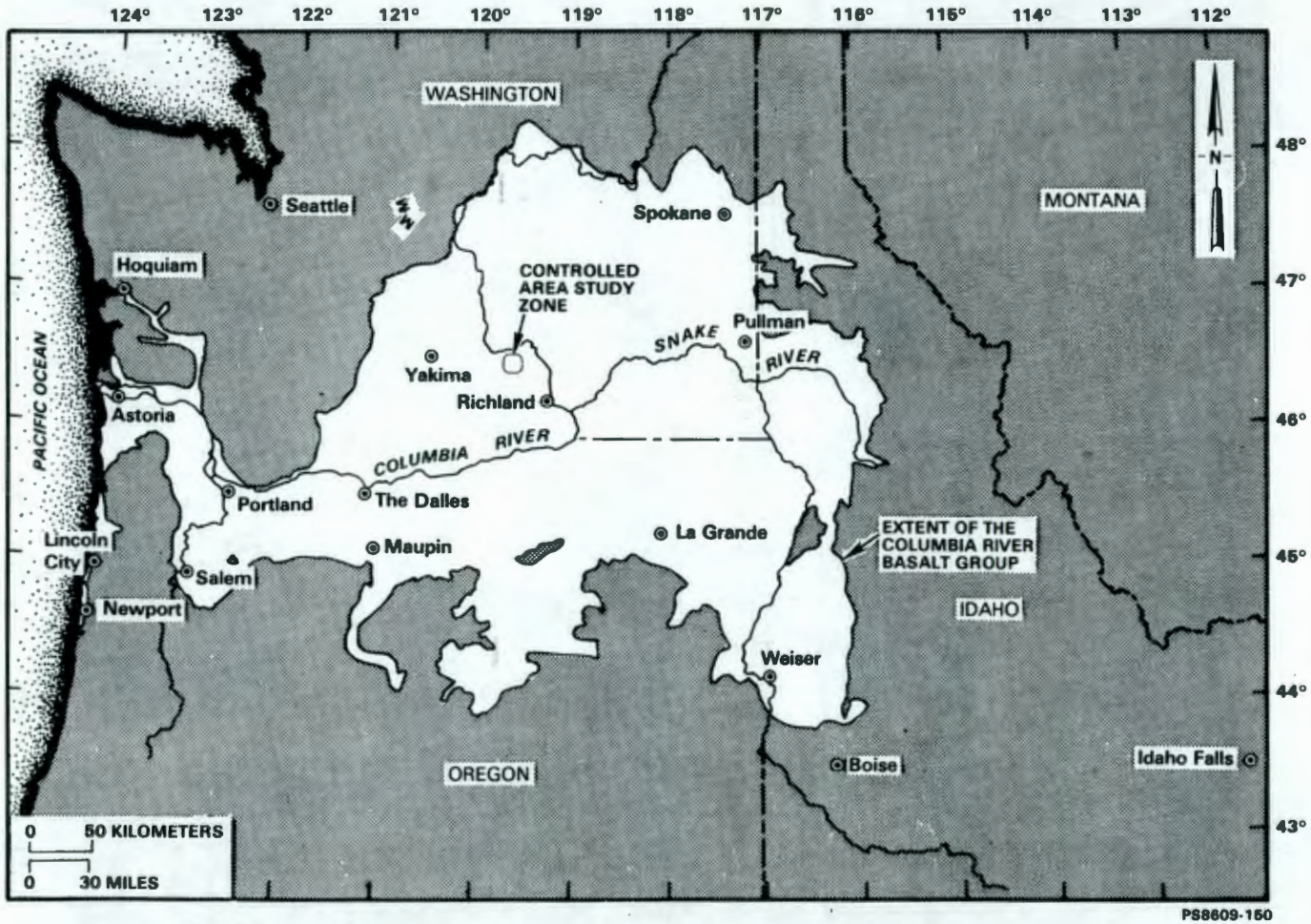

Figure 1.2-2a. Location map showing areal extent of Columbia River Basalt Group in Washington, Oregon, and Idaho.

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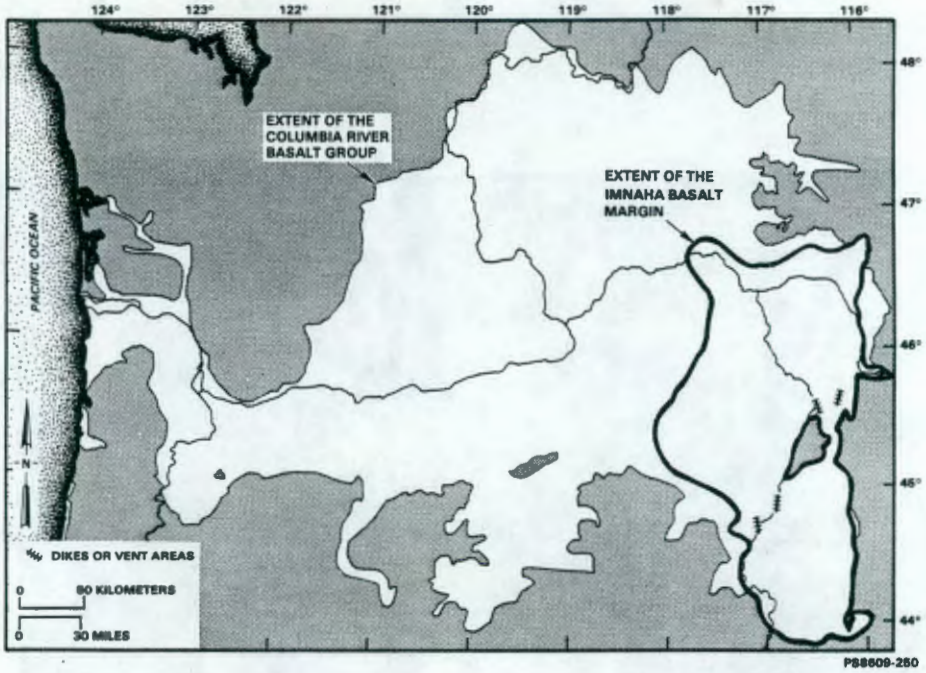

Figure 1.2-2b. Distribution map of the Imnaha Basalt.

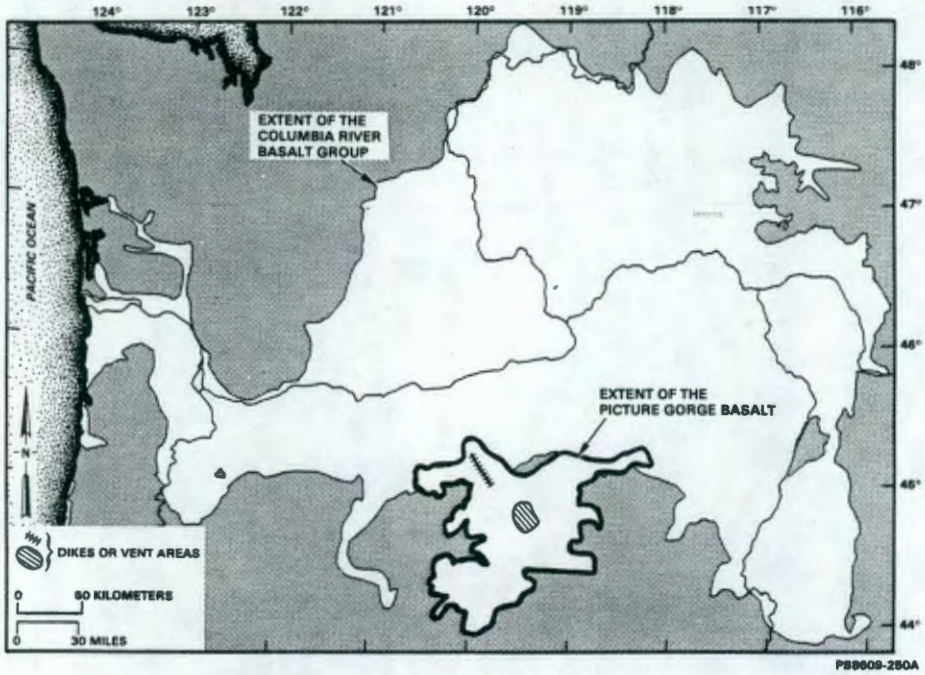

Figure 1.2-2c. Distribution map of the Picture Gorge Basalt.

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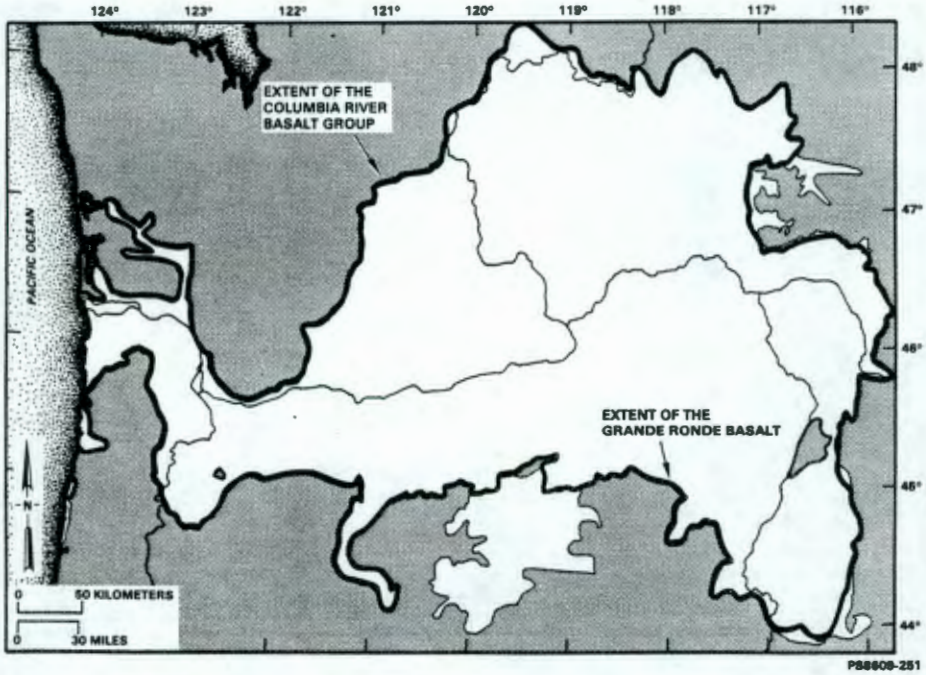

Figure 1.2-2d. Distribution map of the Grande Ronde Basalt.

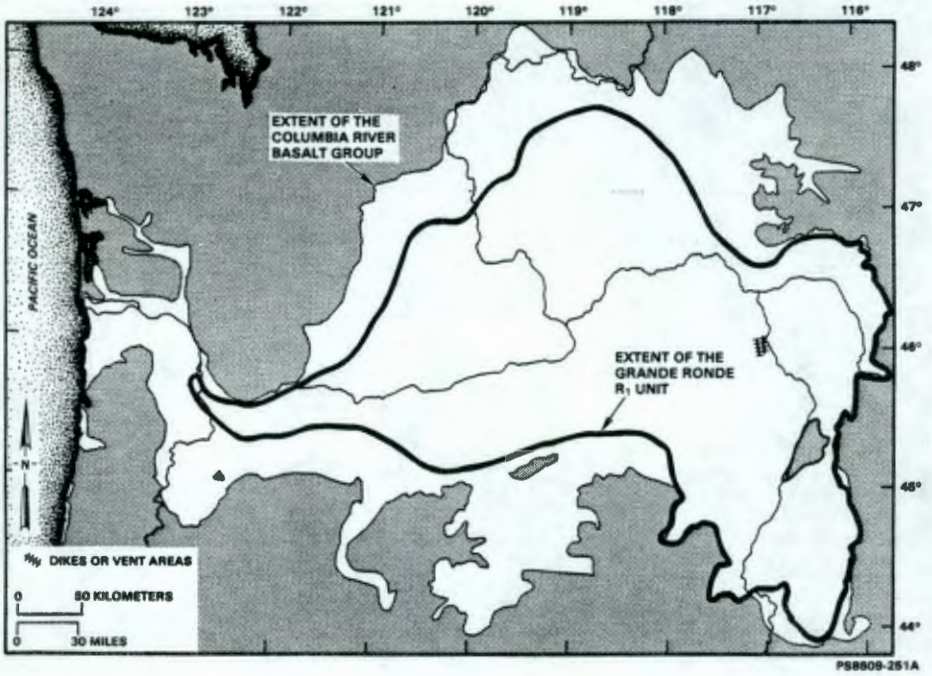

Figure 1.2-2e. Distribution map of the Grande Ronde Basalt R_1 magnetostratigraphic unit.

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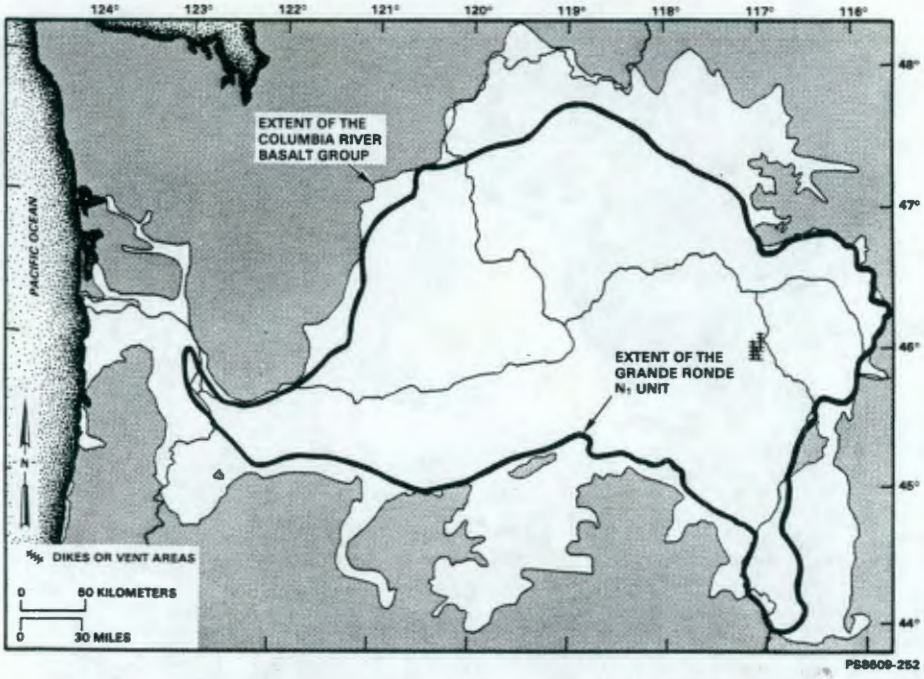

Figure 1.2-2f. Distribution map of the Grande Ronde Basalt N_1 magnetostratigraphic unit.

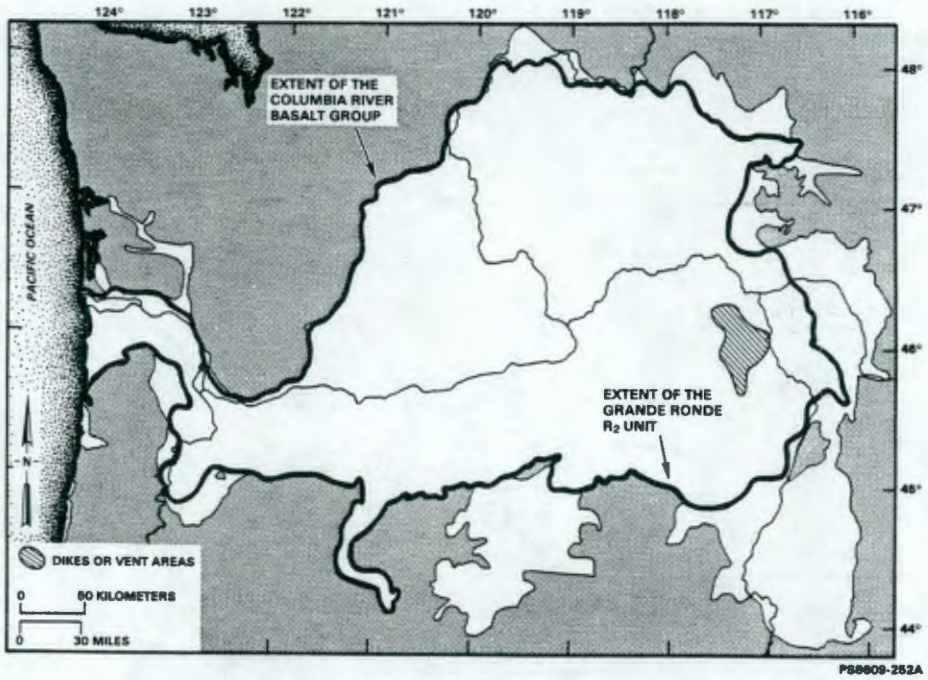

Figure 1.2-2g. Distribution map of the Grande Ronde Basalt R_2 magnetostratigraphic unit.

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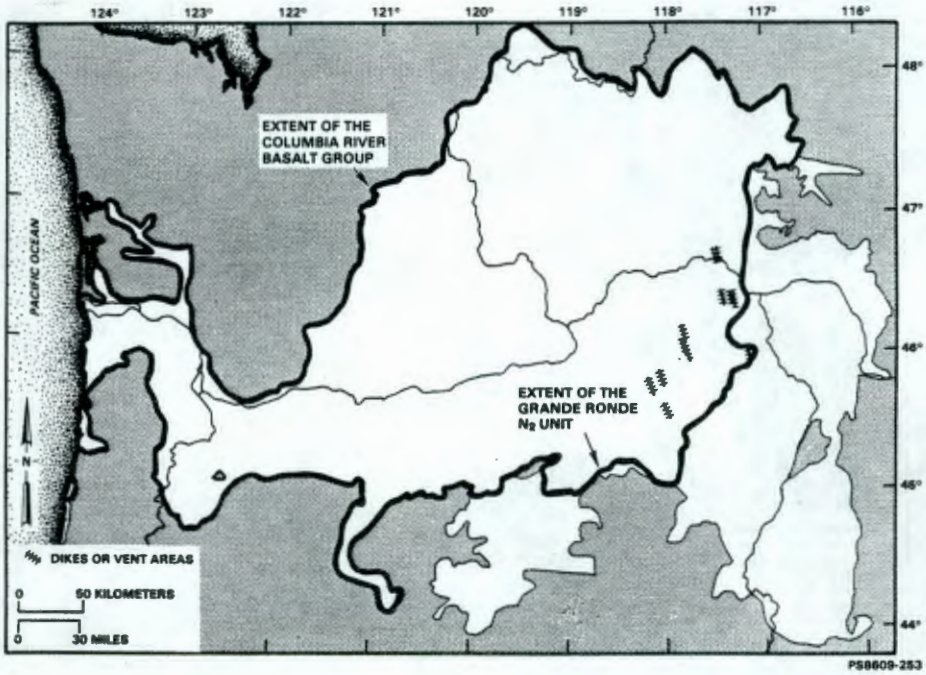

Figure 1.2-2h. Distribution map of the Grande Ronde Basalt N_2 magnetostratigraphic unit.

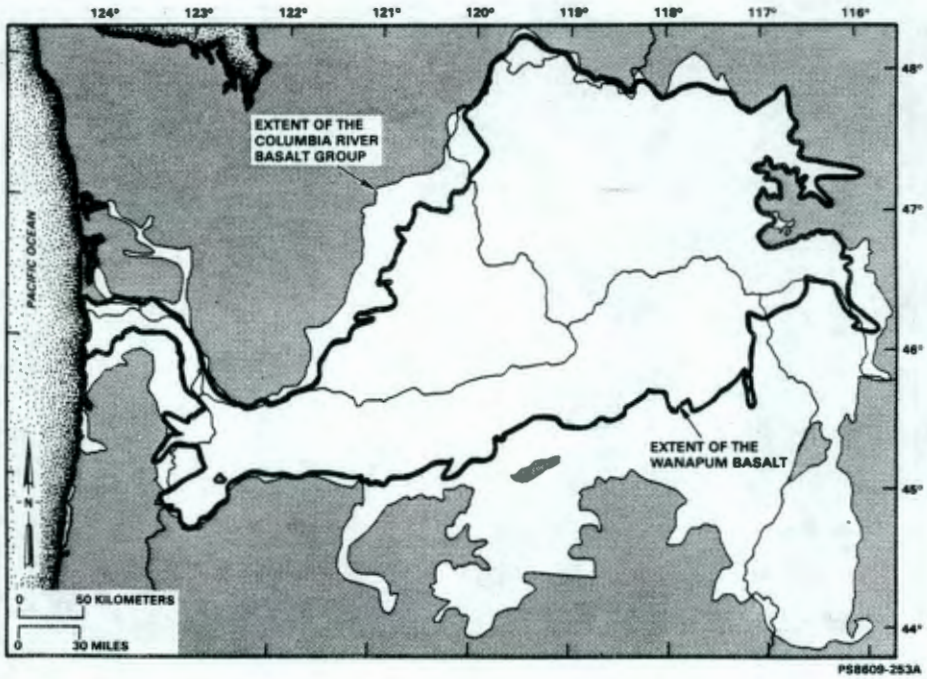

Figure 1.2-2i. Distribution map of the Wanapum Basalt.

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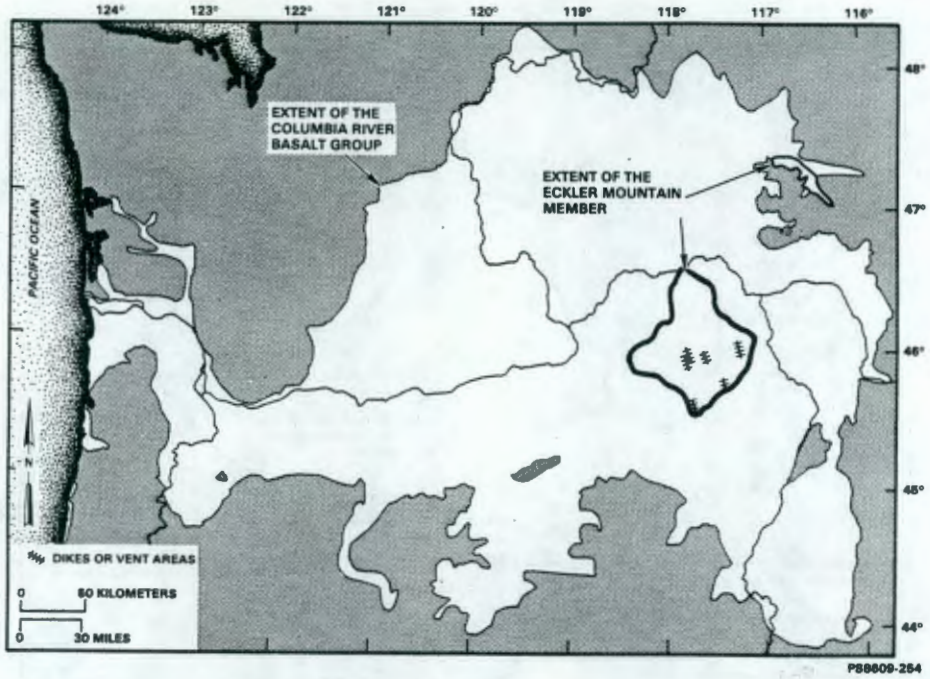

Figure 1.2-2j. Distribution map of the Eckler Mountain Member.

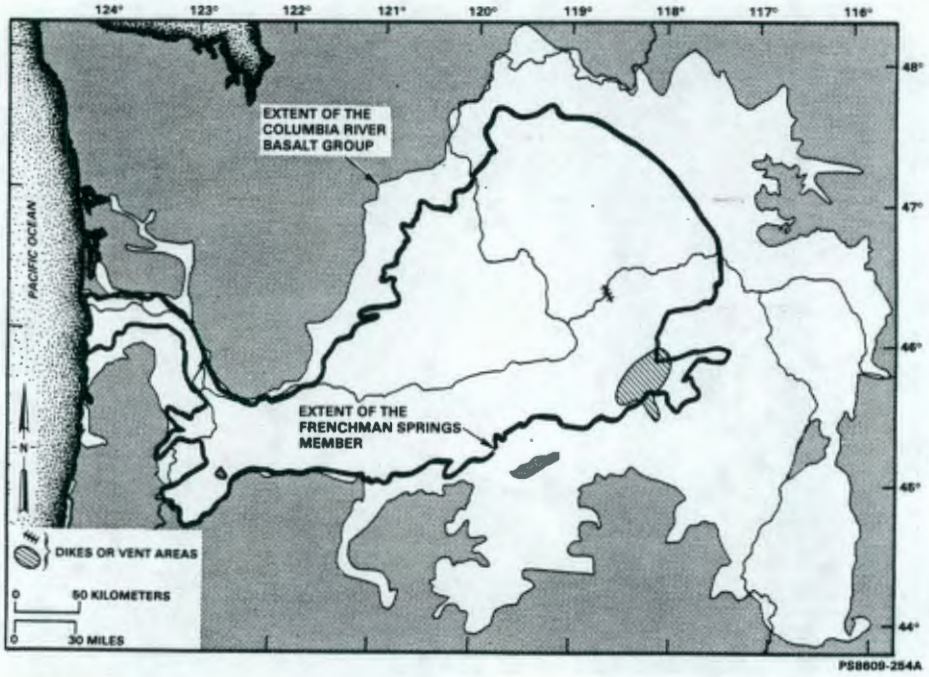

Figure 1.2-2k. Distribution map of the Frenchman Springs Member.

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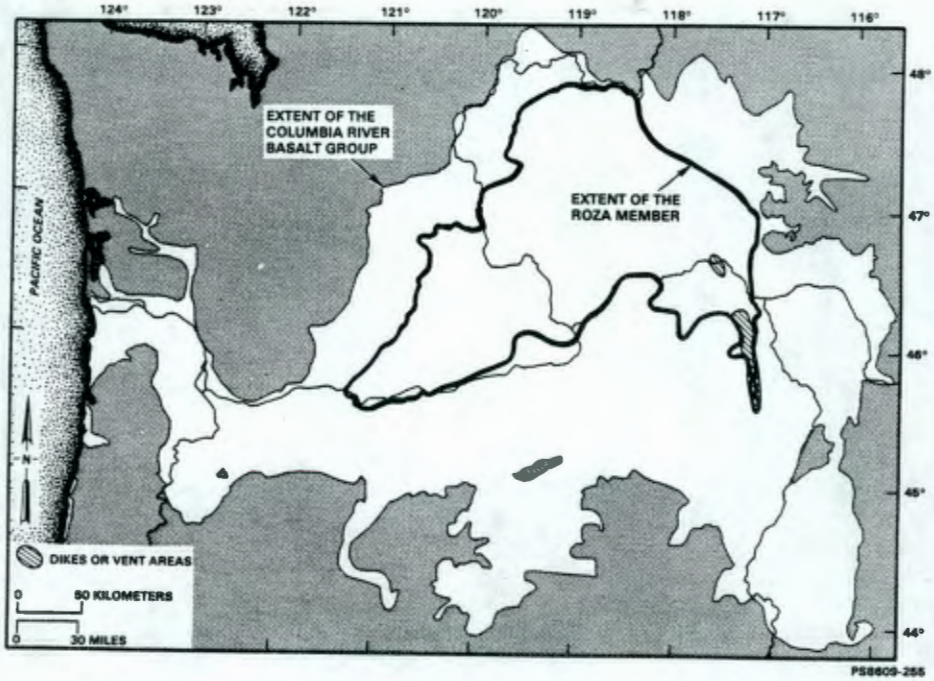

Figure 1.2-2l. Distribution map of the Rosa Member.

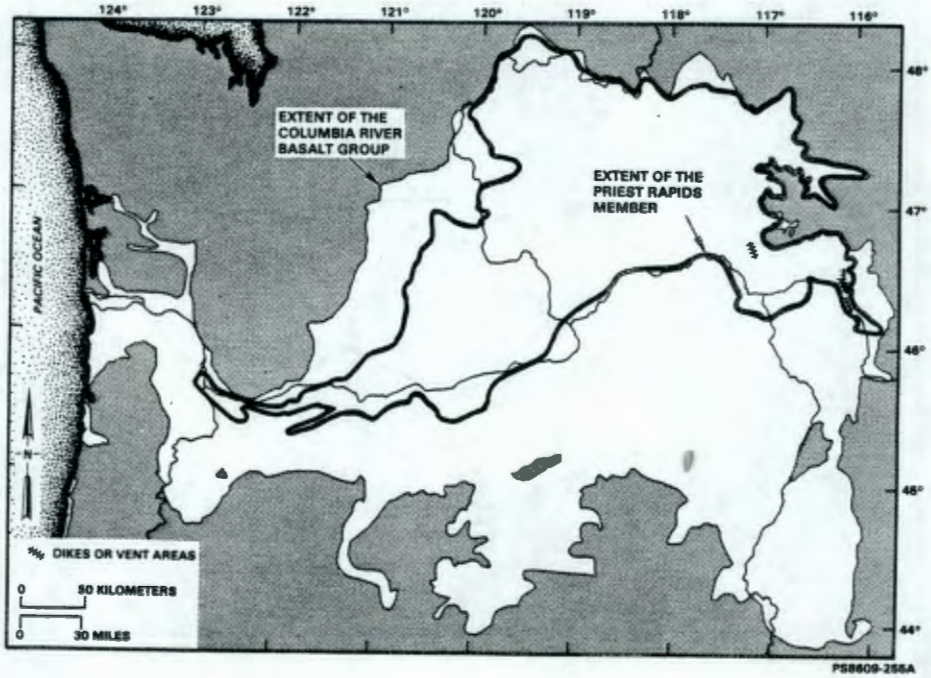

Figure 1.2-2m. Distribution map of the Priest Rapids Member.

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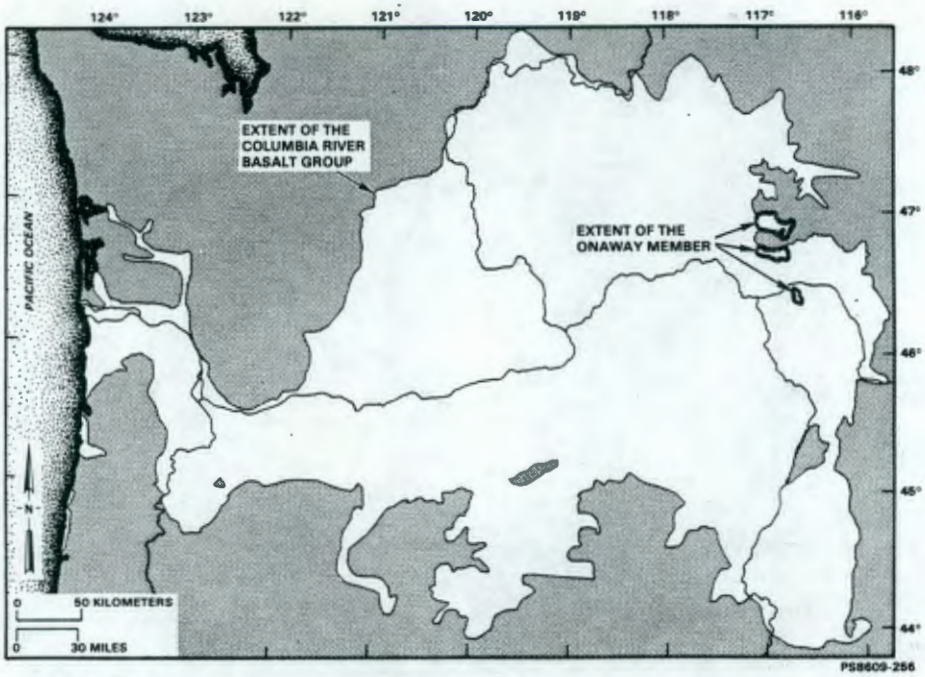

Figure 1.2-2n. Distribution map of the Onaway Member.

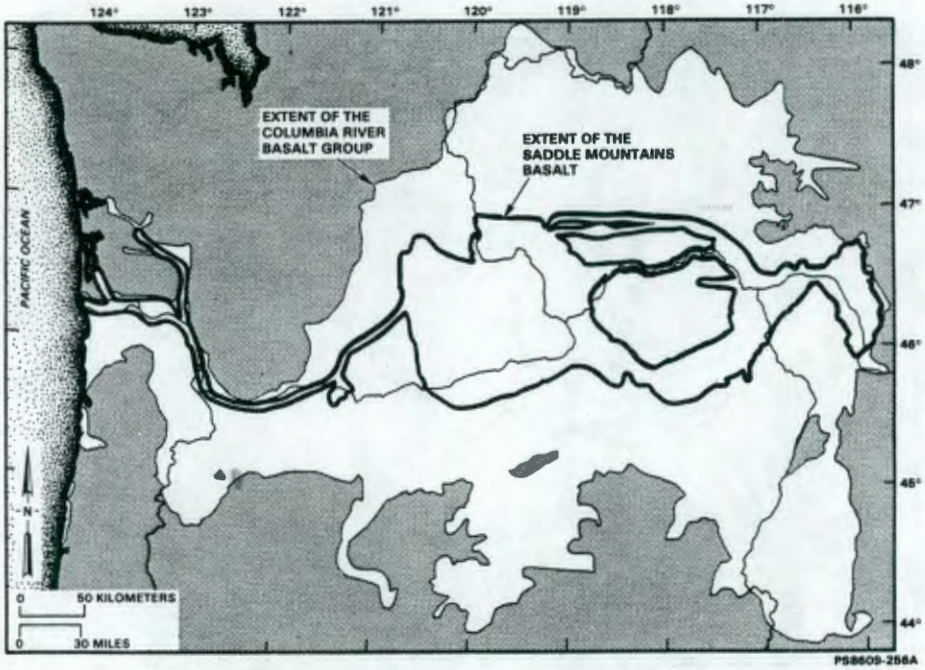

Figure 1.2-2o. Distribution map of the Saddle Mountains Basalt.

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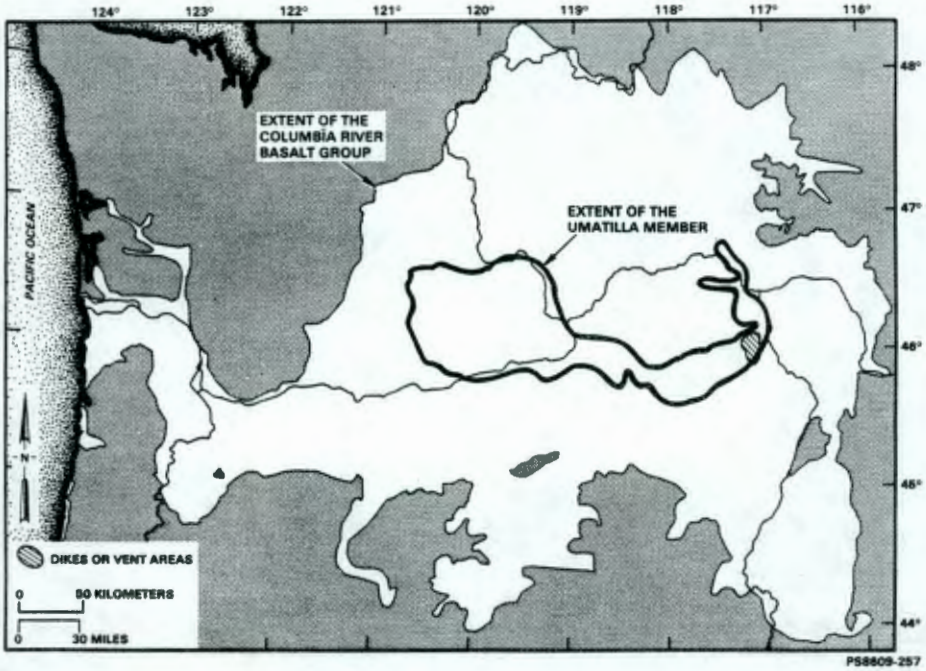

Figure 1.2-2p. Distribution map of the Umatilla Member.

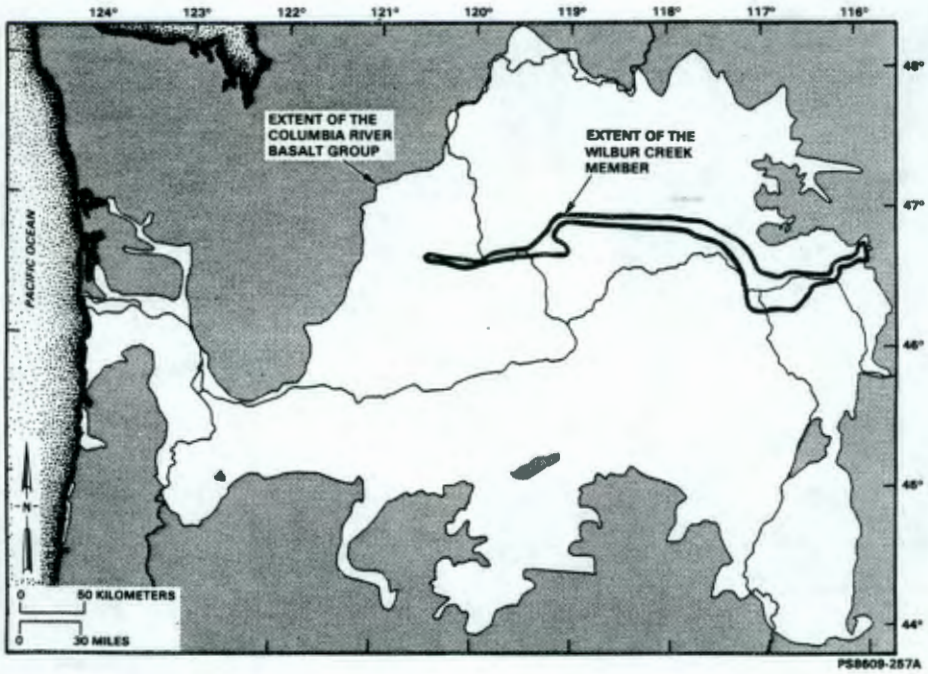

Figure 1.2-2q. Distribution map of the Wilbur Creek Member.

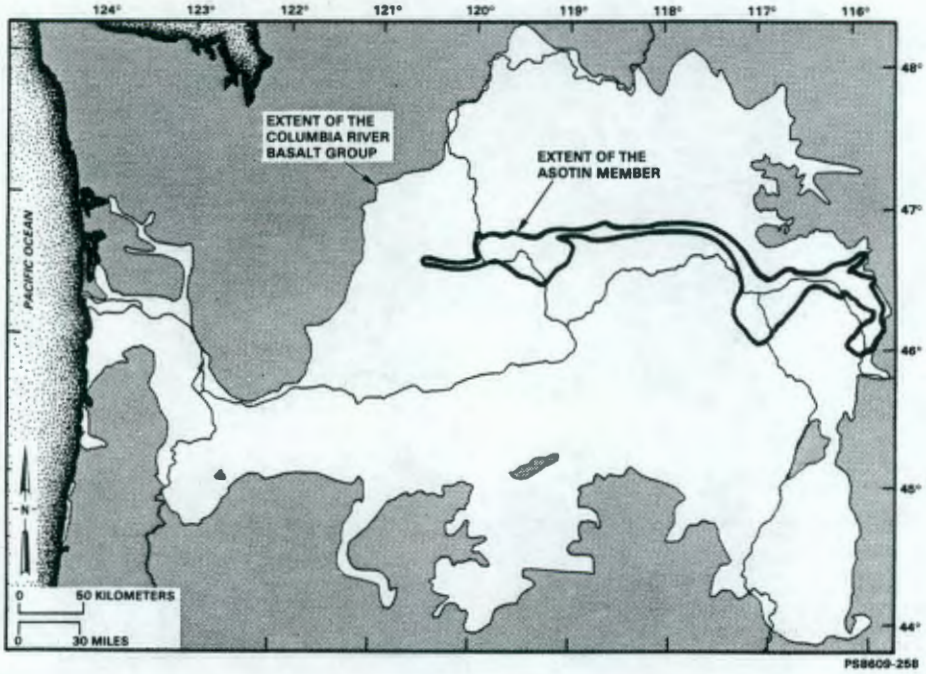

Figure 1.2-2r. Distribution map of the Asotin Member.

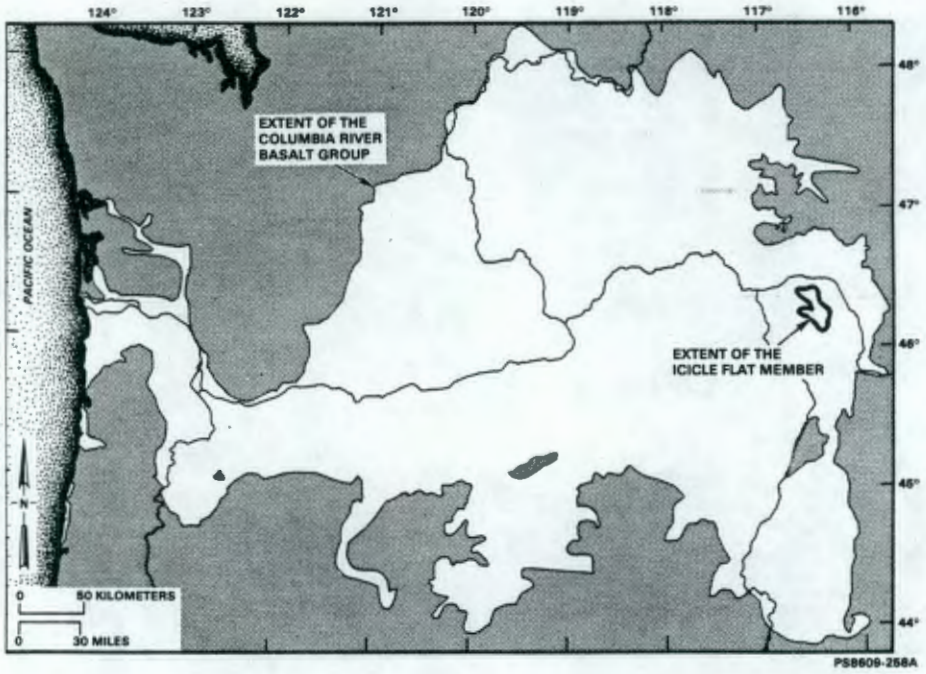

Figure 1.2-2s. Distribution map of the Icicle Flat Member.

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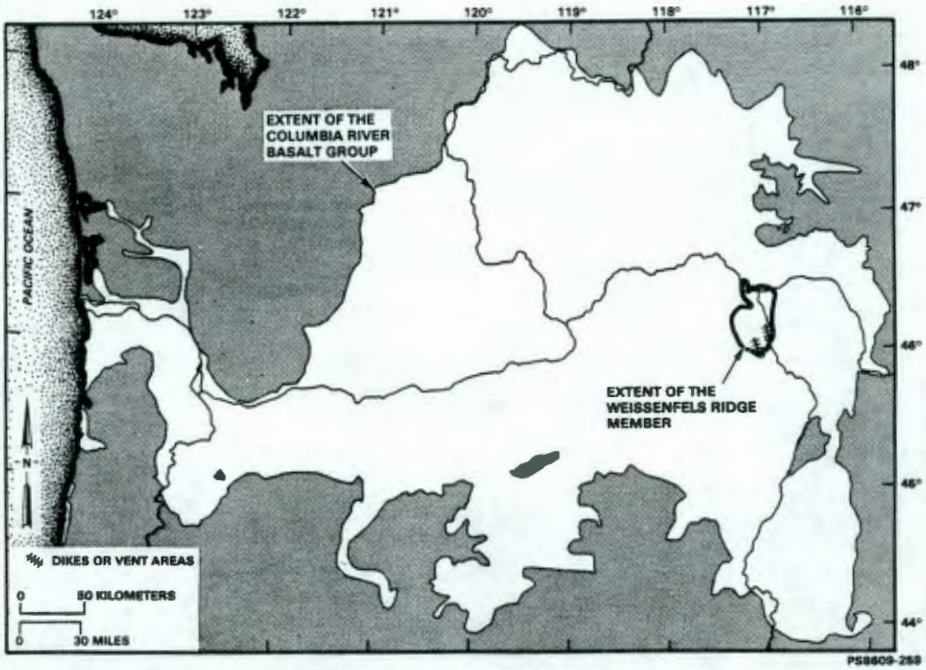

Figure 1.2-2t. Distribution map of the Weissenfels Ridge Member.

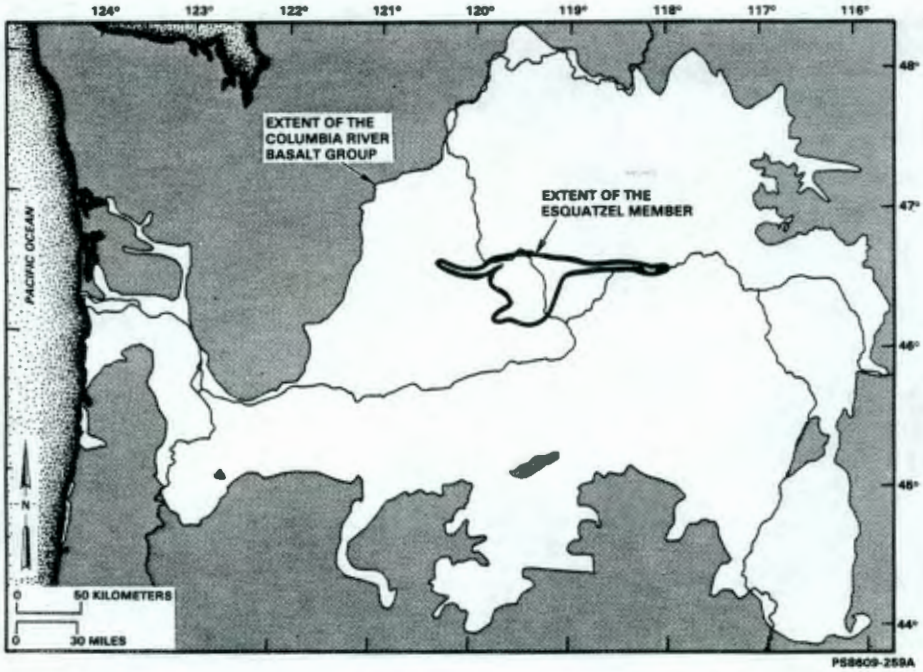

Figure 1.2-2u. Distribution map of the Esquatzel Member.

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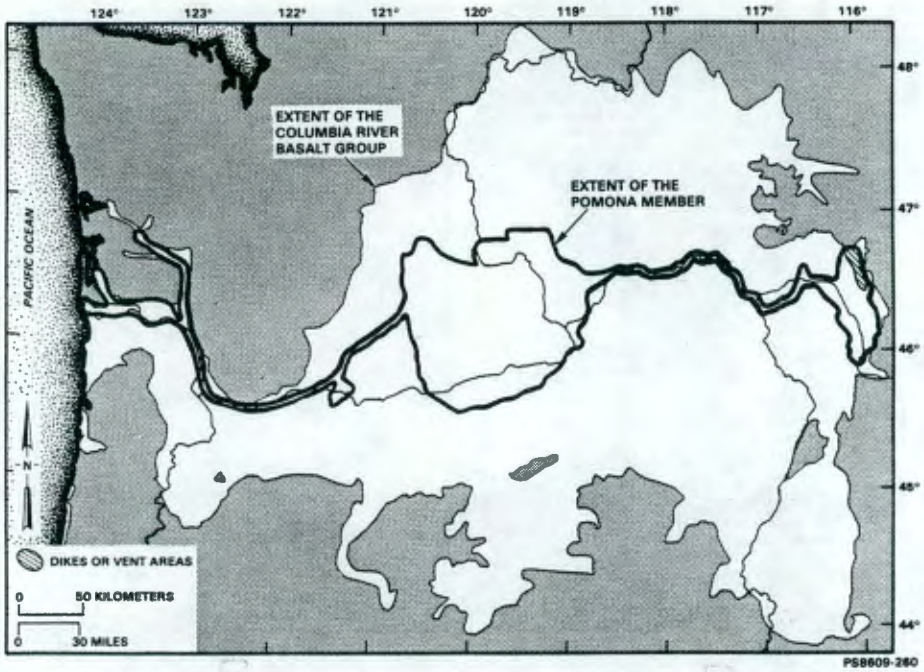

Figure 1.2-2v. Distribution map of the Pomona Member.

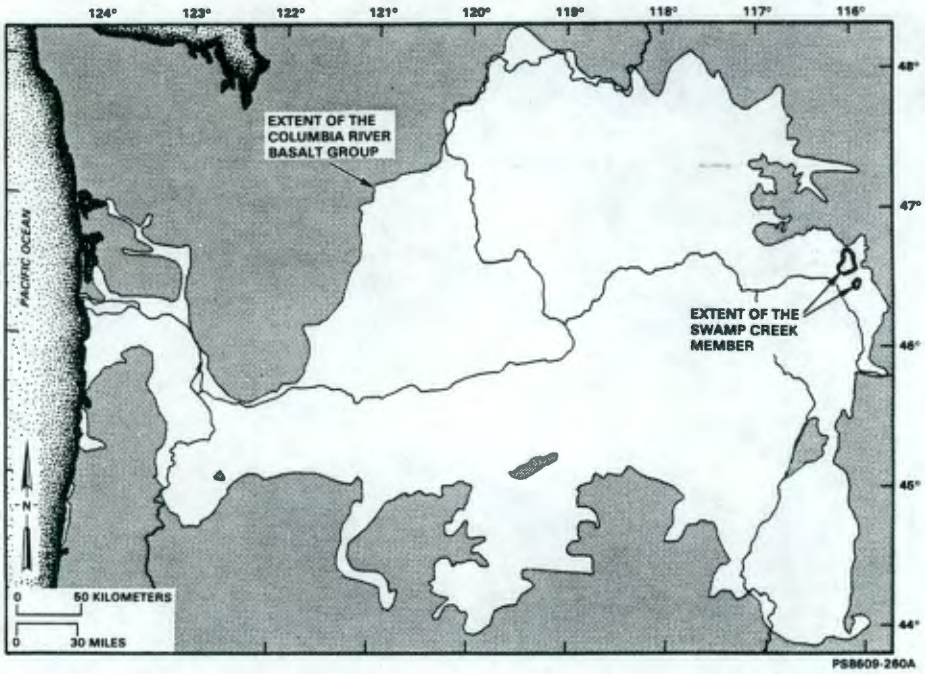

Figure 1.2-2w. Distribution map of the Swamp Creek Member.

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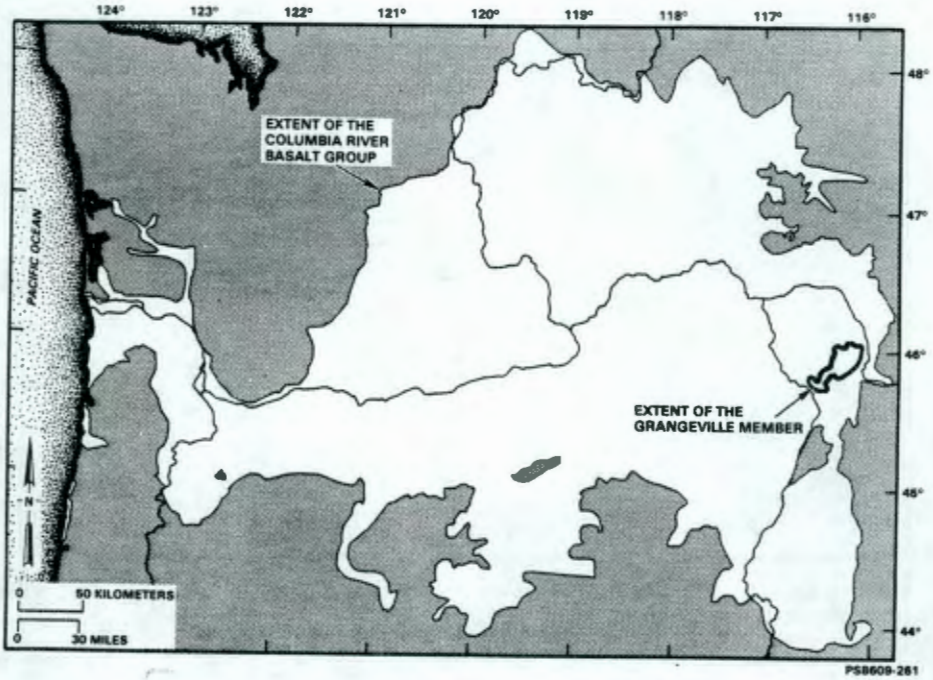

Figure 1.2-2x. Distribution map of the Grangeville Member.

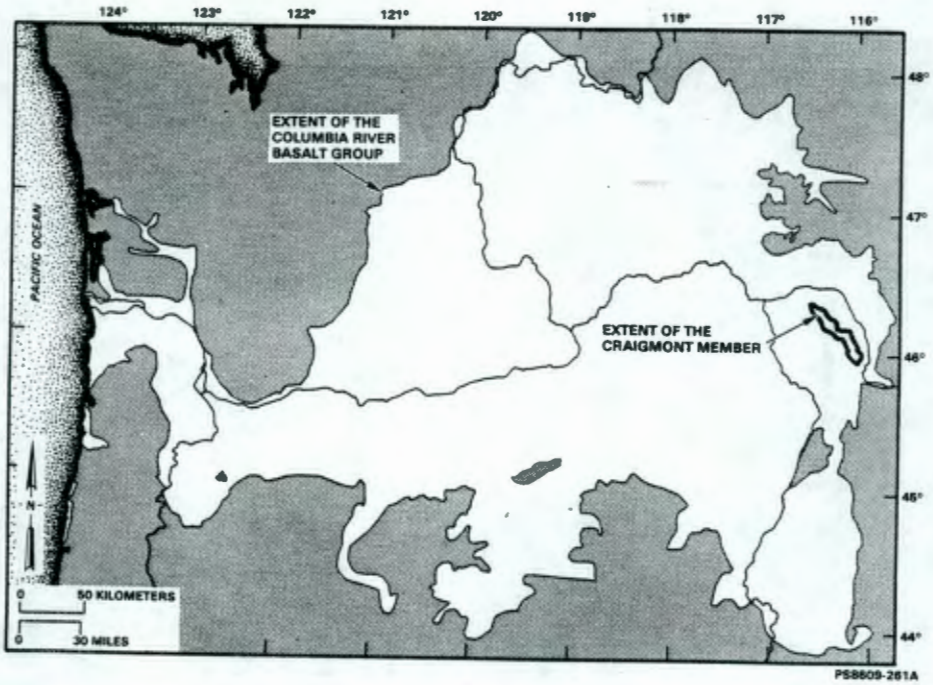

Figure 1.2-2y. Distribution map of the Craigmont Member.

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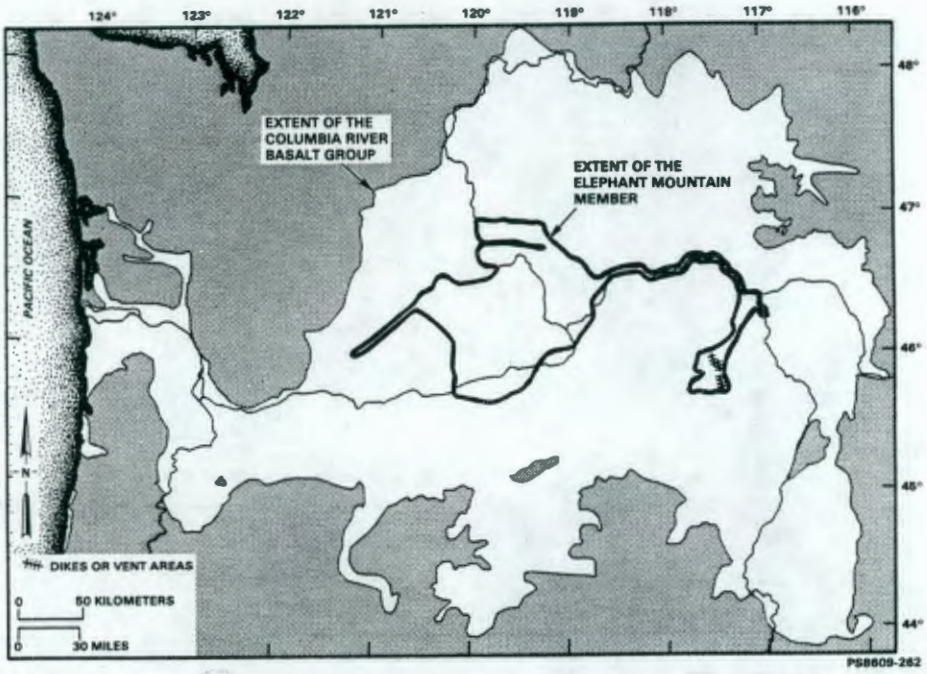

Figure 1.2-2z. Distribution map of the Elephant Mountain Member.

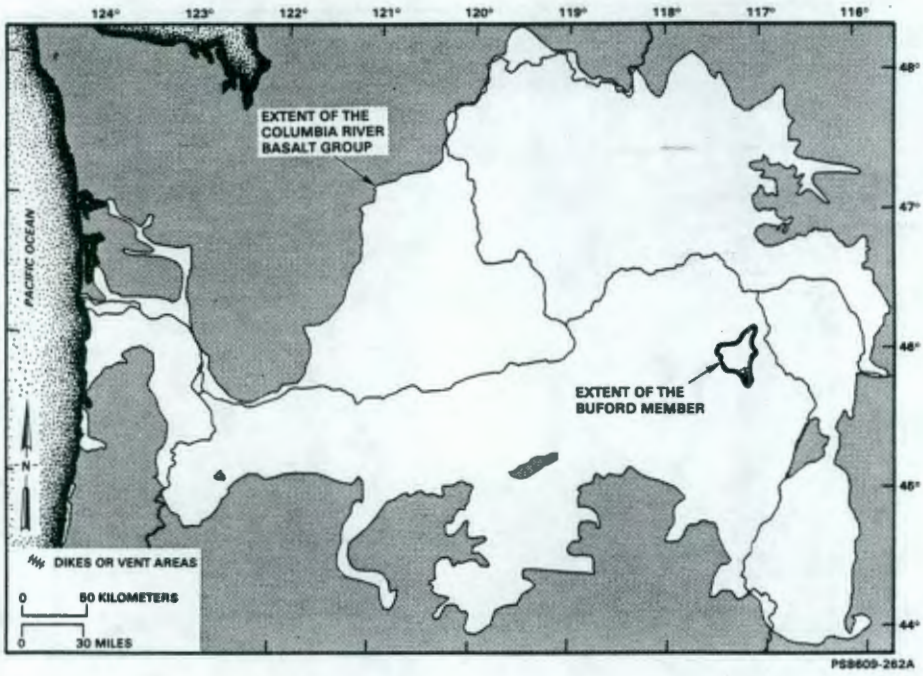

Figure 1.2-2aa. Distribution map of the Buford Member.

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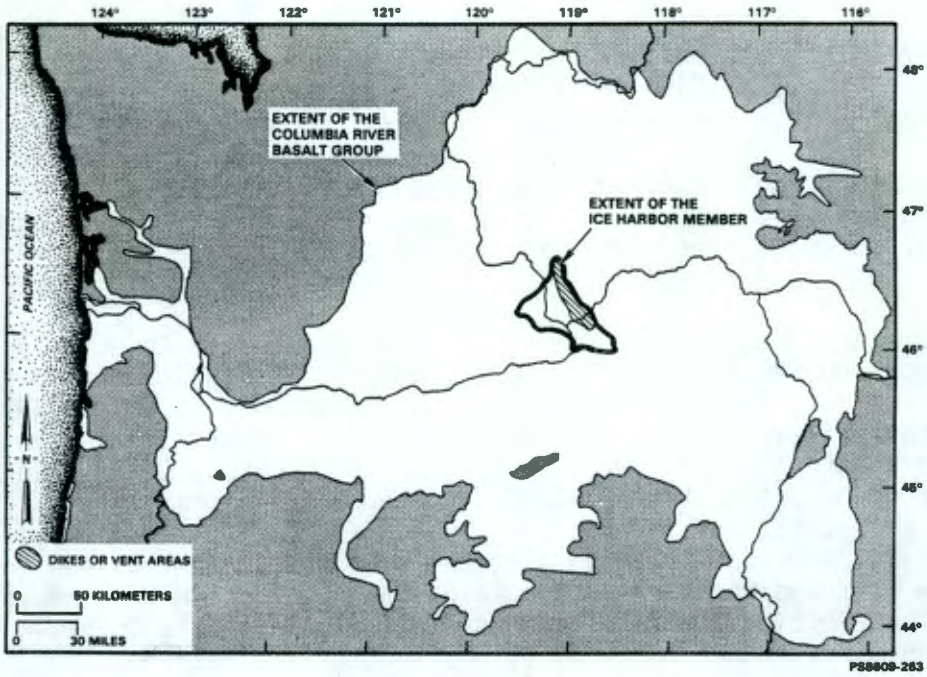

Figure 1.2-2bb. Distribution map of the Ice Harbor Member.

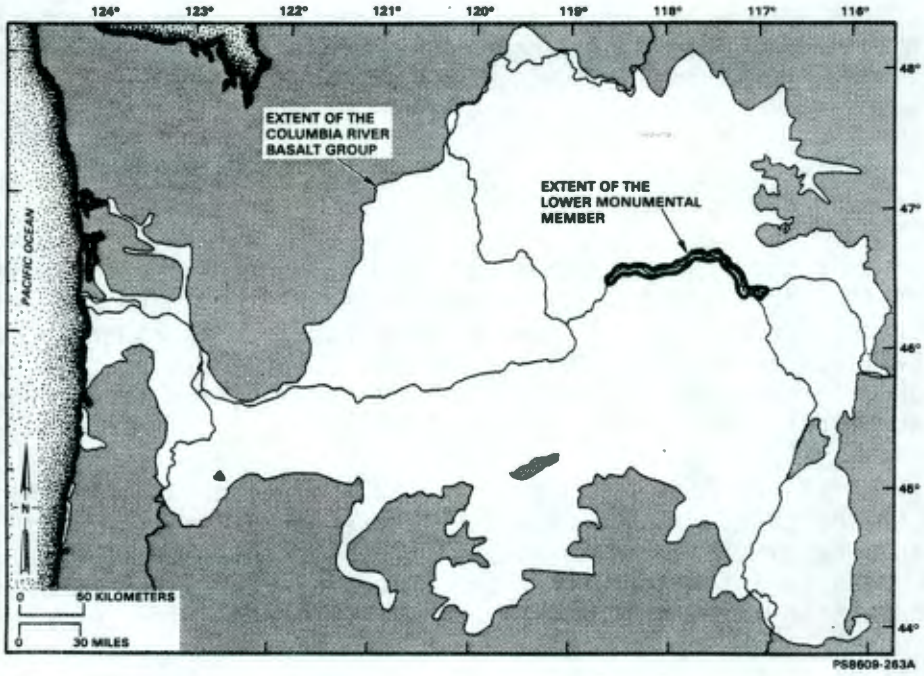

Figure 1.2-2cc. Distribution map of the lower Monumental Member.

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Columbia River basalt flows were erupted from north-northwest-trending fissures or linear vent systems in northcentral and northeastern Oregon, eastern Washington, and western Idaho (see Fig. 1.2-2a). The vent system that fed individual flows probably consisted of a network of closely spaced dikes whose active eruptive lengths were on the order of many tens of kilometers (Swanson et al., 1975, pp. 877-905; Swanson and Wright, 1981, pp. 10-11). It is estimated that individual flows typically had volumes of 10 to 30 km^3 (2.4 to 7.2 mi^3); however, some individual flows are known to have exceeded 500 km^3 (120 mi^3) in volume (Swanson and Wright, 1981, pp. 7-9; Beeson et al., 1985, p. 89).

It is believed that the duration of an eruption of a Columbia River Basalt Group flow perhaps lasted from several days to as long as several weeks (Swanson et al., 1975, pp. 877-905; Swanson and Wright, 1981, pp. 10-11). The large volume and relatively low viscosity of the erupting lavas enabled them to cover large areas and distances. Some of the Columbia River Basalt Group flows, erupted in the eastern plateau, succeeded in reaching the Pacific Ocean (Beeson et al., 1979, pp. 159-166; Tolan and Beeson, 1984, pp. 463-477; Beeson et al., 1985, pp. 87-96). A recently completed hydrocarbon exploration well at the northern boundary of the Pasco Basin (Saddle Mountains well of Shell Oil, see Section 1.7.2) did penetrate the base of the Columbia River Basalt Group. Preliminary determinations from drill logs show that the base of the basalt is approximately 3,490 m (11,450 ft) below ground surface at this location.

Discussions of internal flow features (intraflow structures), primary cooling fractures, and mineralogic and petrologic characteristics of flows are described in this section. Mineralogic and petrologic characteristics of flows are also described in Section 4.1.1.4.

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1.2.1.2.1 Stratigraphic units

Variations in the physical, chemical, and paleomagnetic properties of groups of and (or) individual Columbia River basalt flows have allowed their division into both formal and informal stratigraphic units (Swanson et al., 1979b, pp. 6-7; Beeson et al., 1985, pp. 87-96; Camp, 1981, pp. 669-678). In addition, borehole geophysical log response, thickness, and stratigraphic position also help to differentiate basalt units.

The Columbia River Basalt Group is formally divided into five formations, from oldest to youngest: Imnaha Basalt, Picture Gorge Basalt, Grande Ronde Basalt, Wanapum Basalt, and Saddle Mountains Basalt (see Fig. 1.2-1). Sedimentary units or interbeds within the Columbia River Basalt Group are discussed in Section 1.2.1.3.

Only a brief description is given of the Imnaha and Picture Gorge Basalts, which are not known to occur in the Pasco Basin. Most of the discussion that follows deals with the basalt formations present in the Pasco Basin. The Grande Ronde Basalt is discussed the most extensively because it

contains the candidate horizon. It should be noted that the following discussion is intended to describe the formal regional basalt units.

1.2.1.2.1.1 Imnaha Basalt

The oldest Columbia River Basalt Group formation is the Imnaha Basalt. Flows of Imnaha Basalt cover approximately 34,000 km^2 (13,000 mi^2) in northeastern Oregon, west-central Idaho, and southeastern Washington (Hooper et al., 1984, pp. 476) (see Fig. 1.2-2b). The Imnaha Basalt has an estimated volume of 5,770 km^3 (1,385 mi^3) (Tolan et al., 1987), which is approximately 3.4% of the total volume of the Columbia River Basalt Group. These flows were erupted from about 17 to 16.5 m.y.B.P. (McKee et al., 1981) from fissures found primarily south of the Wallowa-Seven Devils divide in northeastern Oregon/west-central Idaho (Hooper et al., 1984, p. 476) (see Fig. 1.2-2b).

Flows of the Imnaha Basalt are typically 20 to 40 m (65 to 130 ft) thick, but where ponded they have attained thicknesses in excess of 120 m (400 ft) (Hooper et al., 1984, p. 476). The thickest known sections of Imnaha Basalt have been found in the Weiser Embayment of west-central Idaho. Here, exposed Imnaha Basalt sections attain thicknesses of over 700 m (2,300 ft) (Fitzgerald, 1984, p. 9). A composite Imnaha Basalt section in the Weiser Embayment could consist of up to 44 flows and have a thickness of over 914 m (3,000 ft) (Fitzgerald, 1984, p. 9). The Imnaha Basalt is distinguished by its coarse porphyritic texture. Lithologic, mineralogic, and petrologic characteristics of Imnaha flows are summarized in Hooper et al. (1984, pp. 476-483).

The Imnaha Basalt is formally divided into four magnetostratigraphic units based on the magnetic polarity of the individual flows (R_0, N_0, T, R_1) (Swanson et al., 1979a, p. 12; Fitzgerald, 1984, pp. 9-22; see Fig. 1.2-1). On the basis of major oxide and trace element compositions, the Imnaha Basalt has been informally subdivided into 11 compositional units (Hooper et al., 1984, pp. 476-492). These 11 Imnaha Basalt compositional units can be grouped informally into the American Bar and Rock Creek subtypes (Hooper et al., 1984, pp. 476-492). Although there is interfingering of the two Imnaha subtypes, flows of the American Bar subtype predominate in the older portion of the section while flows of the Rock Creek subtype predominate in the younger portion of the section.

The Imnaha Basalt is usually conformably overlain by flows of the Grande Ronde Basalt. Swanson et al. (1979a, p. G12), based on paleomagnetic data, considered it likely that the uppermost portion of the Imnaha Basalt might somewhere be interfingered with the oldest Grande Ronde Basalt flows. However, work reported to date has failed to substantiate this hypothesis (Reidel, 1978b, pp. 371-382; Hooper et al., 1984, pp. 475-478; Fitzgerald, 1984, pp. 9-22).

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1.2.1.2.1.2 Picture Gorge Basalt

The Picture Gorge Basalt has a volume of 2,391 km^3 (570 mi^3) (Tolan et al., 1987), which represents approximately 1.4% by volume of the Columbia River Basalt Group. It was erupted coevally with the Grande Ronde Basalt (Bentley and Cockerham, 1973; Swanson and Wright, 1981, p. 3). The Picture Gorge Basalt consists of up to 65 flows, with 44 being correlatable over distance (Bailey, 1986, p. 102). Flows were erupted from feeder dikes of the Monument dike swarm (Waters, 1961, p. 587) and were primarily confined to north-central Oregon (see Fig. 1.2-2c) in the John Day Basin. Swanson and Wright (1981, p. 3) suggest that the ancestral Blue Mountains uplift may have prevented most of the Picture Gorge flows from spreading northward out of the John Day Basin. The greatest known thickness of Picture Gorge Basalt is approximately 792 m (2,600 ft) (Thayer and Brown, 1966).

The Picture Gorge Basalt contains both aphyric and abundantly plagioclase-phyric flows, which fall into the Picture Gorge chemical type defined by Wright et al. (1973, Table 1). The Picture Gorge Basalt can be subdivided into three informal lithologic members (Swanson et al., 1979a, p. G13). These members, from oldest to youngest, are the basalt of Twickenham, the basalt of Monument Mountain, and the basalt of Dayville (see Fig. 1.2-1). Work in progress by Bailey (1986, p. 22) suggests that the Picture Gorge Basalt may be subdivided into as many as 16 compositional/stratigraphic units.

The Picture Gorge Basalt is nowhere in contact with the older Imnaha Basalt and appears coeval with the middle part of the Grande Ronde Basalt (Swanson et al., 1979a, pp. G12, G21-G22).

1.2.1.2.1.3 Grande Ronde Basalt

The Grande Ronde Basalt, which contains the Cohassett flow, is the most areally extensive and voluminous formation within the Columbia River Basalt Group. Flows of the Grande Ronde Basalt were erupted from fissures and vents throughout the eastern half of the Columbia Plateau (see Fig. 1.2-2d) from approximately 16.9 to 15.6 m.y.B.P. (McKee et al., 1981; Long and Duncan, 1982). During this approximately 1.3-m.y. period, more than 149,000 km^3 (35,700 mi^3) (Tolan et al., 1987) of Grande Ronde Basalt was erupted, which represents about 87.5% by volume of the entire Columbia River Basalt Group. Flows of Grande Ronde Basalt covered most of the Columbia Plateau (Swanson et al., 1979a, Plate I; 1980; 1981; see Fig. 1.2-2d) and flowed west across the Miocene Cascade Range into northwestern Oregon and southwestern Washington (Beeson and Moran, 1979b). A few Grande Ronde Basalt flows crossed the Oregon and Washington Miocene Coast Range through water gaps and reached the Pacific Ocean (Snavely et al., 1973; Beeson et al., 1979) (see Fig. 1.2-2d). The thickest known section of Grande Ronde Basalt, over 2,700 m (8,850 ft), is found in the Rattlesnake Hills No. 1 well on the west edge of the Pasco Basin in south-central Washington (Reidel et al., 1981).

The Grande Ronde Basalt conformably overlies the Imnaha Basalt (Kleck, 1973; Camp, 1976; Reidel, 1978b, p. 16; Fitzgerald, 1984, p. 23) and is

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interfingered with the Picture Gorge Basalt (Bentley and Cockerham, 1973; Swanson et al., 1979a, pp. G21-G22). The Grande Ronde Basalt was previously reported to interfinger with members of the Wanapum Basalt in southeastern Washington (Swanson and Wright, 1976, p. 24; Swanson et al., 1979a, pp. G22-G24; Swanson and Wright, 1981, p. 4). However, recent work by Beeson et al. (1985, pp. 91-93) has demonstrated that the Grande Ronde and Wanapum Basalts do not interfinger. Quite often the Grande Ronde is separated from the overlying Wanapum by a zone of erosion or an interbed.

Flows of Grande Ronde Basalt are typically aphyric, although a few flows scattered throughout the section contain sparse to abundant plagioclase phenocrysts (Camp, 1976; Reidel, 1978b; Bentley et al., 1980, pp. 8-10). Major oxide and trace element compositions of these flows fall within a broad range defined as the "Grande Ronde chemical type" (Swanson et al., 1979a, pp. G16-G21).

The Grande Ronde Basalt is formally subdivided into four magnetostratigraphic units (R_1, N_1, R_2, and N_2) (see Fig. 1.2-1) on the basis of the paleomagnetic polarity of the flows (Swanson and Wright, 1976; Swanson et al., 1979a, pp. G19-G20). Swanson et al. (1979a, p. G19) and Swanson and Wright (1981, p. 3) consider these magnetostratigraphic subdivisions the only reliable plateau-wide subdivisions within the Grande Ronde Basalt. Volume calculations are from Tolan et al. (1987).

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R_1 magnetostratigraphic unit

The R_1 magnetostratigraphic unit covers 96,600 km^2 (37,250 mi^2) in Washington, Oregon, and Idaho (Fig. 1.2-2e). The unit is identified by its reversed magnetic polarity and stratigraphic position. The unit comprises numerous, typically aphyric flows, and the volume is estimated at 36,200 km^3 (8,700 mi^3). Flow vents have been identified in northeast Oregon and southeast Washington.

N_1 magnetostratigraphic unit

The N_1 magnetostratigraphic unit has a slightly larger areal extent (102,300 km^2 (39,450 mi^2)) and smaller volume (31,400 km^3 (7,500 mi^3)) than the R_1 unit. The unit is found throughout most of the Columbia Plateau (Fig. 1.2-2f) and comprises numerous, typically aphyric flows. The unit is distinguished by its normal magnetic polarity and stratigraphic position. Flow vents have been identified in northeast Oregon and southeast Washington.

R_2 magnetostratigraphic unit

The R_2 magnetostratigraphic unit is found throughout most of the Columbia Plateau and westward to the Oregon coast (Fig. 1.2-2g). The unit has the largest areal extent (119,600 km^2 (46,100 mi^2)) and volume (53,400 km^3 (12,800 mi^3)) of the Grande Ronde Basalt magnetostratigraphic units. The unit comprises numerous, typically aphyric flows. The unit is distinguished by its normal magnetic polarity and stratigraphic position. Flow vents have been identified in northeast Oregon and southeast Washington.

N_2 magnetostratigraphic unit

The N_2 magnetostratigraphic unit is found throughout most of the Columbia Plateau and westward to the Oregon coast (Fig. 1.2-2h). The unit has an areal extent of 116,400 km^2 (44,900 mi^2) and volume of 28,200 km^3 (6,700 mi^3). The unit comprises numerous, typically aphyric flows. The unit is distinguished by its normal magnetic polarity and stratigraphic position. Flow vents have been identified in northeast Oregon and southeast Washington.

On a local basis, other workers have demonstrated that it is possible to define informal units within the Grande Ronde Basalt based on a combination of paleomagnetic declination, inclination, polarity, major oxide/trace element composition, lithology, and stratigraphic position (Reidel, 1978, 1983; Beeson and Moran, 1979a; Bentley et al., 1980, pp. 7-10; Long and Landon, 1981, pp. 4-10 to 4-18). A recent publication by Mangan et al. (1986) proposes an informal regional breakdown of Grande Ronde Basalt stratigraphy.

Within the Pasco Basin, the Grande Ronde Basalt is further subdivided into two informal sequences: the Schwana and the Sentinel Bluffs Sequences (Myers/Price et al., 1979) (Fig. 1.2-3). Figures 1.2-4 and 1.2-5 are east-west and north-south trending fence diagrams showing correlations of individual flows within the upper portion of the Grande Ronde Basalt in the Pasco Basin. The division of the sequences is based on magnesium content. The Schwana sequence is comprised mostly of flows of the low-magnesium oxide chemical type (Swanson et al., 1979a, Table 2), but flows of high-magnesium oxide and a single flow of very high-magnesium oxide content do occur. The upper contact of the Schwana sequence is within the N_2 paleomagnetic polarity unit and the base of the sequence has not been penetrated within the Pasco Basin. The Umtanum flow is the uppermost flow of the sequence throughout most of the Pasco Basin (Long and Landon, 1981, pp. 4-16).

The Sentinel Bluffs sequence is composed entirely of flows belonging to the high-magnesium oxide chemical type (Swanson et al., 1979a, Table 2). This sequence is entirely within the N_2 paleomagnetic polarity unit. Within the Pasco Basin, 13 individual flows have been correlated among 20 boreholes and two surface sections. Correlations are based on major-, minor-, and trace-element compositions; paleomagnetic declinations and inclinations; thickness; and stratigraphic position. The Cohassett flow, which has been designated the candidate horizon (DOE, 1987c), is within this sequence.

Within the Pasco Basin the upper portion of the R_2 and all of the N_2 magnetostratigraphic units have been further subdivided (Packer and Petty, 1979; Van Alstine and Gillette, 1981) based on surface (declination and inclination) and subsurface (inclination only) paleomagnetic values. Figure 1.2-6 is a representative paleomagnetic section from borehole DC-12 showing these paleomagnetic subdivisions. Figure 1.2-7 shows the location of boreholes that penetrate the Grande Ronde Basalt.

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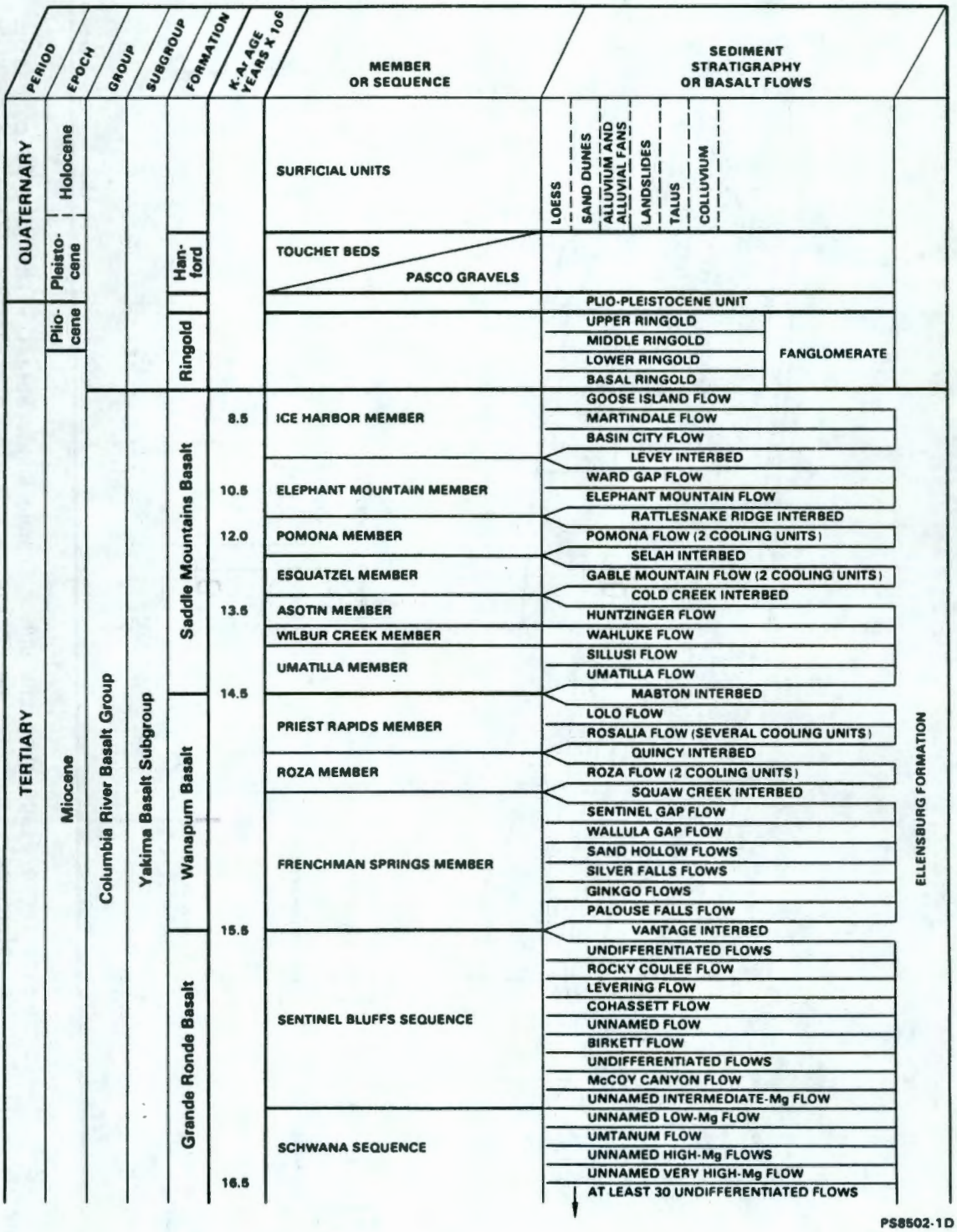

Figure 1.2-3. Stratigraphic nomenclature of units penetrated within the Pasco Basin.

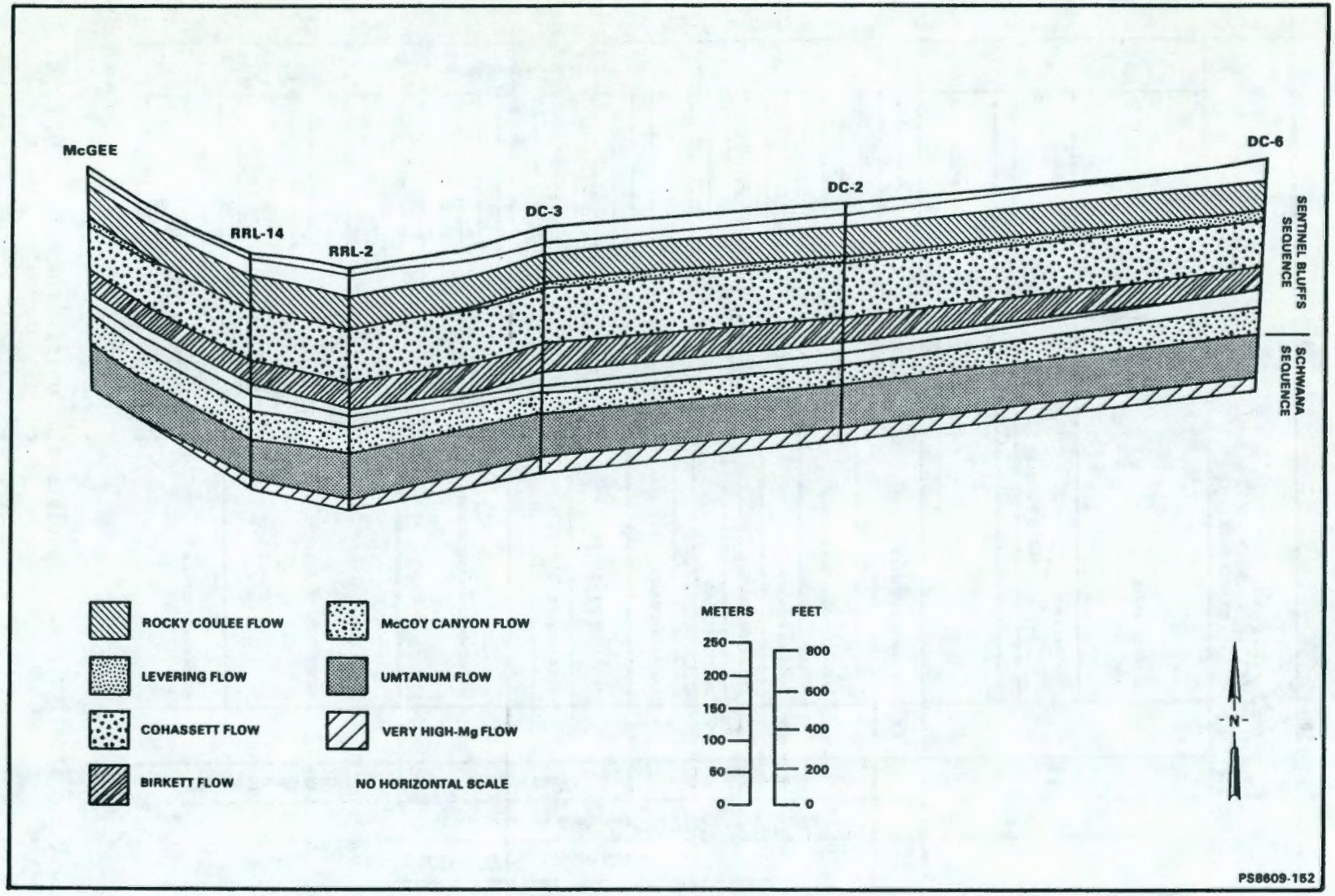

Figure 1.2-4. West-to-east fence diagram of the upper Grande Ronde Basalt within the Pasco Basin. Diagram shows flow correlations only and does not illustrate geologic structure. (See Fig. 1.2-7 for borehole locations.)

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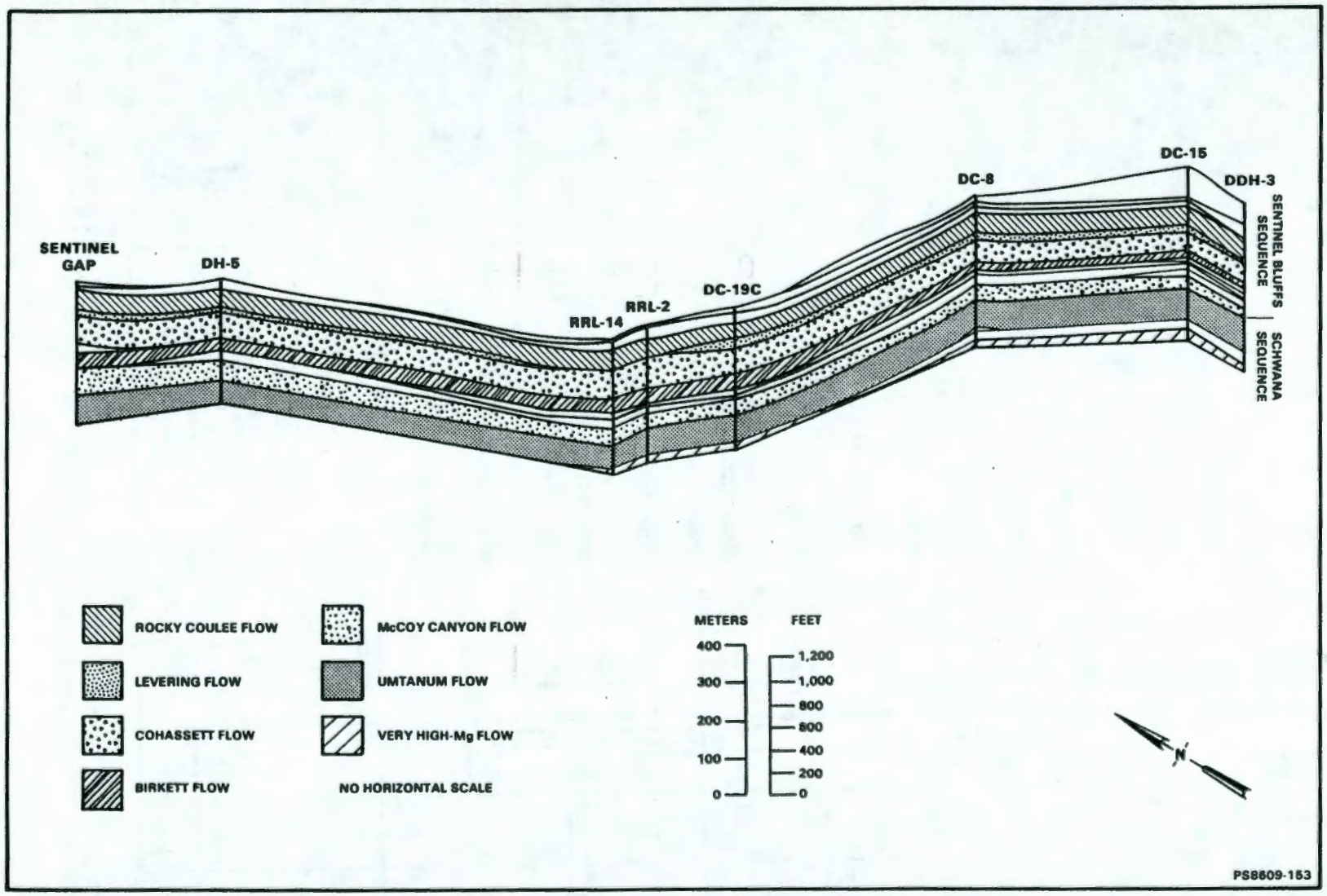

Figure 1.2-5. North-to-south fence diagram of the Grande Ronde Basalt within the Pasco Basin. Diagram shows flow correlations only and does not illustrate geologic structure. (See Fig. 1.2-7 for borehole locations.)

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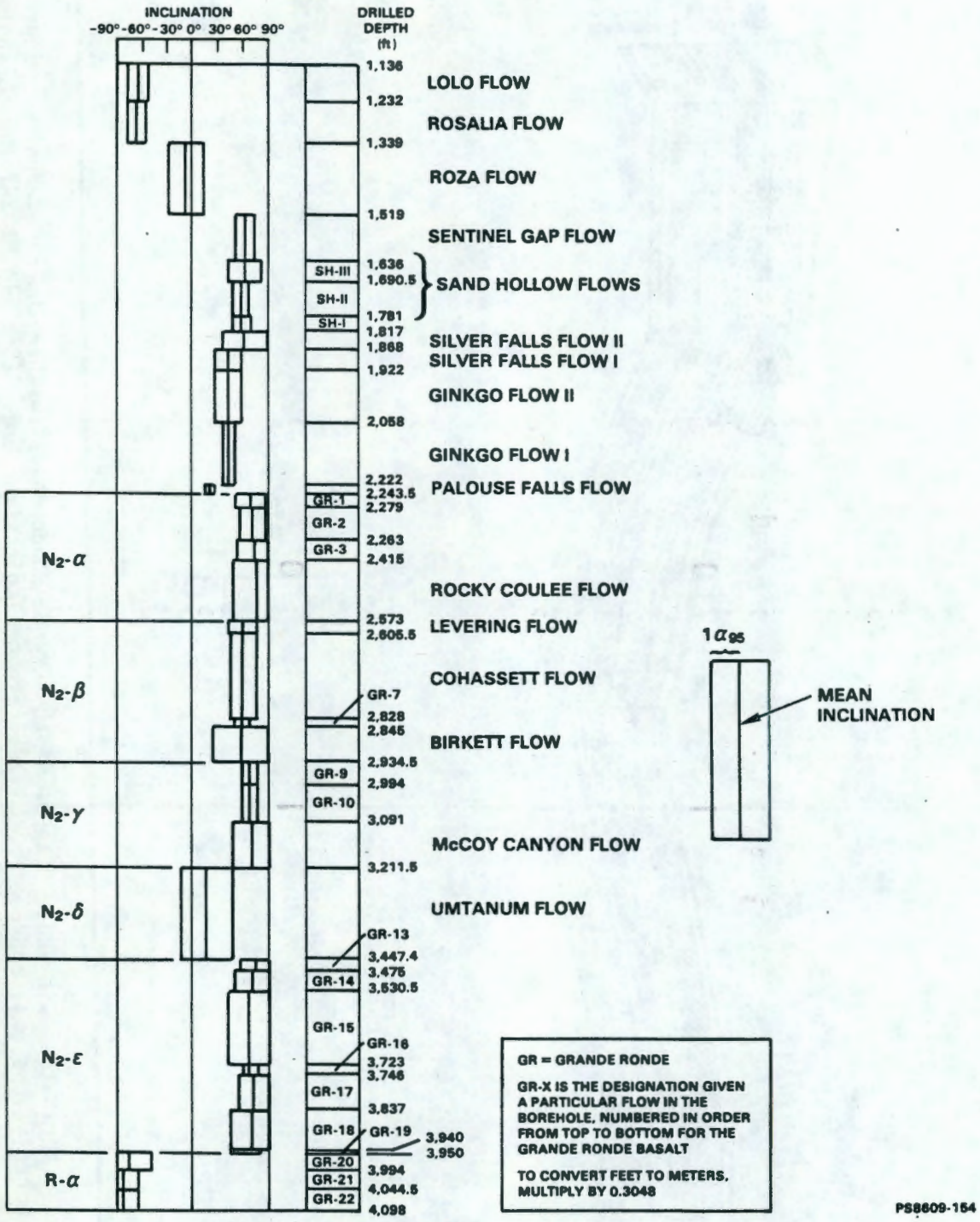

Figure 1.2-6. Example paleomagnetic section from borehole DC-12 for Wanapum and Grande Ronde Basalts.

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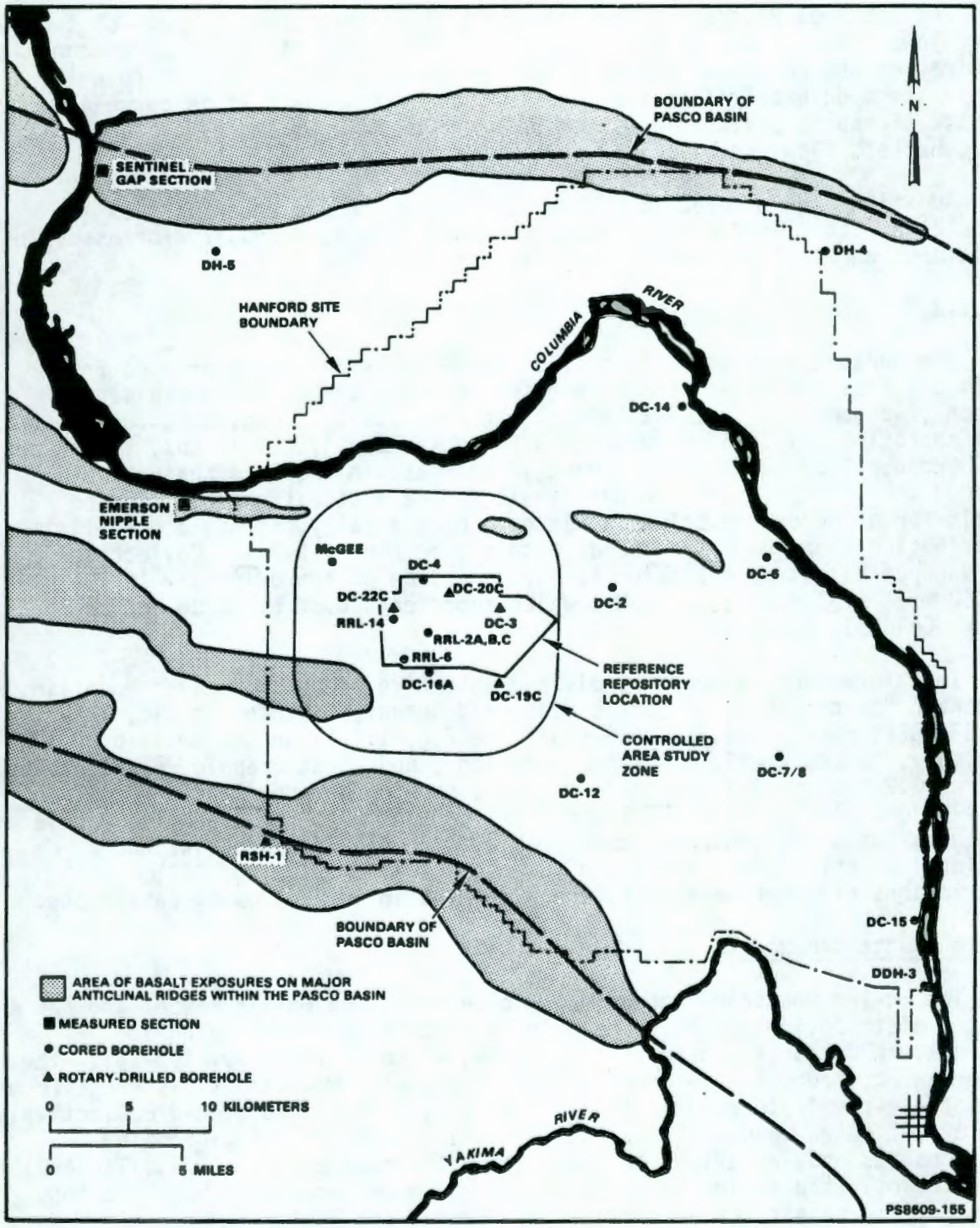

Figure 1.2-7. Location map showing boreholes that penetrate into the Grande Ronde Basalt within the Pasco Basin and two surface section measurement sites for Grande Ronde Basalt.

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The Sentinel Bluffs sequence can be divided into three packets of two to four flows each. These packets are identified by variations in paleomagnetic inclination and chromium content (Long and Landon, 1981, pp. 4-17 to 4-18). Within the middle packet of flows is the Cohassett flow. It is correlated by its stratigraphic position in the middle group of flows and by its thickness. The Cohassett flow can be traced throughout the Pasco Basin.

Additional work needs to be done to further reduce uncertainties in correlating other Grande Ronde Basalt flows. This is necessary for assessing structural and tectonic models (see Section 8.3.1.2.4.3.3).

1.2.1.2.1.4 Wanapum Basalt

The Wanapum Basalt consists of up to 26 flows that were erupted from vents and fissures in eastern Washington, western Idaho, and northeastern Oregon (Swanson et al., 1979a; 1981) (see Fig. 1.2-2). Wanapum time occurred from approximately 15.6 to 14.5 m.y.B.P. (McKee et al., 1977; Lux, 1981; Long and Duncan, 1982) and marked a dramatic decrease in the rate that magma reached the surface. The Wanapum Basalt is the most extensively exposed basalt formation on the Columbia Plateau, but, areally, it has a more limited distribution than the Grande Ronde Basalt (see Fig. 1.2-2i). Collectively, the Wanapum Basalt is estimated to have a volume of approximately 10,700 km^3 (2,560 mi^3) (Tolan et al., 1987), which represents 6.3% by volume of the entire Columbia River Basalt Group.

This formation is formally divided into five members: Eckler Mountain, Frenchman Springs, Roza, Priest Rapids, and Onaway, (Swanson et al., 1979a, pp. G25-G27; Camp, 1981, pp. 669-678) (see Fig. 1.2-1) on the basis of chemistry, paleomagnetic polarity, lithology, and stratigraphic relationships. Figures 1.2-8 and 1.2-9 are fence diagrams showing Wanapum Basalt Formation correlations within the Pasco Basin. The contact with the overlying Saddle Mountains Basalt is generally conformable, although local angular and erosional unconformities are known (Swanson et al., 1979a, p. G27). Descriptions of the five members are presented in the following paragraphs.

Eckler Mountain Member

The Eckler Mountain Member is the oldest Wanapum Basalt member and has a limited distribution, being found only in southeastern Washington and northeastern Oregon (Swanson et al., 1979a, Plate I) (see Fig. 1.2-2j). The member is not found in the Pasco Basin. The Eckler Mountain flows range from plagioclase-phyric to aphyric (Swanson et al., 1979a, p. G30) and collectively have an estimated volume of 173 km^3 (41 mi^3). Based on stratigraphic relationships and variations in composition (Swanson et al., 1979a, Table 2) and lithology, the Eckler Mountain Member has been formally subdivided into three units: basalts of Shumaker Creek, Dodge, and Robinette Mountain (Swanson et al., 1979a, pp. G27-G31) (see Fig. 1.2-1). It was previously reported that Eckler Mountain flows interfingered with both Grande Ronde Basalt and Frenchman Springs Member (Wanapum Basalt) flows in southeastern Washington (Swanson and Wright, 1976, p. 24; 1981, pp. 4-6). However, recent work by Beeson et al. (1985, pp. 91-93) demonstrated that these units do not interfinger. The Eckler Mountain Member has normal magnetic polarity.

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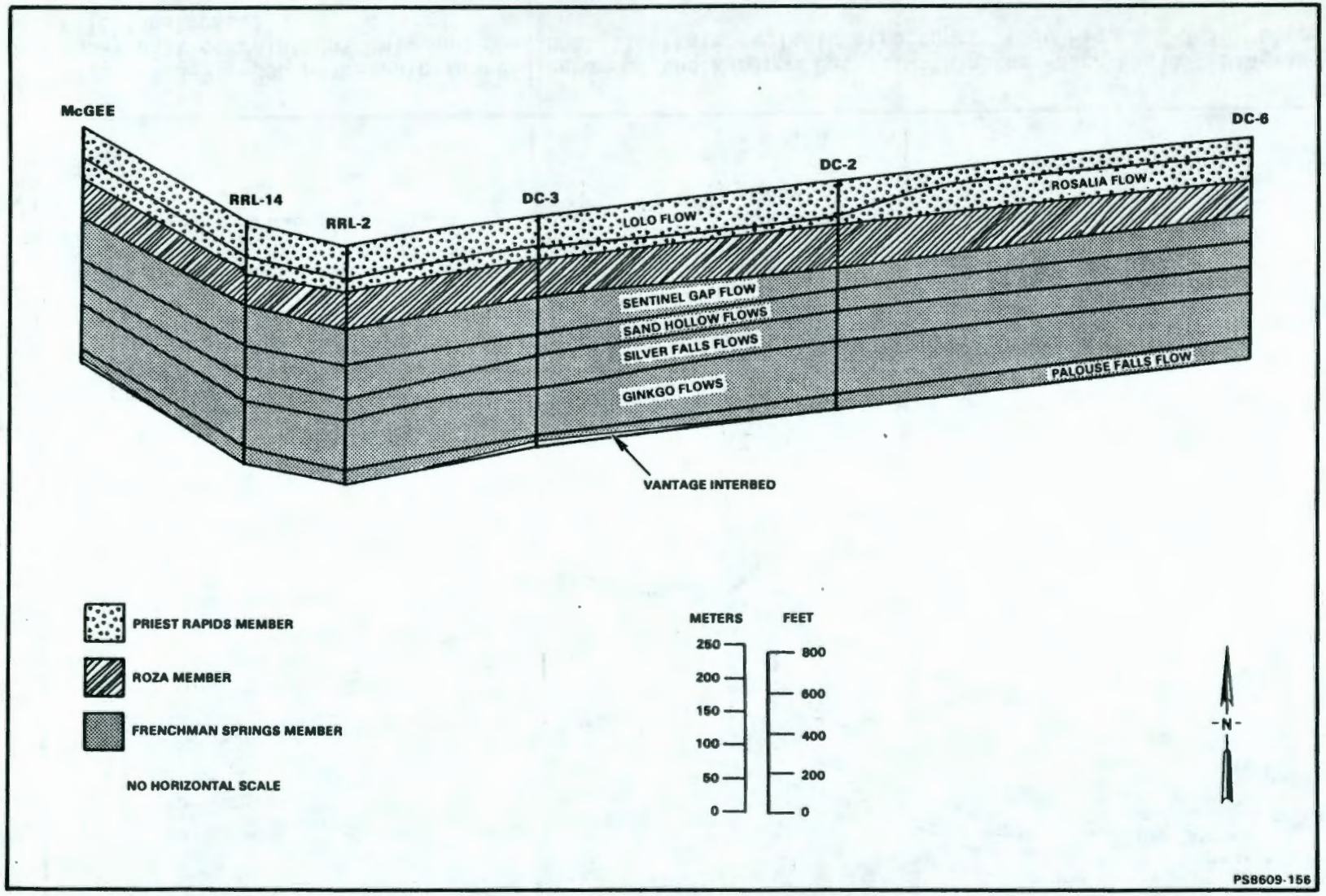

Figure 1.2-8. West-to-east fence diagram of the Wanapum Basalt within the Pasco Basin. Diagram shows unit correlations only and does not illustrate geologic structure. (See Fig. 1.2-7 for borehole locations.)

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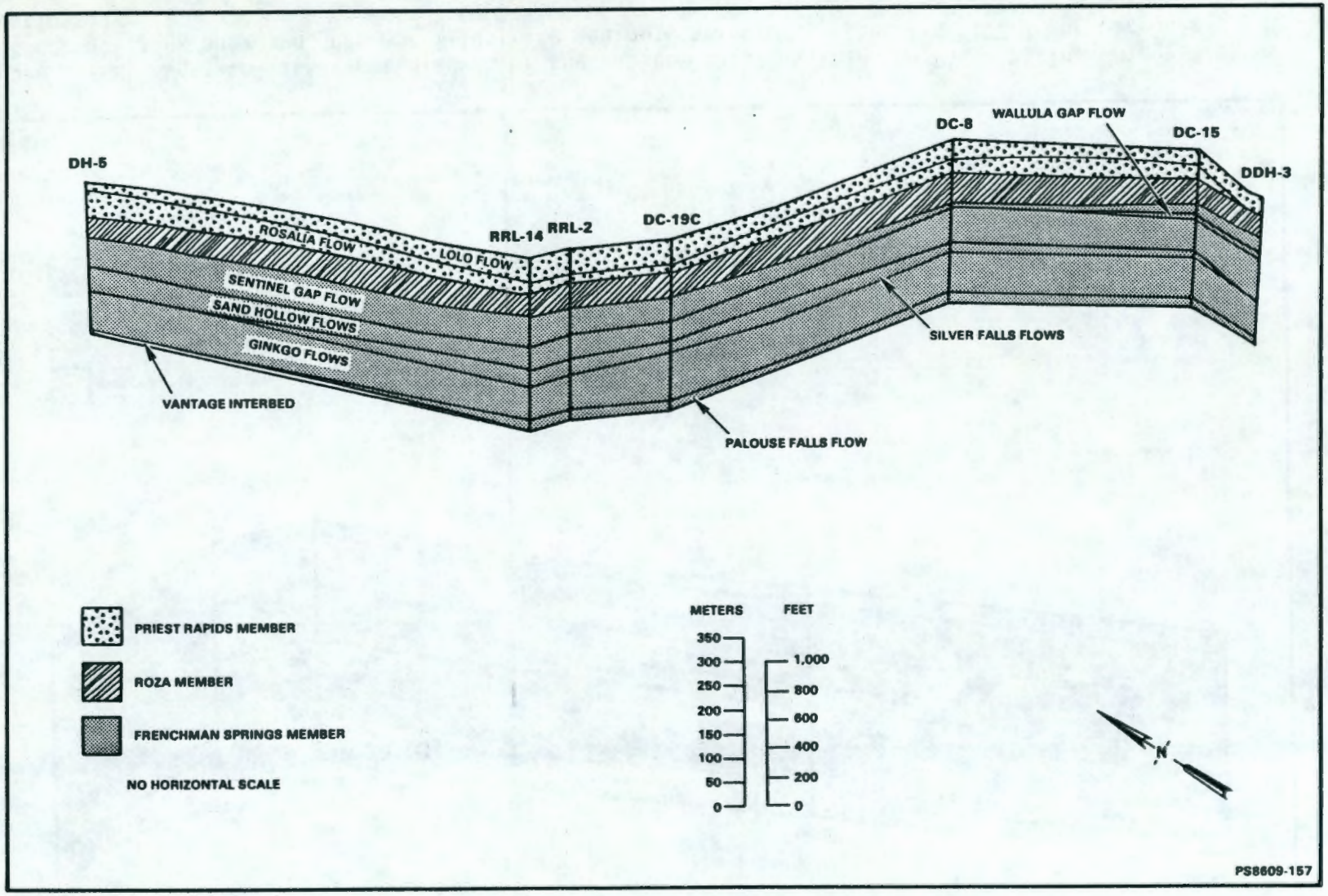

Figure 1.2-9. North-to-south fence diagram of the Wanapum Basalt within the Pasco Basin. Diagram shows unit correlations only and does not illustrate geologic structure. (See Fig. 1.2-7 for borehole locations.)

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Frenchman Springs Member

The Frenchman Springs Member consists of up to 21 flows (Beeson et al., 1985, p. 87) that were erupted from fissures and vents in northeastern Oregon and southeastern Washington (Swanson et al., 1979a, pp. G31-G33). Flows of the Frenchman Springs Member were able to cross the Miocene Cascade Range and even reach the Pacific Ocean (Beeson et al., 1985, pp. 87-91). Collectively, the Frenchman Springs flows cover an area of approximately 69,700 km^2 (26,900 mi^2) and have an estimated volume of about 6,400 km^3 (1,535 mi^3) (Tolan et al., 1987) (see Fig. 1.2-2k). These flows are commonly plagioclase-phyric; but sparsely phyric flows are present. A regional stratigraphic framework has been developed by Beeson et al. (1985, pp. 87-96) on the basis of major oxide/trace elements, composition, paleomagnetic data, stratigraphic position, and to a lesser extent, lithology. The units of the Frenchman Springs Member have normal to excursional magnetic polarity. This framework divides the Frenchman Springs Member into six units, which are identified as basalts of Lyons Ferry, Sentinel Gap, Sand Hollow, Silver Falls, Ginkgo, and Palouse Falls (see Fig. 1.2-1).

Roza Member

The Roza Member was erupted from a relatively narrow, 165-km- (100-mi-) long linear vent system in southeastern Washington and northeastern Oregon (Swanson et al., 1975). The Roza Member generally consists of no more than two flows that have a total estimated volume of approximately 1,300 km^3 (311 mi^3) (Tolan et al., 1987). This unit is found throughout much of the central Columbia Plateau (see Fig. 1.2-21) but apparently failed to cross the Miocene Cascade Range. Abundant small plagioclase phenocrysts are a distinctive characteristic of the Roza Member. Compositionally, the Roza Member is similar to the Frenchman Springs Member (Swanson et al., 1979a, Table 2). The Roza Member has transitional to reserved magnetic polarity (Rietman, 1966; Choiniere and Swanson, 1979).

Priest Rapids Member

The Priest Rapids Member was erupted from vents and fissures in western Idaho (Swanson et al., 1979a, p. G37) approximately 14.5 m.y.B.P. Flows of the Priest Rapids Member covered a large portion of the Columbia Plateau and flowed westward into western Oregon down the channel of the ancestral Columbia River (Waters, 1973; Tolan and Beeson, 1984) (see Fig. 1.2-2m). The total volume of Priest Rapids lava erupted has been estimated to be approximately 2,800 km^3 (670 mi^3) (Tolan et al., 1987). The Priest Rapids Member is informally subdivided into two units based on differences in major oxide compositions, lithology, and stratigraphic position (Wright et al., 1973, p. 377; Swanson et al., 1979a, Table 2). The older Rosalia flow is typically coarser grained with rare olivine and plagioclase phenocrysts. The younger Lolo flow has small olivine phenocrysts (less than 5 mm (0.2 in.)) and rare glomerocrysts or phenocrysts of plagioclase. Both units of the member have reversed polarity.

Onaway Member

Camp (1981, pp. 670-671) identified a fifth member of the Wanapum Basalt based on chemistry and stratigraphic relationships. The Onaway Member has distinctive chemistry (Camp, 1981, p. 673) and underlies and overlies the Priest Rapids Member in the Clearwater Embayment of Idaho. The Onaway Member has very limited distribution (Fig. 1.2-2n) (370 km^2 (142 mi^2)) and volume (7 km^3 (1.7 mi^3)). The Onaway Member consists of two mappable flows belonging to the basalt of Potlatch. This member is only found in the Clearwater Embayment east of Lewiston, Idaho.

1.2.1.2.1.5 Saddle Mountains Basalt

The Saddle Mountains Basalt consists of 14 chemically diverse members (Umatilla, Wilbur Creek, Asotin, Icicle Flat, Weissenfels Ridge, Esquatzel, Pomona, Swamp Creek, Grangeville, Craigmont, Elephant Mountain, Buford, Ice Harbor, and Lower Monumental) and is the youngest formation within the Columbia River Basalt Group (see Fig. 1.2-1). Members of this formation were erupted intermittently over a period from about 14.5 to 6 m.y.B.P. (McKee et al., 1977) during a waning phase of Columbia River basalt volcanism. During this 8.5-m.y. period, approximately 2,390 km^3 (574 mi^3) (Tolan et al., 1987) of lava were erupted, which represents only about 1.4 vol% of the entire Columbia River Basalt Group. Distribution of this formation is limited (see Fig. 1.2-2o), with many of its members confined to structural lows or paleoriver canyons as intracanyon flows (Swanson et al., 1979a, pp. G37-G54). Figures 1.2-10 and 1.2-11 are fence diagrams of Saddle Mountains Basalt correlations within the Pasco Basin. These two figures show only the members that are present in the Pasco Basin (Umatilla, Asotin, Esquatzel, Pomona, Elephant Mountain, and Ice Harbor). The Wilbur Creek Member also occurs but only in a small area north of the Cold Creek syncline. Each of the 14 members is briefly discussed in this section.

Umatilla Member

The Umatilla Member is the oldest (see Fig. 1.2-1) and one of the most widely distributed members in this formation (Swanson et al., 1979a, pp. G40-G42) (see Fig. 1.2-2p). The Umatilla Member consists of up to several flows that were erupted from vents and fissures in northeastern Oregon and southeastern Washington (Swanson et al., 1979a, p. G41) approximately 14.5 m.y.B.P. This member has been informally divided into two units, the Umatilla and Sillusi (see Fig. 1.2-3) based on compositional variations (Laval, 1956; Reidel and Fecht, 1981, pp. 3-16 to 3-19) and stratigraphic position. The Umatilla Member is fine-grained to glassy with rare microphenocrysts of plagioclase to olivine and has normal magnetic polarity. The member is not found in the northern portion of the Pasco Basin (Reidel and Fecht, 1981, pp. 3-16 through 3-19).

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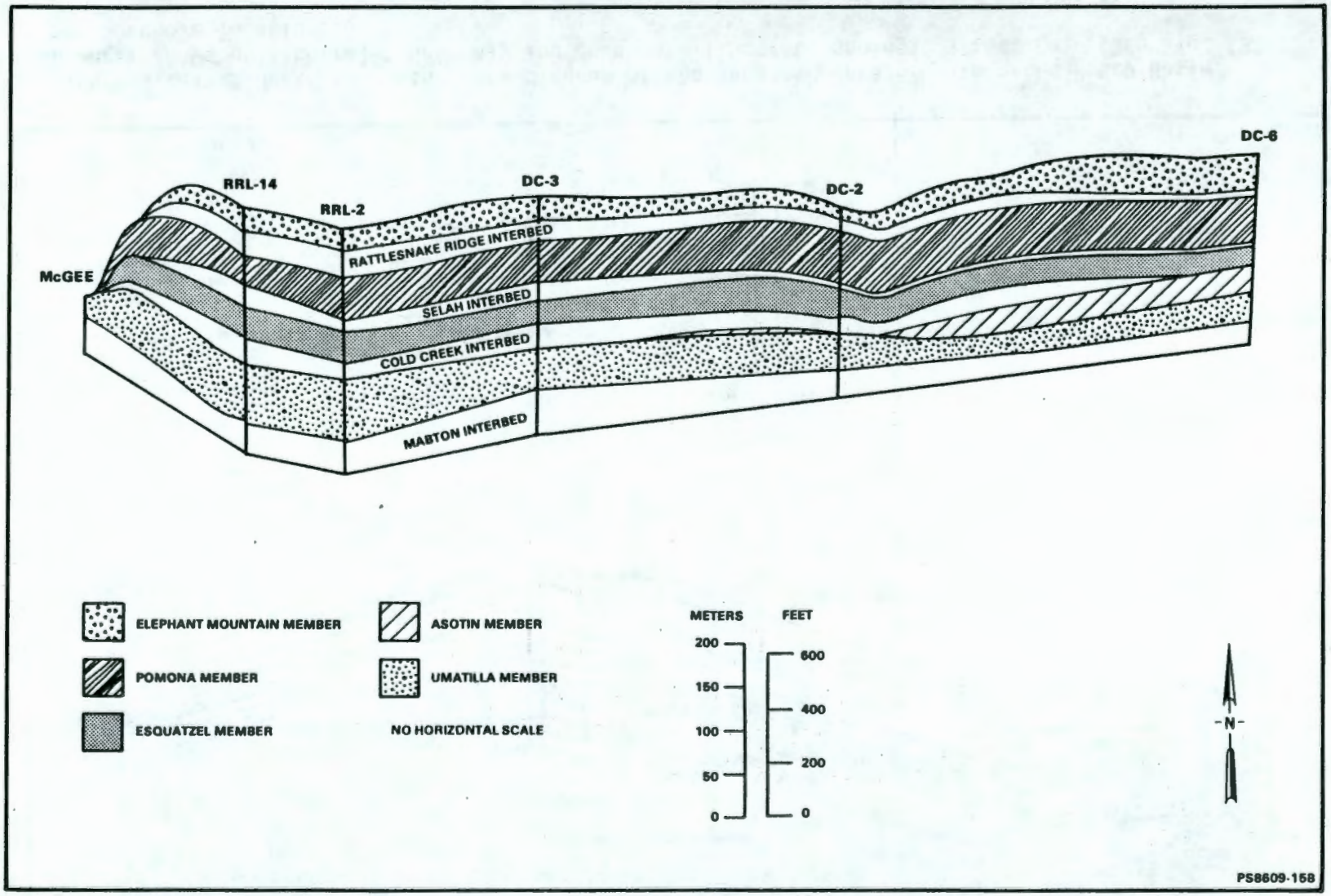

Figure 1.2-10. West-to-east fence diagram of the Saddle Mountains Basalt within the Pasco Basin. Diagram shows unit correlations only and does not illustrate geologic structure. (See Fig. 1.2-7 for borehole locations.)

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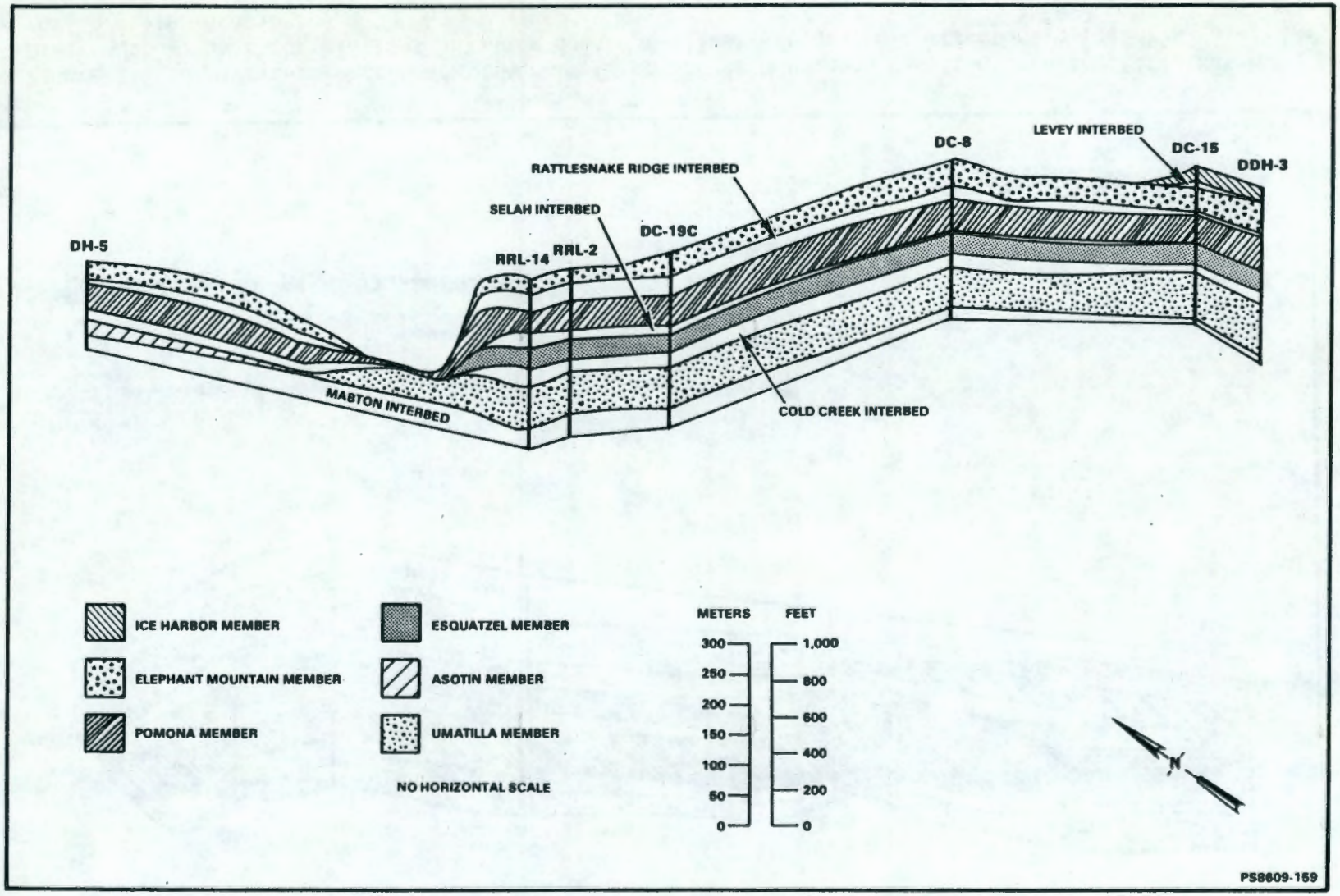

Figure 1.2-11. North-to-south fence diagram of the Saddle Mountains within the Pasco Basin. Diagram shows unit correlations only and does not illustrate geologic structure. (See Fig. 1.2-7 for borehole locations.)

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Wilbur Creek Member

The Wilbur Creek Member, which consists of up to two flows, is confined to the eastern and east-central portions of the Columbia Plateau (Swanson et al., 1979a, Plate I, 1980; Camp et al., 1982, p. 62) (see Fig. 1.2-2q). It is thought that these flows were erupted within the Clearwater Embayment of Idaho and flowed westward down paleoriver canyons, eventually reaching the vicinity of present-day Yakima, Washington (Swanson et al., 1979a, Plate I; Camp, 1981, pp. 669-678; Camp et al., 1982, pp. 62-63). Compositionally, the Wilbur Creek resembles intermediate-magnesium oxide Grande Ronde Basalt flows (Swanson et al., 1979a, p. G42) but can be distinguished from Grande Ronde Basalt on the basis of stratigraphic position. The Wilbur Creek Member is typically fine-grained to glassy and aphyric with sparse microphenocrysts of plagioclase. The member has normal magnetic polarity. In the Pasco Basin, the Wilbur Creek Member has only a very limited distribution north of the Cold Creek syncline (Reidel and Fecht, 1981, pp. 3-21).

Asotin Member

The Asotin Member consists of a single flow, found only in the eastern and east-central portion of the Columbia Plateau (see Fig. 1.2-2r). No Asotin vents or feeder dikes have been located. Based on the distributional pattern of this member, Swanson et al. (1979a, p. G44) suggest that the source area may be the Uniontown Plateau in southeastern Washington; however, Camp et al. (1982, p. 63) suggest that the source area may be in the Clearwater Embayment area. Within the Pasco Basin, the Asotin Member is a single flow known as the Huntzinger flow (Reidel and Fecht, 1981, pp. 3-21 to 3-24) occurring only in the northern portion. The Asotin Member is known to display considerable variation in major oxide composition (Reidel and Fecht, 1981, pp. 3-21 to 3-24). The composition of the Asotin Member in the Pasco Basin ranges from a "true" Asotin Member compositional type to a Wilbur Creek Member compositional type (Reidel and Fecht, 1986). Reidel and Fecht (1986) suggest that the variations observed in the Asotin Member may represent surface mixing of these "end member" flows.

The texture of the Asotin Member varies considerably across the Columbia Plateau from fine-grained and glassy to ophitic. The unit has abundant olivine but sparse plagioclase. The member has normal magnetic polarity.

Icicle Flat Member

The Icicle Flat Member of Camp (1981, pp. 669 to 678) is confined to the Clearwater Embayment of Idaho (Fig. 1.2-2s). The member is known to lie above the Asotin Member, but its relationship to the Grangeville, Swamp Creek, or Pomona Members is uncertain (Camp, 1981, pp. 669-678). A more detailed discussion of the Icicle Flat Member can be found in Camp (1981, pp. 669-678) and Camp et al. (1982, pp. 55-75).

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Weissenfels Ridge Member

The Weissenfels Ridge Member consists of three or more flows that are primarily confined to the Lewiston Basin of southeastern Washington (Swanson et al., 1979a, pp. G44-G45; 1980, map) (see Fig. 1.2-2t). This member has been informally divided by Swanson et al. (1979a, pp. G44-G45) into two units based on differences in composition/lithology (Swanson et al., 1979a, pp. G44-G45) and stratigraphic position. Hooper et al. (1985, map) have shown that this member can be subdivided into four informal units based on detailed mapping. The unit has normal magnetic polarity. The Weissenfels Ridge Member does not occur in the Pasco Basin.

Esquatzel Member

1The Esquatzel Member consists of one flow (occasionally two flow lobes) of limited areal extent (see Fig. 1.2-2u). No known Esquatzel Member vents or feeder dikes have been identified. However, based on intracanyon exposures of the member, Swanson and Wright (1981, p. 8) suggest that the source area lies within the ancestral Snake River drainage. The member is found throughout most of the Pasco Basin, except in the north. A detailed discussion of the Esquatzel Member's occurrence is given in Swanson et al. (1979a, pp. G45-G46) and Reidel and Fecht (1981, pp. 3-24). The Esquatzel Member is identified by chemical composition (Swanson et al., 1979a, Table 2), normal magnetic polarity, lithology, and stratigraphic position. The member is plagioclase phyric to glomerophyric and contains microphenocrysts of clinopyroxene.

Pomona Member

The Pomona Member consists of a single flow that was erupted from feeder dikes in the Clearwater Embayment of western Idaho (Camp, 1981, pp. 669-678) approximately 12 m.y.B.P. (McKee et al., 1977). The Pomona flow was generally confined to the ancestral Clearwater and Snake Rivers as it flowed westward from its source area, spreading laterally only in the central portion of the Columbia Plateau (see Fig. 1.2-2v). The Pomona Member, with an estimated volume of 759 km^3 (182 mi^3) (Tolan et al., 1987), was voluminous enough to reach western Oregon and the Pacific Ocean as an intracanyon flow down the ancestral Columbia River channel (Anderson, 1980; Tolan and Beeson, 1984), a distance exceeding 500 km (310 mi). The Pomona Member has a distinctive lithology and composition (Swanson et al., 1979a, pp. G46-G48) and has reversed paleomagnetic polarity. The Pomona Member has a relatively uniform texture that is fine-grained to glassy with wedge-shaped plagioclase phenocrysts and rare olivine.

Swamp Creek Member

The Swamp Creek Member (Camp, 1981, pp. 669-678) is found only within the Clearwater Embayment area (Fig. 1.2-2w). This member is identified by its chemistry and stratigraphic position (Camp, 1981, pp. 669-678). The Swamp Creek Member occurs above the Pomona Member, but its relation to the other members above the Pomona Member is uncertain (Camp, 1981, pp. 669-678).

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Grangeville Member

The Grangeville Member (Camp, 1981, pp. 669-678) is found only within the Clearwater Embayment of Idaho (Fig. 1.2-2x). The member lies above the Pomona Member and below the Craigmont Member, but its relation to the Swamp Creek and Icicle Flat Members is unknown (Camp, 1981, pp. 669-678). This member is correlated based on stratigraphic position and chemistry (Camp, 1981, pp. 669-678).

Craigmont Member

The Craigmont Member (Camp, 1981, pp. 669-678) occurs above the Icicle Creek and Grangeville Members, but the relationship to the Swamp Creek Member is unknown. The Craigmont Member is found only in the Clearwater Embayment (Fig. 1.2-2y). Physical and compositional characteristics of the member are discussed in Camp (1981, pp. 669-678) and Camp et al. (1982, pp. 55-75).

Elephant Mountain Member

The Elephant Mountain Member consists of at least two flows that were erupted about 10.5 m.y.B.P. (McKee et al., 1977) from feeder dikes and vents found in the Troy Basin area of northeastern Oregon (Swanson et al., 1979a, pp. G48-G50) (see Fig. 1.2-2z). Flows of this member followed the same path as the Pomona Member (see Fig. 1.2-2v), eventually reaching, but apparently not crossing, the Miocene Cascade Range (Anderson, 1985, p. 337). In the central Columbia Plateau, the Elephant Mountain Member has only slightly smaller areal extent than the Pomona Member. Both Elephant Mountain flows display a similar composition, belonging to the chemical type of the Elephant Mountain Member (Wright et al., 1973, p. 377). The texture of these flows is medium- to fine-grained with abundant microphenocrysts of plagioclase. The member has transitional to normal magnetic polarity and is found throughout most of the Pasco Basin.

Buford Member

The Buford Member consists of one flow that is confined to the area within the Troy Basin of northeastern Oregon (Swanson et al., 1979a, pp. G50-G51; Stoffel, 1984) (see Fig. 1.2-2aa). Stoffel (1984) reported that the Buford and Elephant Mountain flows are interfingered. However, the Buford Member flow can be distinguished, on the basis of lithology and composition (Swanson et al., 1979a, Table 2), from the Elephant Mountain flows. The Buford Member is fine- to medium-grained, very sparsely plagioclase, and olivine phyric. The member has reversed magnetic polarity.

Ice Harbor Member

The Ice Harbor Member consists of a series of flows that were erupted along the eastern margin of the Pasco Basin near Ice Harbor Dam (Helz, 1979) approximately 8.5 m.y.B.P. (McKee et al., 1977). The Ice Harbor Member has a limited distribution (see Fig. 1.2-2bb), being confined primarily to the southern and eastern Pasco Basin and surrounding area (Swanson et al., 1979a,

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pp. G51-G53; 1980, maps). On the basis of lithology, composition (Swanson et al., 1979a, Table 2; Helz, 1978), magnetic polarity (see Fig. 1.2-1), and stratigraphic position, Swanson et al. (1979a, pp. G51-G53) informally divided this member into three units (see Fig. 1.2-1). The three units have varied textural and mineralogic characteristics, and Swanson et al. (1979a, pp. G51-G53) should be consulted for detailed descriptions of each.

Lower Monumental Member

The Lower Monumental Member consists of a single intracanyon flow that was confined to near the present position of the Snake River (Swanson et al., 1979a, pp. G53-G54) (see Fig. 1.2-2cc). This flow has been dated by McKee et al. (1977) at 6 m.y.B.P., which makes it the youngest known Columbia River Basalt Group flow. Compositionally, it is similar to the Lolo-type flow of the Priest Rapids Member (Swanson et al., 1979a, Table 2). The member is nearly aphyric and has normal magnetic polarity.

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1.2.1.2.2 Intraflow structures

Intraflow structures are primary, internal features or stratified portions of basalt flows exhibiting grossly uniform macroscopic characteristics. These features originate during the emplacement and consolidation of each flow and result from variations in cooling rates, degassing, thermal contraction, and interaction with surface water. The intraflow structures discussed in this section are distinct from those produced by tectonic activity (see Section 1.2.1.2.3 for a discussion of distinguishing characteristics).

A knowledge of intraflow structure variations is important for repository design and construction considerations. The available thickness of flow interior plays a major role in constraining a repository's placement in the host rock. Intraflow structures are also a consideration for modeling groundwater flow since intraflow structures may have characteristics either favorable or unfavorable to groundwater flow.

Intraflow structures of a typical Columbia River basalt flow are described according to their position in a flow: (1) flow top, (2) flow bottom, and (3) flow interior. Figure 1.2-12 depicts the various types of intraflow structures that are typically observed in a basalt flow; most flows do not show a complete set of these structures.

- Flow top--The flow top is the chilled, glassy upper crust of the flow. It may consist of vesicular to scoriaceous basalt, displaying pahoehoe, aa, or blocky surfaces (MacDonald, 1953); or it may be rubbly to brecciated (Waters, 1960, pp. 355 and 356; Diery, 1967, p. 10; Swanson and Wright, 1981, p. 10). The flow top can contain a combination of several of these physical characteristics at any one location. Flow tops typically contain secondary minerals in void spaces, as observed from drill cores. Detailed discussions of secondary mineral types are in Section 4.1.1.

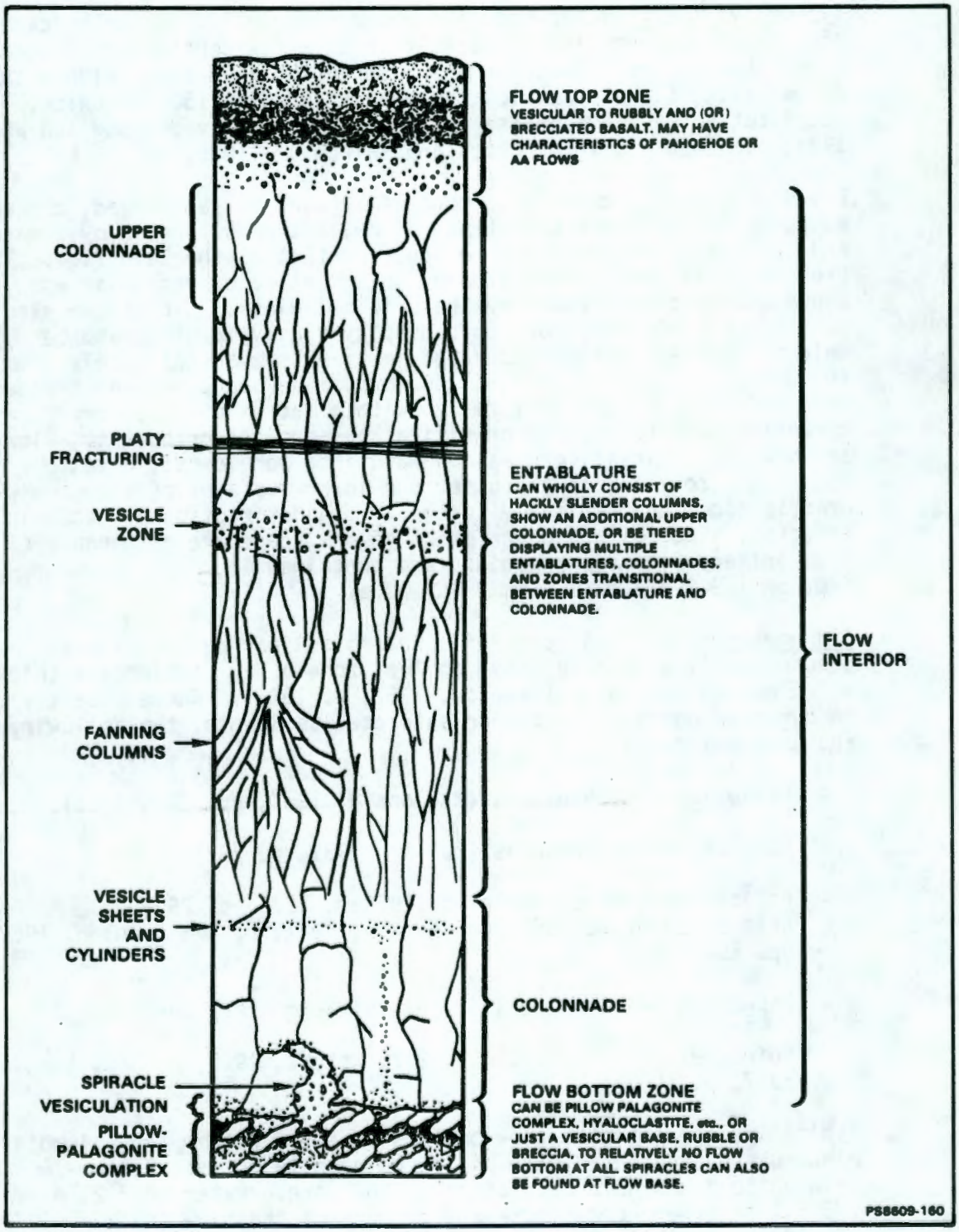

Figure 1.2-12. Idealized columnar section showing the variety of intra-flow structures possible in Columbia River basalt flows. Most flows exhibit less than a complete set of all types of structures.

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Typically, the flow top occupies approximately 10% of the thickness of a flow; however, it can be as thin as a few centimeters or occupy almost the entire flow thickness. In the Umtanum flow, within the Pasco Basin, flow-top breccia greater than 45 m (150 ft) thick, constituting over 50% of the flow, has been observed (Long and WCC, 1984, pp. 1-28 and 1-64; Cross and Fairchild, 1985, pp. 10 to 12).

Flow top breccia occurs as a zone of angular to subrounded, broken volcanic rock fragments that may or may not be supported by a matrix and is located adjacent to the upper contact of the lava flow. The breccia is often characterized by an admixture of vesicular and nonvesicular clasts bound by the original glass. Clasts can also be scoriaceous, clinkery, or ropy; display glassy margins; and be welded together. Fragments range in size from approximately 1 mm (0.004 in.) up to 1 m (3.0 ft) or more. The space between fragments may be filled or partially filled with a matrix of secondary minerals, such as calcite or silica; palagonite; or basalt. Flow-top breccia typically grades downward into more dense, often vesicular, rock. Both the upper and lower surfaces of flow-top breccia zones are typically irregular. A description of tectonic breccias, along with a description of how these are distinguished from primary flow top breccias, are contained in Section 1.3.2.2.2.6.

- Flow bottom--The basal part of a Columbia River basalt flow is predominantly a thin, glassy, chilled zone a few centimeters thick, which may be vesicular (Swanson, 1967, p. 1086). Where basalt flows encountered bodies of water or saturated sediments, the following features may result:

  - Hyaloclastite complexes (MacDonald, 1967, pp. 30 and 31).

  - Foreset bedded breccias (Fuller, 1931, p. 282).

  - Pillow-palagonite complexes (Fuller, 1931, p. 290; Waters, 1960, pp. 361-364; Mackin, 1961, p. 17; Swanson, 1967, pp. 1084-1086).

  - Peperites (MacDonald, 1967, p. 29; Schmincke, 1967).

  - Spiracles (Fuller, 1931, p. 292; Waters, 1960, p. 358; Swanson, 1967, p. 1086).

Typically, the thickest flow bottoms observed within the Columbia Plateau are associated with pillow-palagonite zones. Pillow-palagonite zones have been observed that are greater than 23 m (75 ft) thick and constitute 30% or more of the flow (Mackin, 1961, pp. 13-15; Griggs, 1976, p. 9).

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- Flow interior--Within the interior of a basalt flow, the predominant intraflow structures are zones characterized by patterns of cooling joints. These are commonly referred to as colonnade and entablature (Tomkeieff, 1940, p. 96).

  Colonnade consists of relatively well-formed polygonal columns of basalt, usually vertically oriented and typically 1 m (3 ft) in diameter or larger. Colonnade, as defined by Tomkeieff (1940), occurs in the basal portion of flows. In Columbia River basalts, colonnade can make up the entire flow or there can be one or more colonnades present, which are tiered with entablatures.

  Entablature is composed of irregular to regularly jointed small columns frequently less than 0.5 m (1.5 ft) in diameter. Entablature columns are commonly fractured into hackly, fist-sized fragments that can mask the columnar structure. Entablatures typically display a greater abundance of cooling joints than do colonnades (see Section 1.2.1.2.3). Entablature columns can be oriented vertically, exhibit regular patterns such as rosettes and fans, or appear completely disordered. Flows at a few localized occurrences on the Columbia Plateau have been observed to consist wholly of entablature (Waters, 1960, p. 351).

  Transition zones with characteristics intermediate between entablature and colonnade are observed in Grande Ronde Basalt flows. These zones include column diameters between 0.5 and 1.0 m (1.3 and 3.0 ft) and have been termed columnar-entablature.

  Contacts between entablature and colonnade tiers are distinct in some places and gradational in others. Contacts between these two intraflow structures appear to represent a change only in microscopic textures and cooling joint abundance and geometry.

  A general arrangement of colonnade, entablature, flow top, and flow bottom in Columbia River basalts is shown in Figure 1.2-12. Simpler and more complex arrangements of the intraflow structures shown in Figure 1.2-12 are commonly observed in flows on the Columbia Plateau.

- Other internal features--Other intraflow features observed within the interior of Columbia River basalts include the following:

  - Vesicle pipes (Waters, 1960, p. 358; Laval, 1956, p. 21; Mackin, 1961, p. 11).

  - Vesicle cylinders and sheets (Goff, 1977, pp. 15-30; McKee and Stradling, 1970, p. 2039).

  - Vesicle zones (Mackin, 1961, p. 9; Diery, 1967, p. 55; Long and WCC, 1984, Chapter I-II).

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- Laminae or dispersed diktytaxitic vesiculation (Waters, 1941, p. 1958; Anderson, 1978, p. 32).

- Platy fracturing (Mackin, 1961, p. 22; Swanson, 1967, p. 1083; Diery, 1967, pp. 25 and 32; Beeson and Moran, 1979b, p. 13) (see Fig. 1.2-12).

Near the Pasco Basin, vesicle cylinders, vesicle sheets, and vesicle pipes are primarily observed in relatively thin (5- to 30-m- (16- to 100-ft-) thick) flows, composed solely of colonnade and flow top. Vesicle zones within the flow interior of relatively thick (30- to 80-m- (100- to 260-ft-) thick) Grande Ronde Basalt flows in the Pasco Basin range from relatively thin sheets, centimeters thick, to zones that are meters thick and laterally continuous for many kilometers. Diktytaxitic vesiculation (interstitial microvesiculation) in the Pasco Basin is most pronounced in the relatively thin Grande Ronde Basalt flows and in Wanapum Basalt and Saddle Mountain Basalt flows. The Cohassett flow, in the Pasco Basin, contains a well-defined, laterally continuous vesicular zone and a few discontinuous zones.

Platy fracturing has been observed at many locations on the Columbia Plateau but has not been identified in drill core from within the Pasco Basin. The lack of recognized platy fracture zones in boreholes may be due to either their absence, or to the fact that they exist but are not recognized as platy fracture zones.

There appear to be two types of platy fracturing. One type is observed in many Wanapum Basalt flows (e.g., the Roza flow) and is apparently typical of what has been observed by many investigators on the Columbia Plateau. The distinguishing feature of this style of platy fracturing is that individual platelets are relatively regular and thin, delineated by curvilinear joints, and confined to columns. The other type of platy fracturing consists of platelets defined by anastomosing joints that cross columnar boundaries. The latter is the style of platy fracturing in Grande Ronde Basalt flows prevalent at Sentinel Gap and observed elsewhere; it also occurs in the Cohassett flow at Sentinel Gap.

Lava tubes have not been described in literature as occurring in Columbia River basalts on the Columbia Plateau. Waters (1960, pp. 353, 354) observed lava tubes in basalts near Troutdale, Oregon, and believed these to be Columbia River basalts. However, subsequent mapping of the flows in the Troutdale area (Trimble, 1963) showed them to be olivine basalts of the Boring lava and not part of the Columbia River basalts. Because of the emplacement history of Columbia River basalts described by Swanson et al. (1975), the potential occurrence of lava tubes is low and, if anywhere, may be expected near the margins of flows.

Sag flowouts (McKee and Stradling, 1970; Hodges, 1978, pp. 1,281-1,289) occur on the Columbia Plateau and have been noted on the northwestern margins of the Pasco Basin (Mackin, 1961, pp. 9-11). They are recognized as a localized pattern of complex tiering of colonnades and entablatures and result in some isolated flow-top material occurring below the top of a flow.

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1.2.1.2.2.1 Intraflow structure variations

As noted in the previous section, Columbia River basalts exhibit a variety of internal arrangements of intraflow structures. Previous investigators on the Columbia Plateau recognized characteristic arrangements of cooling joints in Columbia River basalts (Laval, 1956, p. 20; Mackin, 1961, pp. 15-17; Swanson, 1967, p. 1083). These jointing characteristics are observed in many flows to be continuous for long distances but in some cases change abruptly (Mackin, 1961, p. 7). This work was built on by Long (1978, pp. 12-13), leading to the development of a classification of flows into "types" based on the arrangement of intraflow structure jointing.

Generally, Columbia River basalt flows can be grouped into one of three types of intraflow structure arrangements, which are shown in Figure 1.2-13. This classification system was developed from detailed field observations of Grande Ronde Basalt flows in and near the Pasco Basin (Long and Davidson, 1981, p. 5-5). Though this system was developed using only the Columbia River basalts in this area, it appears to be functional for basalt flows described throughout the Columbia Plateau.

Type I flows are typically thin (5 to 30 m (15 to 100 ft) thick), consist entirely of colonnade without entablature, and are capped by a flow top. Type II flows are typically very thick (50 to 80 m (160 to 260 ft) thick), consist of alternating tiers of entablature and colonnade, and are capped by a flow top. Fanning columns in the entablature occur sporadically. Type III flows are relatively thick (30 to 60 m (100 to 200 ft) thick), comprised of a flow top, a single entablature commonly exhibiting fanning columns, and an underlying colonnade. An upper colonnade of poorly formed larger columns is sometimes present in either Type II or Type III flows.

The three types are end members, and lateral gradations or abrupt changes can, and do, occur. Variations occur in two ways. In one case, jointing patterns change such that the flow type classification changes. In the other case, thicknesses of colonnades and entablatures may vary without resulting in a change in flow-type designation.

Lateral variation in thickness of intraflow structures can occur gradually in some flows and suddenly in others at a given location. The BWIP studies of photomosaics taken at exposures in and near the Pasco Basin show that lateral changes in intraflow structures in the Umtanum flow occur over relatively short distances, whereas gradual changes are observed in the McCoy Canyon flow (Long and Davidson, 1981, pp. 5-28 through 5-32; Long and WCC, 1984, pp. I-37 through I-47). At the present time, variations in intraflow structures appear highly dependent on the flow in which they are contained and the emplacement and cooling history of the flow. Planned studies on the origin of intraflow structures under given conditions of emplacement are discussed in Section 8.3.1.2.3.3.2.

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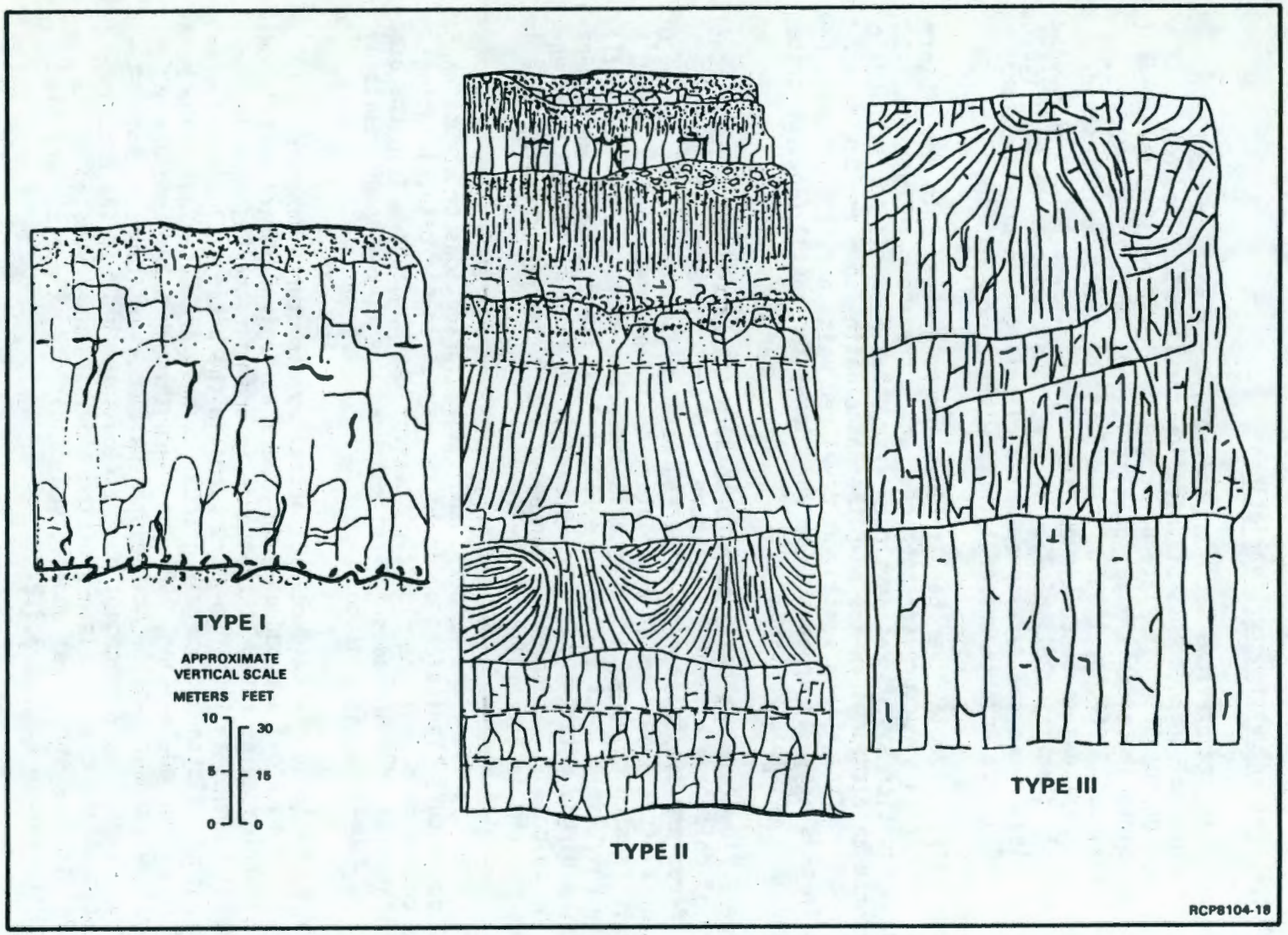

Figure 1.2-13. Types of intraflow structure arrangements.

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Intraflow structures are also recognizable in the subsurface through interpretation of borehole data. Differences between flow tops, vesicular zones, and relatively dense basalt in flow interiors are recognizable in drill core via megascopic lithologic characteristics and interpretation of borehole geophysical logs (Cross and Fairchild, 1985). The flow top is recognized by its often brecciated, vesicular character directly below the upper flow contact. Flow bottom is recognizable as any vesiculation, rubble, or breccia that exists directly above the chilled, glassy, lower contact of the flow. The flow interior is identified as that portion of the flow that is between the flow top and any flow bottom features. The flow interior may have zones of internal vesiculation.

Distinction between colonnade and entablature in drill core is currently interpreted based on megascopic determination of changes in the shade of gray of the core (which is related to abundance of inclusions in the glass constituent of the rock (Long, 1978)) and, to some extent, by microtextural characteristics of samples taken from the core. Colonnade and entablature distinctions from drill core currently have higher uncertainties than do interpretations of flow top, flow bottom, vesicular zones, and flow interiors (Cross and Fairchild, 1985). Planned petrographic textural analysis of core samples based on outcrop sampling should aid in reducing these uncertainties (see Section 8.3.1.2.3.3.2).

Geophysical logs aid in the determination of intraflow structures. This is particularly true for rotary-drilled boreholes from which drill core is not obtained. Intraflow structures such as flow tops, vesicular or vuggy rock, and flow bottom features are indicated by intervals of higher porosity response from the various logging tools. The neutron porosity log provides the clearest definition of the intraflow structures, although the sonic and gamma-gamma density logs also respond to these high porosity zones (Fig. 1.2-14). Interpretations of geophysical log responses are corroborated by interpretation of the borehole drill core when it is available. Uncertainties associated with geophysical log interpretation include difficulty in distinguishing between flow breccia and internal vesiculation, in a few cases, and inherent resolution of no better than 1 m (3 ft). Plans to relate physical rock property measurements to geophysical logging are discussed in Section 8.3.1.2.3.3.2. This work may aid in distinguishing between flow breccia and vesiculation.

1.2.1.2.2.2 Origin of intraflow structures

An understanding of the origin of intraflow structures is useful in predicting their spatial occurrence in the subsurface of the Pasco Basin. The capability to predict the potential size and distribution of intraflow features between boreholes in the area of the proposed repository is important to repository design and construction. Another application is the prediction of groundwater flow, where size and distribution of intraflow structures are important parameters, for modeling pathways and transmissivity.

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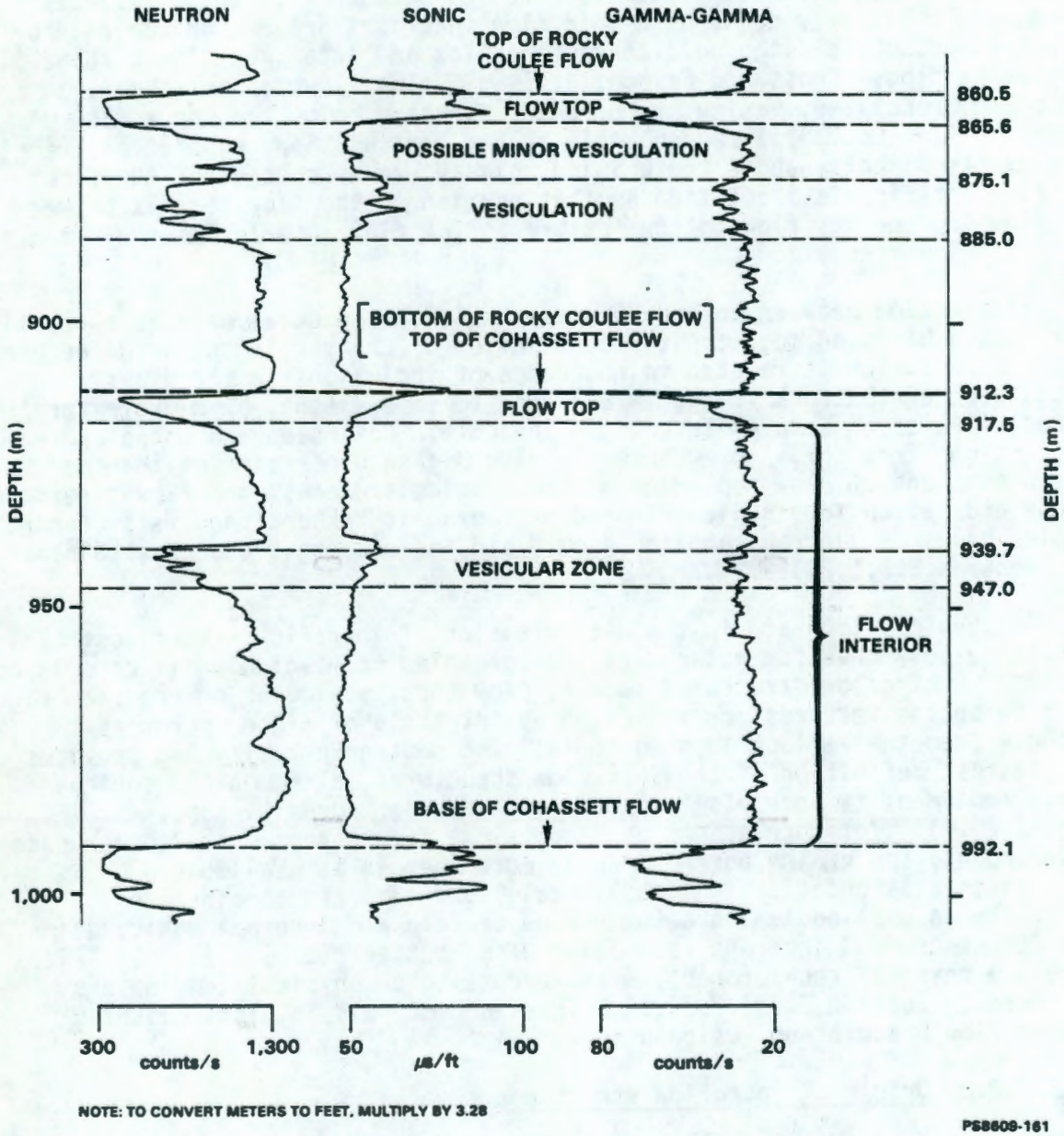

Figure 1.2-14. Geophysical log responses for flow tops and vesicular zones in the Rocky Coulee and Cohassett flows in borehole RRL-2A. Borehole RRL-2A is a cored borehole, and drill core was used to corroborate these interpretations.

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Origin of flow tops

The origin of intraflow structures that occur at the tops of flows are generally well documented and understood by investigators on the Columbia Plateau. Flow tops produced subaerially form by outgassing of volatile constituents, cooling of the upper flow surface, and (or) rapid chilling and fracturing of the flow surface during emplacement. In some instances, the origin of flow top is not fully understood, as in the case of thick flow-top breccia that exists in the Umtanum flow in portions of the Pasco Basin (Long and Davidson, 1981, pp. 5-48). An admixture of vesicular and nonvesicular clasts, chilled rinds on clasts, and high glass content of the Umtanum flow-top breccia appears to indicate an interaction of the still molten flow with water (Long and WCC, 1984, pp. I-137 and I-138). Currently planned outcrop studies (see Section 8.3.1.2.3.3.2) will be used to understand the phenomenon of great thicknesses of flow top breccia.

Origin of flow bottom features

Flow bottom features are also generally well documented and their origins understood on the Columbia Plateau. Typically, the basal portion of a basalt flow is a thin (a few centimeters), black, glassy rind that forms when the bottom of the flow comes in contact with the cool upper surface of the underlying flow during emplacement. Most thick flow bottom occurrences are attributable to flows invading bodies of water or saturated sediments (Fuller, 1931; Waters, 1960, pp. 356-365; Swanson, 1967, pp. 1083-1086; MacDonald, 1967, pp. 26-30). Flow bottom features of this nature (e.g., pillow zones, spiracles) have been observed on the margins of the Pasco Basin and elsewhere on the Columbia Plateau. However, these flow bottom features have not been observed in boreholes in the Pasco Basin. The predominant flow bottom features encountered in boreholes within the Pasco Basin are either vesicular zones or brecciated zones.

Origin of flow interior features

Various theories concerning the origin of flow interior features are abundant in literature. Primarily the discussions have centered on the origin of columnar jointing. Other flow interior features not related to columnar jointing, such as occurrence of vesiculation, diktytaxitic texture, and platy fracturing, have been described but less attention to origin is presented.

Three early hypotheses proposed for the origin of columnar jointing in igneous rocks were (1) crystallization (Watt, 1804), (2) convection (Sosman, 1916; Lafeber, 1956; Kantha, 1981), and (3) thermal contraction (Mallet, 1875). Of these, thermal contraction of solidified lava during cooling is the most widely accepted mechanism for producing columnar jointing in either colonnade or entablature (James, 1920; Fuller, 1938; Tomkeieff, 1940; Waters, 1941; Spry, 1962; Swanson, 1967, p. 1083; Ryan and Sammis, 1978).

The differences in joint patterns between colonnade and entablature have been attributed by most investigators to differences in cooling rate. That is, it is generally believed that entablatures result from a more rapid

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cooling rate (Tomkeieff, 1940; Swanson, 1967, p. 1083; Saemundsson, 1970, p. 73). Existing theories currently do not satisfactorily explain the cause of variable cooling rates in the interior of flows. Explanations for the variable cooling rates include the potential effect of slightly varying chemical compositions on heat conduction within zones in a flow (Swanson and Wright, 1981, p. 10; Kantha, 1981, p. 260), the effect of water on the surface of a flow or ingressing via vertical cooling joints (Fuller, 1949; Waters, 1960, p. 353; Saemundsson, 1970, p. 74; Long and Wood, 1986), late-stage movement of a cooling flow (Waters, 1960, pp. 351-353), or the potential effect of degassing of the emplaced flow (Lipman et al., 1985).

Several authors seem to favor the effect of water on a cooling basalt flow. Saemundsson (1970, p. 74) studied interglacial lava flows in Iceland and concluded that entablatures were formed by rapid cooling due to catastrophic inundation resulting from dammed streams. Justus (1978) suggested that fracture-controlled quenching of a flow by water results in features observed in entablatures. Fuller (1949) and Waters (1960, p. 353) both stated that fanning joints or the jumbled nature of entablature may be due to water inundation of the flow. Long and Wood (1986) also support water inundation and suggest it accounts for textural differences observed between entablature and colonnade.

Swanson (1967, p. 1083) noted textural differences between entablature and colonnade (greater glass content in entablature) and attributed these differences to more rapid solidification of the entablature. However, he does not suggest a method to induce the rapid solidification. Long (1978, pp. 56-65), Long et al. (1980), and Long and Davidson (1981, pp. 5-40 through 5-45) have also demonstrated petrographic textural differences between entablatures and colonnades. As an alternative hypothesis, Lofgren (1983, p. 230) has shown that different petrographic textures observed in basalts can be produced in melting experiments by varying the number of available nucleation sites while holding temperature constant. Any hypothesis must be able to explain Type II (multitiered) flows, such as the Cohassett flow in the Pasco Basin. A better understanding of the origin of intraflow structures will aid the ability to predict the vertical arrangements of intraflow structures within a flow and the extent of their lateral continuity. Further analysis of the origin of intraflow structures, including entablature and colonnade, are discussed in Section 8.3.1.2.3.3.2.

Vesicular features in a flow interior, such as vesicle cylinders and diktytaxitic textures (microvesiculation), are explained by Goff (1977, pp. 15-30). Goff suggests that vesicle cylinders are due to rapid exsolution of water vapor from a cooling, water-rich basalt. Vesicle sheets result when vesicle cylinders spread out laterally. Diktytaxitic rock results from the final stage of water vapor exsolution before solidification of the flow. Vesicular zones in flows like the Cohassett flow in the Pasco Basin are explained by McMillan et al. (1985) as vapor exsolution from the still molten flow. The vapor bubbles nucleate, migrate upward, and coalesce. They rise until they encounter more viscous lava preceding the downward-progressing solidification front. Both these explanations appear to be viable ways to account for the origin of these features observed in the upper Grande Ronde flows of the Pasco Basin.

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As discussed previously, several investigators have noted the occurrence of platy fracturing. These features have been observed in many locations on the Columbia Plateau, including surface exposures in the Pasco Basin. They have not, however, been identified in drill core from the Pasco Basin. Two types of platy fracturing appear to be present in Columbia River basalts: platy fracturing within columns and platy fracturing in relatively thin bands that transect columns laterally. Swanson (1967, p. 1083) states that horizontal, parallel joints in colonnades probably formed in response to contraction of single columns during cooling. Waters (1941) observed platy fracturing developed along very thin diktytaxitic bands. Platy zones observed during the course of the BWIP investigations in Grande Ronde Basalt have been noted to be bands that cross columnar boundaries and to be laterally persistent (up to hundreds of meters).

It may be that platy fracture zones are tectonic in origin, caused by lithostatic unloading of flows. Origins of either type of platy jointing have not been clearly established. However, their primary or tectonic origin needs to be established if possible, because these are zones of relatively horizontal, high-density fracturing and because bands of platy jointing occur in the Cohassett flow at least on the margins of the Pasco Basin. Plans to further evaluate their origin are discussed in Section 8.3.1.2.3.3.2.

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1.2.1.2.3 Cooling joints

Cooling joints in basalt flows of the Columbia River Basalt Group are ubiquitous fractures that were formed during the solidification of the flows. As discussed in the previous section, the cooling joints form columns, subdivisions of columns, and zones of irregular basalt blocks. Cooling joints result from tensional stress in response to contraction of solidified portions of a flow as it cooled below the solidus (Spry, 1962, pp. 202-205). Cooling joints in Columbia River basalts may be classified as one of two types: column defining and column subdividing. Column-defining joints bound columns in the basalt flows, and column-subdividing joints divide the columns usually into joint blocks of irregular shape. Even zones of more randomly oriented fractures are considered to have column-defining joints that are more persistent than the column-subdividing joints, although these are difficult to identify.

As primary features, cooling joints are distinct from secondary tectonic fractures such as faults, shear zones, and joint sets. These secondary fractures are distinguishable by their appearance and occurrence. Tectonic fractures typically occur in zones of parallel to subparallel, closely spaced fractures; they may have breccias or clay minerals associated with them; and they may contain features such as slickensides and chatter marks. The zones cross cooling joints and disrupt the pattern of the cooling joints. The zones may persist through a flow and into adjacent flows.

Recognition of these differences is readily made at outcrop exposures. In core, however, these differences are not as evident due to the small

exposure, and detection of some small tectonic features is difficult. Fractures belonging to tectonic joint sets are probably much less prevalent than primary cooling joints, and the possible misidentification of a tectonic joint as a primary cooling joint is considered to have negligible impact on the description of cooling joint parameters that follows. The more obvious tectonic fractures that have been identified in coreholes are described in Sections 1.3.2.2.2.6 and 1.3.2.2.2.7. The exposures that will be available in the exploratory shaft will provide a better opportunity than existing core samples to identify tectonic joint sets, if present. Plans for cooling joint investigations in the exploratory shaft are described in Section 8.3.1.2.3.3.3.3.

1.2.1.2.3.1 Cooling joint parameters

Limited data exists on the cooling joint parameters of Columbia River Basalt Group flows. In the literature, where cooling joints are discussed, the description is centered around the depiction of intraflow structures and does not detail smaller scale parameters, which are important to repository design and waste isolation. The detailed data that do exist have been primarily completed or supported by the BWIP. Long (1978, pp. 17-27), Myers/Price et al. (1979, pp. III-77 to III-85), and Long and Davidson (1981, pp. 5-17 to 5-22) presented general descriptions of cooling joints.

Cooling joint data discussed in this section include the following parameters, which were derived from data outside the controlled area study zone:

- Cooling joint persistence.
- Frequency or spacing.
- Orientation.
- Width.
- Percent infilled with secondary minerals.
- Roughness.
- Platy fracture zones.

Little is known about the other cooling joint parameters outside the controlled area study zone. Section 8.3.1.2.3.3.3 discusses plans to collect and interpret the other cooling joint parameters. Cooling joint data from within the controlled area study zone are discussed in Section 1.2.2.1.5.

Cooling joint persistence

Persistence of cooling joints can be measured effectively at outcrops or in underground openings only and cannot be measured from drill core. Moak and Wintczak (1980, p. 4-54) obtained underground data from the Pomona flow entablature during detailed line mapping in the BWIP Near-Surface Test Facility. Their work suggests that cooling joints with dips between 66° and 90° are the column-defining cooling joints and have persistence that are greater on the average than joints with dips less than 66°. Persistences for the column-defining joints could not be determined because of the limited height of the exposures in the tunnels. However, Moak and Wintczak (1980,

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pp. 4-59) suggest the steeply dipping joints could have persistence up to 2.4 m (8 ft) in length. Although a high angle persistence of 2.4 m (7.9 ft) is suggested from the underground facility, ongoing field mapping activities include observations suggesting that column-defining joints may be persistent through the thickness of an intraflow structure (tens of meters). Low-angle cooling joints (less than 66° of dip) were found to be continuous only within a single column 15 to 30 cm (6 to 12 in.) in diameter. Section 8.3.1.2.3.3.3.1 will address proposed data collection activities concerning persistence.

Frequency and spacing

Cooling joint frequencies, measured from vertical and horizontal scanlines (2 to 7 m (6.5 to 22 ft) in length) at Sentinel Gap and Emerson Nipple surface sections (see Fig. 1.2-7), were collected for the Museum, Rocky Coulee, Cohassett, McCoy Canyon, and Umtanum flows (Long, 1978, pp. 49-52; Long and Davidson, 1981, pp. 5-20 to 5-24; and Long and WCC, 1984, pp. I-68 to I-78). Frequencies range from 1 to 37 joints per meter. The data suggest that basalt flows probably cannot be separated into different populations based on cooling joint frequency (Long and WCC, 1984, Table I-5) and that variability of cooling joint frequency determinations from outcrop are greater within flows than between flows. Long and WCC (1984, Table I-5) also showed that entablatures exhibit a greater number of cooling joints per meter than colonnades.

Cooling joint frequencies derived from core data were plotted against position in the basalt flow. The core data were taken from the Museum, Rocky Coulee, and McCoy Canyon flows of Grande Ronde Basalt in the DH-5 core hole (outside the controlled area study zone (see Fig. 1.2-7)). Generally, these plots did not delineate intraflow structures (Long, 1978, pp. 35-41; Long and Davidson, 1981, pp. 5-23 to 5-24; and Long and WCC, 1984, pp. I-69 to I-81). As suggested by Long and WCC (1984, p. I-69), this lack of correlation between fracture frequency and position in the flow may be due to a dominantly vertical orientation of colonnade fractures and a vertical data collection method (vertical core hole) that would tend to sample vertical fractures less frequently. However, this suggestion was made prior to any data on the distribution of cooling joint orientation in basalt flows and comparisons of average joint frequencies with intraflow structures (i.e., colonnades and entablatures) in core data. Average frequencies derived from core data that were collected more recently (McGee and DC-16A core holes (Rockwell, 1987)) do correlate well with intraflow structures in the flow interior. Fracture frequencies from core data will be discussed in greater detail in Section 1.2.2.1.5.1 because the McGee and DC-16A core holes are within the controlled area study zone.

The average frequencies were determined from the McGee and DC-16A core holes, which are vertical in orientation. Without knowing what orientation the cooling joints are overall, one could argue that cooling joints may be dominantly vertical, and a vertically derived core would not sample the joints representatively. To check this concept, core drilled in both vertical and horizontal directions from the same locality (and preferably from the same intraflow structure) would be needed for comparison. The only core that met these criteria is the Pomona core from the Near-Surface Test Facility (outside

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the controlled area study zone). The basalt that was cored there is a member of the Saddle Mountains Basalt and is within the entablature portion of the flow and displays small, but easily discernible, columns that are oriented vertically. Average joint frequencies are 14.1 joints per meter for the horizontal core and 14.8 joints per meter for vertical core (Moak and Wintczak, 1980, pp. C-27 to C-34). Not only are the joint frequencies about the same for both horizontal and vertical directions, but the vertical frequency is slightly greater than the horizontal frequency. This result is not consistent with expected results if vertical joints were dominant. In the Pomona entablature, cored at the Near-Surface Test Facility, the vertical joints clearly do not dominate, even though the basalt there displays a readily apparent set of vertical columns. These results also suggest that the frequencies derived from vertical core may be as representative of overall frequency as frequencies from horizontal core in other basalt formations as well (i.e., Grande Ronde Basalt). Only by comparing vertical and horizontal core frequencies in the Cohassett and adjacent flows will the answer become certain (see Section 8.3.1.2.3.3.3.3 for plans to log and interpret horizontal core in the Exploratory Shaft Facility).

When cooling joint frequency (fractures per meter) is inverted, the result is average spacing (meters per fracture). Sometimes spacing is a more useful parameter than frequency, especially for rock mechanics applications (ISRM, 1981, pp. 17-19). Meints (1986, pp. 97-116) reported cooling joint spacing data from 18 surface sites in the Rocky Coulee and Museum flows at Vantage and Sentinel Gap (the Museum flow is a local name for the uppermost Grande Ronde Basalt flow at the Sentinel Gap section (see Fig. 1.2-7)). Results indicated that the cooling joint spacing follows a log normal distribution for the orientation groups (groups of cooling joints with similar attitude). Figure 1.2-15 shows a histogram and cumulative distribution function for cooling joint spacing in one orientation group (high-angle group).

The study of cooling joint spacing reported in Meints (1986, pp. 97-116) also compared flows and intraflow structures on the basis of cooling joint spacing. Results suggest that colonnade fracture spacing is similar in the Museum and Rocky Coulee flows at Vantage. Also, fracture spacing in the Museum flow colonnade at Vantage and Sentinel Gap is similar to the Rocky Coulee flow columnar-entablature at Vantage. Comparisons of all other possible combinations of flow, intraflow structure, and locality showed no similarities in spacing. This suggests that cooling joint spacing is highly variable, both between flows and within flows and cannot be used to differentiate flows, intraflow structures, or even localities that are not very close together. The relationships between the distance among sampling localities and the similarities of joint spacing were not studied. Plans for distinguishing cooling joint spacing and other parameters between sampling localities are in the section on joint modeling, Section 8.3.1.2.3.3.3.4.

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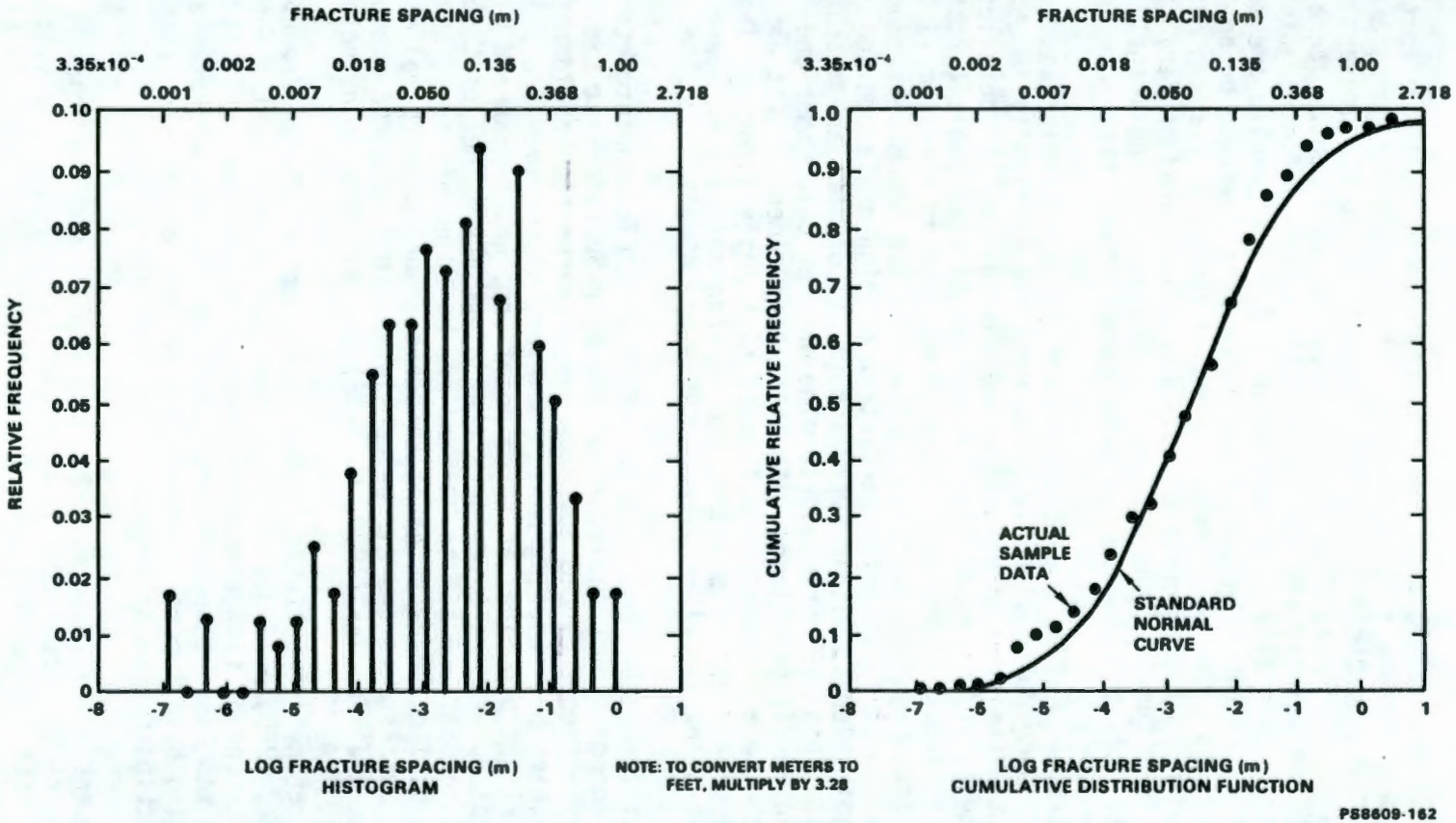

Figure 1.2-15. Relative frequency histogram and cumulative relative frequency for high-angle log fracture spacings in the Rocky Coulee flow. Number of samples = 185, median = 0.065 m spacing (taken from Meints, 1986, p. 107).

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Orientation

Figures 1.2-12 and 1.2-13 show patterns of columnar jointing that are typical of certain intraflow structure types. However, the figures are deceptive with respect to the total numbers of cooling joints present in basalts because the column-dividing joints (which actualy constitute a greater percentage of cooling joints) are not shown. The column-defining joints that form the columns are generally more persistent and, as a result, are more obvious in outcrop. Although the column-defining joints may be predominantly vertical or subvertical, the more common column-dividing joints are not. The discussion of cooling joint orientation data (although based on very little data) points out that the existing data do not suggest a predominantly vertical or subvertical orientation for basalt cooling joints.

Earlier work (Long, 1978, pp. 35-49) concerning orientation was confined to the study of cooling joint dip only because of the difficulty in obtaining strike measurements from unoriented drill core and the lack of detailed attitude measurements at outcrops. The percentage of high-angle (greater than 60°) cooling joints and the maximum cooling joint lengths over 1 m (3 ft) of DH-5 core were plotted against position in the flow for the Museum, Rocky Coulee, and McCoy Canyon flows. The percentage of high-angle cooling joints and the maximum joint length within every 1 m (3 ft) of core are measures of cooling joint dip. This was done to determine whether colonnades and entablatures could be differentiated with these measurements. (It was thought colonnades should have a greater percentage of high-angle joints.) The diagrams showed a great deal of scatter, and no apparent pattern emerged that would identify intraflow structures (Long, 1978, pp. 48-49).

Moak and Wintczak (1980, pp. 4-28 to 4-54) identified "joint sets" from core data in the Pomona flow entablature of the Near-Surface Test Facility. Histograms of strike frequency did not show any patterns that could not be attributed to anything but sampling bias. However, histograms of dip angle frequency showed slight groupings at three positions, which Moak and Wintczak (1980, p. 4-38) interpreted as three separate joint sets. The joint sets are at 0° to 37°, 38° to 65°, and 66° to 90° and are based on dip angle only, without regard to strike. Because joint sets are groupings of parallel joints that require that both strike and dip be consistent in a set, the groupings identified by Moak and Wintczak (1980, p. 4-38) are not true joint sets.

The lack of definitive patterns in the histograms of strike frequency (Moak and Wintczak, 1980, p. 4-38) may have been due in part to the method used to orient the core by fluxgate magnetometer. Packer and Petty (1979, pp. 9-11, 19) and Van Alstine and Gillett (1981, pp. 50-54) suggest that this method for orienting basalt core is unreliable and may be in error as much as 30° without correcting for secondary magnetic components.

In a more recent study (Meints, 1986, pp. 39-69), cooling joint orientation data were collected from outcrops at Sentinel Gap and Vantage and from drill core. Both the outcrop and core data were collected from the Museum and Rocky Coulee flows. The outcrop data came from 18 separate sites, and the core data came from boreholes DH-5, DC-2, DC-4, DC-12, DC-16, RRL-2,

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and RRL-6 (see Fig. 1.2-7). The drill core was oriented using the paleomagnetic inclination and declination of the flow. Cooling joint orientation data were plotted as poles on lower hemisphere stereonets and compared statistically to determine whether there were similarities within and between intraflow structure types as well as within and between study localities. The results from outcrop data show that within the Rocky Coulee flow at Vantage, the three separate intraflow structure types (i.e., colonnade, columnar entablature, and entablature) correspond to three recognizable fracture pole patterns (Fig. 1.2-16). Although distinctive pole patterns are recognizable as corresponding to particular intraflow structure types, comparisons of similar intraflow structure types between separate collection localities show that fracture patterns in the areas may be different. This result suggests that there is a great deal of local variation within each intraflow structure type.

Comparisons were also made between pole plots from core and outcrop data (Meints, 1986, pp. 70-96). Results were mixed and sometimes difficult to explain. For example, in comparing Museum flow (Type I flow, only colonnade present) outcrop and core plots, the Vantage outcrop plot was statistically different from the core plot, but the Sentinel Gap outcrop plot was statistically similar to the core plot. Comparisons were also made between Rocky Coulee outcrop plots and core plots. However, since the intraflow structures were not differentiated in the Rocky Coulee core data (the Rocky Coulee is a Type II flow with tiers of colonnades, columnar entablatures, and entablatures), the results have little utility here.

There are recognizable problems with outcrop versus core comparisons. The core data were collected along vertically oriented core only; thus, vertically oriented joints tend to be sampled less. The outcrop data were collected in rectangular mapping areas on outcrop faces that have multiple orientations. The combination of multiple collection orientations at outcrop by an area rather than a line (as in core) tends to reduce any sampling orientation bias.

It is not clear whether the mixed results of outcrop plots versus core plots can be explained by the geology or whether the sampling and comparison problems completely mask the effects of the geology. To answer the question, the bias introduced by vertical boreholes must be removed or corrected and intraflow structures must be identified in core samples. See Section 8.4.1.2.3.3.3.2 for plans to study vertical borehole bias and orientation of joints.

Cooling joint width

Most of what is known about cooling joint width is from core holes within the controlled area study zone and is discussed in Section 1.2.2.1.5. However, cooling joint widths are reported in Long and Davidson (1981, pp. 5-23 to 5-26) for the Rocky Coulee and McCoy Canyon flows in borehole DH-5 and in Moak and Wintczak (1980, pp. 4-28 to 4-37) for the Pomona flow entablature in the Near-Surface Test Facility (all outside the controlled area study zone). Long and Davidson (1981, pp. 5-23) report that cooling joint widths in the Rocky Coulee

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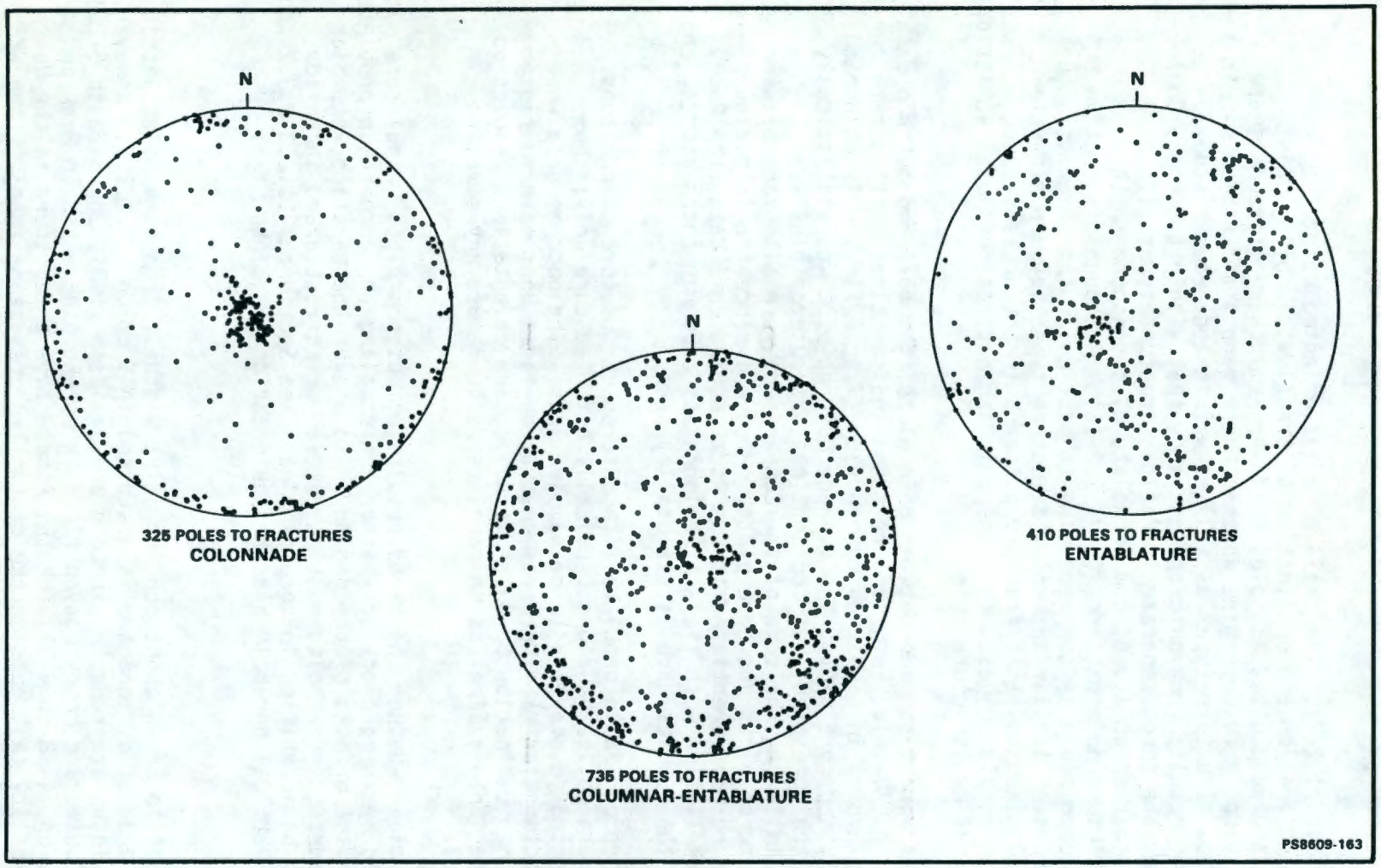

Figure 1.2-16. Lower hemisphere pole projections of fracture planes for three intraflow structures in the Rocky Coulee flow at Vantage. Individual sampling sites of like intraflow structures were combined to meet sample size requirements for statistical analysis. Plots indicate that within the Rocky Coulee flow at Vantage, the colonnade, columnar-entablature, and entablature intraflow structures consist of separate fracturing populations.

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and McCoy Canyon flows average between 0.1 and 0.3 mm (0.004 and 0.012 in.). Histogram plots of cooling joint widths (Long and Davidson, 1981, pp. 5-25 and 5-26) show that the distribution of widths is not symmetrical, but is skewed with the smaller widths more common than larger widths. Moak and Wintczak (1980, p. 4-28) report that the cooling joint width in the Pomona flow entablature averages approximately 0.2 mm (0.008 in.) and varies by 0.1 mm (0.004 in.). Histograms in Moak and Wintczak (1980, pp. 4-34 to 4-37) are similar to those in Long and Davidson (1981, pp. 5-25 to 5-26) and show also that the distribution of cooling joint widths is not symmetrical but is skewed to the smaller widths.

Percent infilled with secondary minerals

Of the 1,454 cooling joints logged in drill core DH-5 for the Rocky Coulee, Museum, and McCoy Canyon flows, 83% were completely filled with secondary minerals and 17% were at least partially unfilled. According to Long (1978, p. 35), the percentage of completely filled cooling joints for each flow was Museum, 87%; Rocky Coulee, 77%; and McCoy Canyon, 86%. Long and Davidson (1981, pp. 5-25 to 5-26) indicated that in the same core (DH-5) reported in Long (1978), the vast majority of unfilled or partially unfilled cooling joints were smaller in width than 0.3 mm (0.012 in.). Since wider cooling joints are less frequent than narrower ones, it was not known whether the width distribution of unfilled joints was similar or dissimilar to the width distribution of completely filled joints. According to Moak and Wintczak (1980, p. 4-6), all cooling joints in the core of the Pomona entablature taken at the Near-Surface Test Facility appeared to be totally filled with clay or other materials. Lindberg (1986, pp. 47-51) reports that clay is the predominant infilling type followed by silica and zeolite. The types of secondary minerals in cooling joints are discussed in Section 4.1.1.

Roughness

A random sampling of approximately 200 points on cooling joints in core (both horizontal and vertical core) from the Near-Surface Test Facility (Pomona entablature) was checked for roughness (Moak and Wintczak, 1980, p. C-87). The more steeply dipping cooling joints, which tend to be the column-defining joints, are more likely to be rough. The cooling joints of lower dip angle tend to be rough also, but they have a higher probability of being smooth than the steeply dipping joints. Barton (1984, pp. 48 to 56), using International Society of Rock Mechanics terminology (ISRM, 1981, pp. 21-30), describes Cohassett flow cooling joint roughness in core as in the range of smooth-planar to rough-undulating.

Platy fracture zones

Platy fracture zones are zones of closely spaced fractures observed at some outcrops. Some platy fracture zones display a knobby character while others display a series of curvilinear, subhorizontal fractures. The zones may or may not cross column boundaries, making the interpretation of their origin difficult. See Section 1.2.1.2.2 for additional discussion of platy fracture zones.

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1.2.1.2.3.2 Cooling joint origin

The previous descriptions of cooling joint parameters provide a good base for models of cooling joint origin. The development of hypotheses regarding the origin of columnar jointing is discussed by Tomkeieff (1940, pp. 89-146). The widely accepted hypothesis is that of contraction and is presented in Spry (1962, pp. 191-216).

Spry (1962, pp. 191-216) gives two explanations for fracture propagation. It could be produced by the instantaneous formation of many adjacent simple units or by a mechanism involving the continuous propagation of fractures. The latter being the preferred explanation.

The initated fracture penetrates the rock mass as it hardens in discrete intervals, producing the striae, banding, or "chisel marks" seen on many of the column faces (Ryan and Sammis, 1978, pp. 1295-1308). More recent work by Degraff et al. (1985) has shown that by continuing the study of detailed fracture morphology, the origin model can be expanded. Their conclusions were that cooling joint propagation direction can be determined from the asymmetry of joint segments. These propogation direction indicators agree with those predicted by a thermal model, which explains the contrast in fracture patterns between intraflow structures as the result of quenching by water (Long and Wood, 1986, pp. 1144-1155).

Cross-joint fractures can be either straight or curved. The curved cross joints are referred to as ball-in-socket joints and are predominant in the colonnade portions of the flows (Spry, 1962, pp. 191-216). Laboratory tests by Bridgman (1952, pp. 74-79) suggest analogies between tensional rupture and shear failure of basalt and steel, respectively, to the fracturing nature of cross jointing observed in colonnade sequences. Spry (1962, pp. 191-216) suggested that, with respect to the high temperatures in which cross joints form, the stress distribution is such that rock failure may be due partly to shear and partly to tensional rupture, depending on existing physical conditions and the mechanical properties of the basalt. An understanding of the origin of cooling joints is far from complete. More work needs to be done similar to the recent work of Degraff et al. (1987). See Section 8.3.1.2.3.3.3.4 for plans for origin modeling of cooling joints.

1.2.1.2.4 Mineralogy, petrology, and bulk chemical composition

Stratigraphic applications of primary mineralogic, petrologic, and bulk chemical compositions have been discussed previously. Hydrochemical application of these data are also pertinent as they can be used to evaluate dissolution and exchange reactions. Secondary mineralogy and geochemistry can also affect groundwater chemistry, not only through dissolution and exchange, but also through precipitation and dehydration reactions. The groundwater chemistry, in turn, establishes the waste package environment and influences radionuclide sorption and transport through similar kinds of reactions (see

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Section 3.9). A detailed discussion of the mineralogy, petrology, and bulk chemical composition of the host rock and surrounding units and mineral stability is contained in Sections 4.1.1.3 and 4.1.1.4.

Because of the multitude of studies available on the mineralogic, petrologic, and chemical composition of the Columbia River basalts, only general references are given for each stratigraphic formation. These references can be consulted for the identification of more detailed work that has been completed, such as university masters and doctoral theses. General reviews can be found in the following:

- Imnaha Basalt (Swanson et al., 1979a, pp. G8 to G12; Hooper et al., 1984; and Fitzgerald, 1984).
- Picture Gorge Basalt (Swanson et al., 1979a, pp. G12 to G15; Bailey, 1986).
- Grande Ronde Basalt (Camp, 1976; Reidel, 1978b; Swanson et al., 1979a, pp. G16 to G24).
- Wanapum Basalt (Swanson et al., 1979a, pp. G25 to G37; Camp, 1981, pp. 669-678).
- Saddle Mountains Basalt (Swanson et al., 1979a, pp. G37 to G54; Camp, 1981, pp. 669-678; Shubat, 1979; Reidel and Fecht, 1986).

1.2.1.3 Interbedded and suprabasalt deposits

A wide variety of late Cenozoic epiclastic, volcanic, and volcaniclastic rocks and deposits lie within the Columbia Plateau (Fig. 1.2-17). A general discussion of these units follows in chronologic order; a more detailed dicussion of the interbedded and suprabasalt deposits within and adjacent to the site is given in Section 1.2.2.2. Further studies of the interbedded and suprabasalt sediments required to support hydrologic, tectonic, and paleoclimatic modeling are presented in Sections 8.3.1.2.3.3.1, 8.3.1.2.3.3.4, and 8.3.1.2.4.4.1.

1.2.1.3.1 Miocene deposits

Most sedimentary deposits of Miocene age on the Columbia Plateau are interbedded with the Columbia River Basalt Group. All major sedimentary interbeds within the Spokane Valley and parts of the St. Joe and Couer d'Alene River valleys in the northeastern Columbia Plateau are assigned to the Latah Formation (Griggs, 1976, pp. 1-39). In parts of the southern Columbia Plateau, the lacustrine Mascall and fluvial Simtustus Formations are locally interbedded with the Columbia River Basalt Group (Farooqui et al., 1981a, pp. 32-33; Smith, 1986, pp. 63-72). Other Miocene-age deposits in Oregon,

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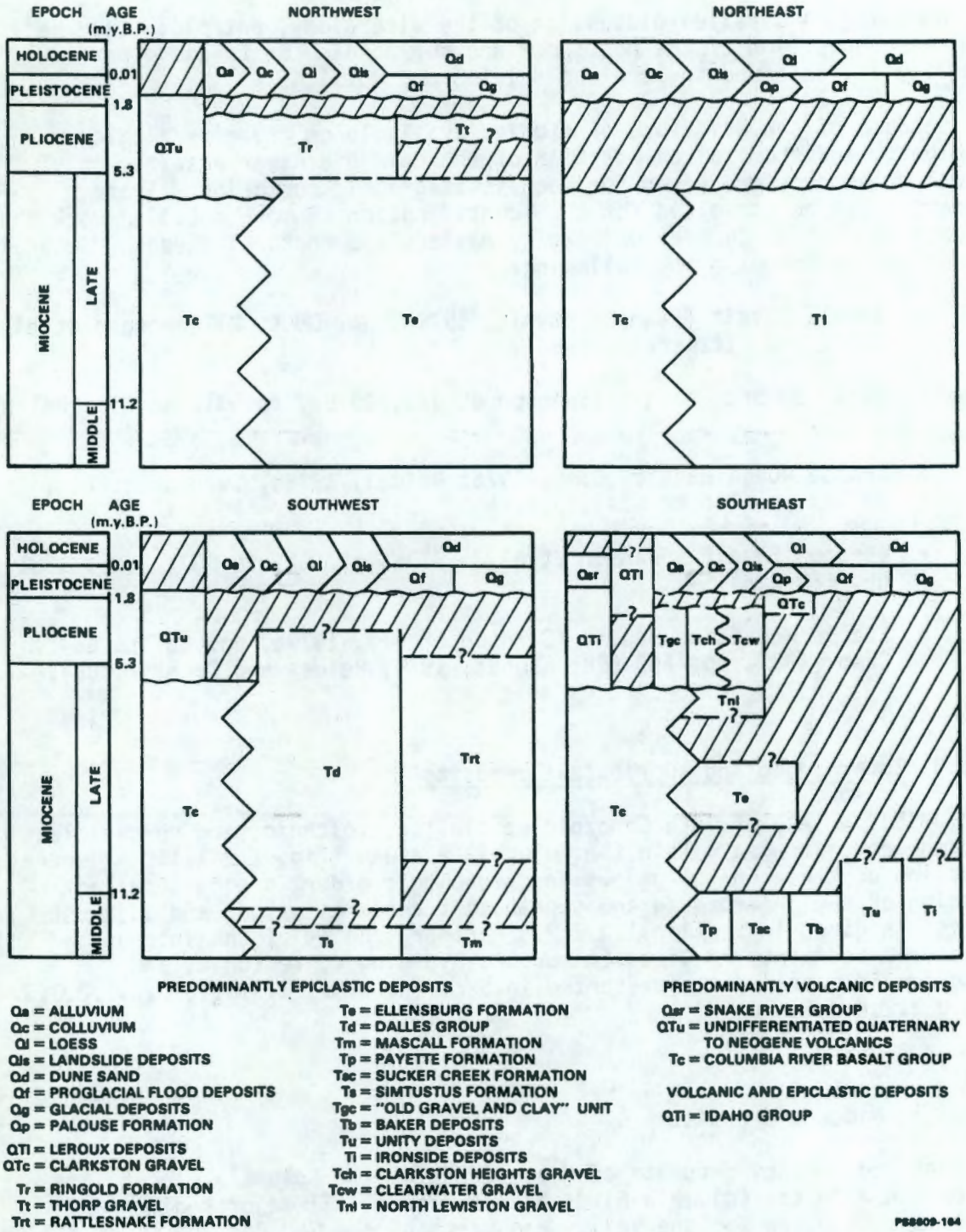

Figure 1.2-17. Stratigraphic nomenclature for late Cenozoic sedimentary and volcanic deposits within the Columbia Plateau.

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equivalent to the Columbia River Basalt Group, include the fluvio-lacustrine Baker, Unity, and Ironside deposits (Farooqui et al., 1981a, pp. 34-37). In southwestern Idaho, interbeds are included in the Payette and Sucker Creek Formations (Strowd, 1980 pp. 22-24; 41-42; 47-48). Fluvial gravels below the Monumental flow (6 m.y.B.P.), referred to as North Lewiston Gravels (Webster et al., 1982, pp. 670-672), are locally exposed along the Snake River and represent deposits from the ancestral Clearwater and Salmon Rivers.

The Ellensburg Formation includes epiclastic and volcaniclastic sedimentary rocks that are interbedded with the Columbia River Basalt Group in the central and western part of the Columbia Plateau (Schmincke, 1964, pp. 375-376; Swanson et al., 1979b, p. G25; Waitt, 1979, pp. 1-3, Rigby and Othberg, 1979, pp. 9-15). The age of the Ellensburg Formation is principally Miocene, although locally it may be equivalent to early Pliocene. The thickest accumulations of Ellensburg Formation lie along the western margin of the Columbia Plateau where Cascade Range volcanic and volcaniclastic materials interfinger with the Columbia River Basalt Group. Within the Pasco Basin, deposits of the Ellensburg Formation are primarily restricted to the Wanapum and Saddle Mountains Basalts. The lateral extent and thickness of interbedded sediments generally increase upward in the section (Reidel and Fecht, 1981, p. 3-30). Two major facies, volcaniclastic and fluvial, are present either as distinct or mixed deposits (Reidel and Fecht, 1981, p. 3-30).

Members (interbeds) of the Ellensburg Formation are defined based on the upper- and lower-bounding basalt flows. Basalt flows may be discontinuous, however, especially on and adjacent to Yakima folds. Therefore, the process of naming interbeds is complicated. Over the central Columbia Plateau and Pasco Basin, correlative interbeds include the Vantage, Mabton, Cold Creek, Selah, and Rattlesnake Ridge units (see Fig. 1.2-3), although many other named and unnamed members exist locally (Reidel and Fecht, 1981, pp. 3-30 to 3-40).

Included in the Ellensburg Formation is a well-rounded quartzitic gravel informally referred to as Snipes Mountain conglomerate (Schmincke, 1964, p. 221). It is distributed in a broad zone that extends southwestward from the Pasco Basin to near Hood River, Oregon, and represents the former course of the Columbia and Yakima Rivers prior to diversion of the Columbia through Wallula Gap (Fecht et al., 1985, pp. 29-30). The upper portion of the Snipes Mountain conglomerate is believed to be equivalent to the Neogene basal Ringold unit.

1.2.1.3.2 Late Miocene to Pliocene deposits

Suprabasalt sediments were deposited in most synclinal valleys of the Yakima Fold Belt and within other structural basins on the Columbia Plateau during the late Neogene (late Miocene to Pliocene time). These deposits of epiclastic, volcaniclastic, and volcanic affinities are discussed geographically for the margins of the Columbia Plateau first and then for the central portion of the plateau where the controlled area study zone is located.

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Southern Columbia Plateau

Neogene deposits in northern Oregon belonging to The Dalles Group are divided into five formations, each formation assigned to a separate drainage basin (Farooqui et al., 1981a, pp. 131-140). However, it has not been demonstrated that formations within The Dalles Group developed in closed basins; thus, their formational status appears tenuous. The Rattlesnake Formation of central Oregon consists of fanglomerate, sandstone, volcanic mudstone, and welded tuff that unconformably overlie the Columbia River Basalt Group and the Mascall Formation (Farooqui et al., 1981a, pp. 33-34). Although the deposits are confined principally to the John Day Basin, a welded tuff unit is of regional extent.

Eastern Columbia Plateau

Suprabasalt sediments in the Walla Walla Valley referred to as "old gravel and clay" (Newcomb, 1965, pp. 20-22) represent locally derived alluvial deposits. These sediments are interpreted as equivalent to the Ringold Formation, located within the central Columbia Plateau. Other deposits of late Miocene to Pliocene age include the epiclastic Clarkston Heights Gravel and Clearwater Gravel and volcanic, volcaniclastic, and epiclastic deposits of the Idaho Group.

Northern Columbia Plateau

The northern Columbia Plateau generally lacks late Neogene sedimentary deposits. This is apparently because the area remained relatively high with respect to base level, and, therefore, very little deposition took place. Whatever deposits did accumulate were subsequently removed by proglacial cataclysmic floods.

Western Columbia Plateau

Late Neogene deposits on the western Columbia Plateau are limited to intermediate to silicic volcanic and volcaniclastic rocks associated with periodic eruptions along the ancestral Cascade Range.

Central Columbia Plateau

Late Neogene deposits younger than Columbia River Basalt Group are represented by the Ringold Formation within the Pasco and Quincy Basins of the central Columbia Plateau (Gustafson, 1973; Newcomb et al., 1972, pp. 10-16; Grolier and Bingham, 1978, pp. 38-50; Rigby and Othberg, 1979, pp. 15-17). The fluvial-lacustrine Ringold Formation was deposited in generally east-west trending valleys by the ancestral Columbia River and its tributaries in response to development of the Yakima Fold Belt (see Section 1.3). While exposures of the Ringold Formation are limited to the White Bluffs within the central Pasco Basin, and to Smyrna and Taunton Benches within the Othello Basin, extensive data on the Ringold Formation are available from boreholes

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in these basins. The Ringold overlies Columbia River basalt throughout most of the controlled area study zone and thus can be used to help constrain the age of past tectonic movement in the underlying basalt.

The Ringold Formation is classified into three facies associations (referred to as stratigraphic section types by Tallman et al., 1981, pp. 2-3 to 2-7). The different section types (Fig. 1-2.18) represent variations in the paleogeography during Ringold time. Section Type I, composed of gravel and associated sand and silt, represents a migrating channel deposit of the major, throughgoing, ancestral Columbia and (or) Snake River systems confined to the central portion of the Pasco Basin. Section Type II is composed mostly of overbank sand, silt, and clay deposited along the margins of the basin, beyond the influence of the main channel. Section Type III, a fanglomerate, occurs locally around the extreme margins of the basin and is composed of mostly angular basaltic debris, derived from sidestream alluvium shed off bedrock ridges.

Two approaches have been used to subdivide Section Type I Ringold Formation deposits in the central Pasco Basin. One is based on lithofacies and the other on upward-fining cycles. Newcomb (1958, pp. 328-337) divided the Ringold into three lithofacies: a coarse-grained middle unit bounded above and below by fine-grained units. Tallman et al. (1979, pp. 18-19) added a fourth lithofacies unit, the coarse-grained basal Ringold unit, which underlies the fine-grained lower Ringold unit in the west-central Pasco Basin. The basal Ringold unit is further subdivided into a coarse- and fine-grained subunit within the central Cold Creek syncline (Bjornstad, 1984) (see Section 1.2.2.2). A second approach is that used by PSPL (1981, pp. 2R-15 to 2R-19) south and east of Gable Mountain where they divided the subsurface Ringold Formation into four fluvial cycles (Units I through IV). Studies are planned to determine the distribution, relationship, and correlation among Ringold facies within the Pasco Basin (see Section 8.3.1.2.3.3.1).

The age of the Ringold Formation is important for determining timing and rates of deformation. Within the Pasco Basin, the Ringold Formation is interpreted to be late Miocene to late Pliocene in age. While vertebrate fossils from the White Bluffs suggest an early Blancan (late Pliocene) age (Gustafson, 1973, pp. 140-142), the exact upper limit is debatable, depending on interpretations by several authors of the magnetostratigraphy. The major reversed magnetozone within the upper Ringold unit along the White Bluffs was interpreted by Packer and Johnston (1979, pp. 38-42) to lie within the Gilbert reversed epoch (3.4 to 5.12 m.y.B.P.) (Mankinen and Dalrymple, 1979, p. 624). Gustafson (1985, p. 91) has interpretated a biostratigraphically younger reversed sequence at Taunton, north of the Pasco Basin, to also be within the Gilbert reversed epoch. This requires that the top of the White Bluffs sequence be reassigned to an older reversed event (i.e., greater than 3.9 m.y.B.P.) within the Gilbert epoch. On the basis of the fossil and paleomagnetic data, the top of the middle Ringold unit, which lies near river level along the White Bluffs, appears to lie near the base of the Gilbert reversed epoch (5.12 m.y.B.P.). Ages of the lower and basal Ringold units are

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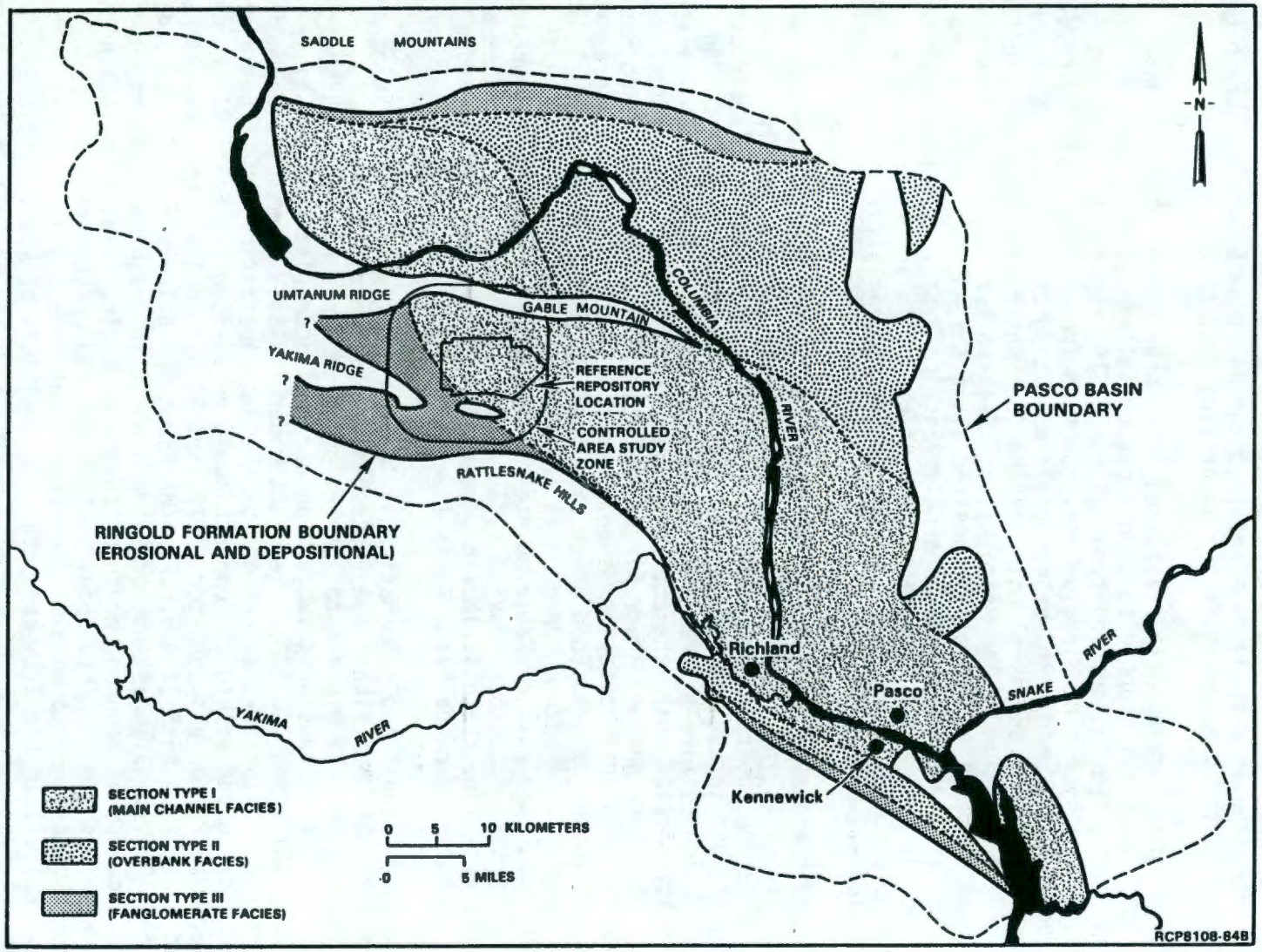

Figure 1.2-18. Distribution of Ringold Formation section types.

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less well restrained but are believed to be younger than the Ice Harbor basalt flow dated at 8.5 m.y. (Tallman et al., 1981, p. 2-25, Fecht et al., 1985, p. 32).

Preliminary interpretations based on recent detailed mapping along the White Bluffs suggest that broad lakes may have existed in the region during much of upper Ringold time. This is significant from a tectonic standpoint, since a likely mechanism for lake development may relate to accelerated late Neogene uplift of, or basining behind, the Horse Heaven Hills at Wallula Gap (Newcomb, 1958, p. 339) (see Sections 1.3.2.2 and 8.3.1.2.4.3.1).

1.2.1.3.3 Pliocene deposits

Deposits of strictly Pliocene age on the Columbia Plateau include the Thorp, Clarkston Heights, and Clearwater Gravels. Deposits of Thorp Gravel, located in the Kittitas Valley along the western Columbia Plateau, are believed to be laterally equivalent to the Pliocene-age upper Ringold unit (Waitt, 1979, p. 12). Fission track dates on tephra from the upper part of this deposit are Pliocene (approximately 3.7 m.y.B.P.). Deposits of Thorp Gravel consist of deeply weathered, weakly cemented, and well rounded gravel and coarse sand that occur in high terraces along the Yakima River and its tributaries. Thorp Gravel rests unconformably on the Columbia River Basalt Group and Ellensburg Formation and consists mainly of sidestream gravels of, locally derived Columbia River basalt and mainstream gravels of silicic to intermediate volcanic and plutonic rocks (Rigby and Othberg, 1979, pp. 17-19; Waitt, 1979, pp. 9-12).

Two other Pliocene deposits, also of fluvial origin, were deposited in the southeastern Columbia Plateau. The Clarkston Heights and Clearwater Gravels were deposited between 2 to 6 m.y.B.P. by the ancestral Salmon and Clearwater Rivers (Webster et al., 1982, pp. 672-675). These were deposited prior to the capture of the Snake River by the Columbia River (Wheeler and Cook, 1954), which occurred sometime during late Pliocene or early Pleistocene time.

1.2.1.3.4 Plio-Pleistocene deposits

The late Pliocene to early Pleistocene is generally characterized as a period of regional incision on the Columbia Plateau. Within the Pasco Basin this is reflected by the abrubt termination and eroded nature of the top of the Ringold Formation (Brown, 1960, pp. 4-6; Newcomb et al., 1972, pp. 15-16; Bjornstad, 1985, p. 524).

The exact timing and duration of incision is unknown; however, it probably occurred during the interval from 1 to 2 m.y.B.P. Incision is bracketed between 0.9 m.y.B.P. and equal to, or greater than, 3.4 m.y.B.P., the respective ages of the basalt from Haystack Butte (Bela, 1982, Map) and

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the youngest age reported for the Ringold Formation. Haystack Butte lava lies near river level within the Columbia River Gorge, approximately 150 km (90 mi) southwest of the Pasco Basin, indicating that incision (as much as 150 m (492 ft) in the Pasco Basin) had ceased by this time.

Plio-Pleistocene incision is reported for several other localities on the Columbia Plateau, suggesting incision was a regional event. Among these, there is evidence just north of the Pasco Basin, where Johnson Creek has incised a canyon up to 120 m (394 ft) deep (Cochran 1978, p. 8). Elsewhere, incision at approximately 2 m.y.B.P. is reported in the Columbia River Gorge (Tolan and Beeson, 1984, p. 476). Regional incision in the Columbia Basin likely led to the capture of the Snake River in the vicinity of Hells Canyon (Wheeler and Cook, 1954). This is suggested by the incised Glenns Ferry Formation of the Idaho Group, which has a minimum age of approximately 2 m.y.B.P. (Kimmel, 1982, pp. 563-573).

Other deposits of late Pliocene and (or) Pleistocene age include the Clarkston Gravel, which was deposited by the ancestral Salmon River prior to Snake River capture (Webster et al., 1982, p. 676). The Idaho Group, a series of epiclastic, volcaniclastic, and volcanic deposits, locally overlies the Columbia River Basalt Group in southwestern Idaho (Strowd, 1980, pp. 52-58). The Idaho Group, along with Cascade volcanics along the western margins of the Columbia Plateau, were deposited intermittently during Plio-Pleistocene time. Volcanism during the Plio-Pleistocene also produced the Simcoe Volcanics. The oldest reported date for Simcoe lavas is 4.81 plus or minus 0.22 m.y.B.P., while the youngest flows may be as recent as late Pleistocene (Anderson, 1985, p. 337) (see Section 1.3.2.1).

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1.2.1.3.5 Quaternary deposits

Aggradation of sediments resumed during the Quaternary following the period of late Pliocene to early Pleistocene incision. Quaternary deposits are associated with a variety of depositional processes, including those associated with volcanism, glaciation, lakes, rivers, wind, and mass wasting (see Section 1.1.3) (see Fig. 1.2-17). In the central Columbia Plateau the Quaternary record is dominated by proglacial cataclysmic flood deposits with lesser amounts of fluvial and eolian deposits, which lie below, between, and above flood deposits (see Section 1.2.3.2.2). Nonflooded areas on the Columbia Plateau are often mantled by alluvium, colluvium, or loess (wind-blown silt). The following is a discussion of volcanic, glacial, cataclysmic flood, and other deposits of Quaternary age on the Columbia Plateau.

1.2.1.3.5.1 <u>Volcanic deposits</u>

Silicic to intermediate volcanic rocks of Quaternary age are associated with the western and southern margins of the Columbia Plateau. These are discussed further in Section 1.3.2.1.

Volcanic deposits in the Pasco Basin are limited to occasional, thin layers of air-fall tephra from a few millimeters to 10 centimeters in thickness. Several tephra layers provide key time-stratigraphic markers (see Section 1.2.2.2.4). At least eight major tephras were erupted from Mount St. Helens between 150 and 35,000 yr ago (Mullineaux et al., 1975, pp. 329-335), excluding the May 18, 1980, eruption that blanketed eastern Washington. Glacier Peak erupted numerous times between about 11,000 and 13,000 yr ago (Smith et al., 1977, pp. 197-206; Westgate and Evans, 1978, pp. 1554-1567; Porter, 1978, pp. 30-41). Ash deposits from the eruption of Mt. Mazama, now Crater Lake, Oregon, are dated at 6,600 yr old (Wilcox, 1965, pp. 807-816). Many more tephra are present on the Columbia Plateau, which as yet have no known correlation or volcanic source.

1.2.1.3.5.2 Glacial deposits

Because of its latitude, low relief, and topography, the majority of the Columbia Plateau was ice free during Pleistocene glaciation (Fig. 1.2-19). Glacial deposits are restricted to the northern margin of the Columbia Plateau; these include till, ice-contact stratified drift, and outwash. The most extensive glacial deposits occur on the northwestern portion of the plateau, where they were deposited by the Okanogan Lobe of the Cordilleran ice sheet (Easterbrook, 1979) (see Section 1.1.2.2). Glacial drift resulting from alpine glaciation occurs along the western margin of the plateau in the Kittitas, Wenatchee, and Chelan Valleys (Rigby and Othberg, 1979, pp. 25-28) and in the southeastern Columbia Plateau around the highlands along the border of Oregon and Idaho.

1.2.1.3.5.3 Cataclysmic flood deposits

Proglacial flood deposits blanket low-lying areas over most of the central Columbia Plateau (see Fig. 1.2-19). As discussed in Section 1.1.3, these deposits formed when ice dams in western Montana and northern Idaho were breached, allowing large volumes of water to spill across eastern and central Washington. Most cataclysmic flood deposits that are preserved are late Pleistocene; the last major flood sequence is dated at about 13,000 m.y.B.P. by the presence of Mount St. Helens "S" tephra (Mullineaux et al., 1978, p. 178). The largest and most frequent floods came from glacial Lake Missoula in northwestern Montana; however, smaller floods may have escaped downvalley from glacial Lakes Clark and Columbia along the northern margin of the Columbia Plateau (Waitt, 1980, pp. 668-671). A third source of Pleistocene flood waters came down the Snake River from glacial Lake Bonneville (Malde, 1968, p. 1). Lake Bonneville flood deposits have not been positively identified within the Pasco Basin. This may be due to erosion and (or) burial by younger flood deposits from Lake Missoula. The last Lake Bonneville flood occurred about 14,000 to 15,000 yr B.P. (Scott et al., 1982, pp. 582-586).

Two types of flood deposits are normally observed: a coarse-grained main-channel facies and a fine-grained, slack-water facies. Within the Pasco Basin these are referred to as the Pasco Gravels and Touchet Beds members of the Hanford Formation (Myers/Price et al., 1979, pp. III-66 to II-68).

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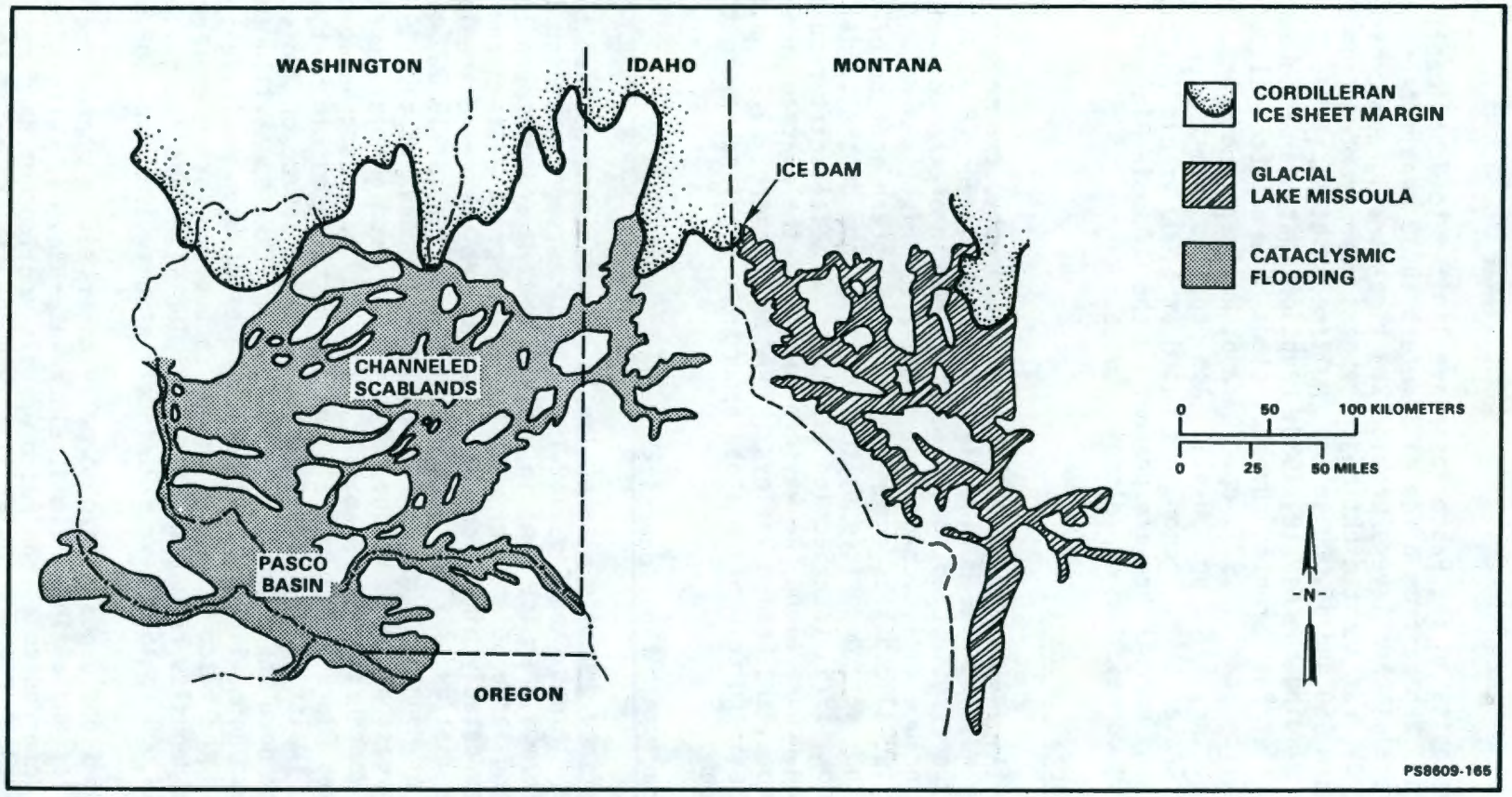

Figure 1.2-19. Extent of the Cordilleran Ice Sheet, glacial Lake Missoula, and proglacial cataclysmic flooding during Pleistocene glaciation.

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Deciphering the history of cataclysmic flooding in the Pasco Basin is complicated not only by floods from multiple sources, but also because paths of Lake Missoula floodwaters migrated and changed course with the advance and retreat of the Cordilleran ice sheet (Baker and Bunker, 1985, pp. 32-34). Cataclysmic floods inundated the central Columbia Plateau several times during the Pleistocene. At least three major flooding episodes (early, middle, and late Pleistocene) are recognized in the Pasco Basin, although many more minor flood events probably occurred during each of these major episodes. The evidence for the different ages of flooding include changes in magnetic polarity, truncated clastic dikes, and soil development atop flood sequences.

The number of floods represented in rhythmite sequences is presently under debate (Baker and Bunker, 1985, pp. 34-35). Erosional nonconformities and (or) weathered surfaces are indicated within some rhythmite sequences in southern Washington. Conclusive evidence for only one or two disconformities, however, are usually observed within the rhythmite facies of the central Columbia Plateau. Two such localities exist, one in south-central Pasco Basin (Tallman et al., 1981, p. 2-11) and the other at Cummings Bridge (Bjornstad 1980, p. 59; WCC, 1981b, pp. 31-32) in the Walla Walla Valley. Both localities show a distinctive nonconformity as indicated by truncated clastic dikes. Late-Wisconsin flood deposits (approximately 13,000 yr old) lie atop this nonconformity. Elsewhere, at Badger Coulee in the southern Pasco Basin, Bunker (1982, p. 17) interpreted two floods within a sequence of slack-water rhythmites that showed only a single nonconformity associated with the Mount St. Helens set-S horizon. Weathering characteristics in some older flood sequences suggest they are middle Wisconsin or older (greater than 30,000 yr). This is supported by a radiocarbon date of greater than 32,000 yr B.P. on wood fragments from one of the truncated dikes and thorium/uranium dates on calcic soils within the Pasco Basin (Tallman et al., 1981, pp. 2-25 to 2-26).

Recently, Waitt (1980, 1984, 1985) and Atwater (1984) have proposed as many as 40 or more late-Wisconsin floods, one for each observed slack-water rhythmite. The mechanism for rhythmite development, as suggested by Waitt, is through periodic jökulhlaups from glacial Lake Missoula. An alternative hypothesis for the development of rhythmites is through transient flood surges during a single flood (Bretz, 1929, p. 534; Baker, 1973, pp. 46-47). The evidence that more than one rhythmite may be related to a single flood (Bjornstad, 1980, pp. 62-75; Bunker, 1982, pp. 27-30) is supported by (1) the presence of gradational inter-rhythmite contacts, suggestive of continuous subaqueous deposition between some rhythmites; (2) the fact that bergmound debris, which typically caps slack-water deposits along the western Pasco Basin is lacking between slack-water rhythmites; (3) the scarcity of truncated clastic dikes within slack-water sequences; and (4) the presence of only a single major unconformity within slack-water flood deposits of the central Columbia Plateau.

Clastic dikes are commonly associated with, but not restricted to, cataclysmic flood deposits on the Columbia Plateau. While there is general agreement that clastic dikes formed during cataclysmic flooding, a primary mechanism to satisfactorily explain the formation of all dikes has not been identified (WPPSS, 1981, pp. 2.5-58 to 2.5-64). Among the more probable

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explanations are fracturing initiated by hydrostatic loading and hydraulic injection associated with receding floodwaters. Seismicity may also have a role in their formation, although there is no evidence available at the present to establish a connection.

1.2.1.3.5.4 Other Quaternary deposits

Other suprabasalt deposits of Quaternary age include lacustrine, alluvial, colluvial, eolian, and landslide deposits (see Section 1.1.3). The fluvio-lacustrine LeRoux deposits within the LaGrande Basin in the southeastern Plateau are of probable Quaternary age but may extend into the late Tertiary (Farooqui et al., 1981a, pp. 37-38). Alluvium is present, not only as a surficial deposit along major river and stream courses, but also in the subsurface, where it is found underlying and interbedded with proglacial flood deposits. Two types of alluvium are recognized in the Pasco Basin: quartzitic mainstream and basalt-rich sidestream alluvium. Colluvium (talus and slopewash) is a common Holocene deposit in moderate-to-high relief areas, and, like dune sand, which is found locally in the arid central plateau, it is not commonly preserved in the stratigraphic record.

Varying thicknesses of windblown silt (loess) mantle much of the Columbia Plateau. At least four different ages of loess are recognized (Richmond et al., 1965, pp. 231-242). Pleistocene to Holocene loess mantles much of the arid to semiarid central Columbia Plateau, although it is thickest (up to 70 m (229 ft)) in the Palouse Hills (see Section 1.1.2.2). Here, loess of middle Pleistocene age (125,000 to 175,000 yr B.P.) is included in the Palouse Formation (Rigby and Othberg, 1979, pp. 23-25). However, based on reversed magnetism of the lower Palouse section (Foley, 1982, p. 89), formation of the Palouse Hills probably began during the early Pleistocene (more than 790,000 yr B.P.).

Landslide deposits are of variable age and genesis. Most are associated with north limbs of Yakima folds or along steep river embankments such as the White Bluffs in the Pasco Basin (see Fig. 1.1-8).

1.2.2 STRATIGRAPHIC FRAMEWORK OF THE CONTROLLED AREA STUDY ZONE

This section provides a detailed description of the stratigraphic units within the controlled area study zone. Most of the discussion on basalt in this section is focused on flows within (1) the N_2 unit of the Grande Ronde Basalt, and (2) the Wanapum Basalt. These units form the repository isolation system. Particular emphasis is given to the Cohassett flow, the candidate horizon. Descriptions of units within the Saddle Mountains Basalt, basalt interbeds, and suprabasalt sediments within the controlled area study zone are also presented. The stratigraphic units within the controlled area study zone that have been penetrated by boring are shown in Figure 1.2-20.

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PERIOD	EPOCH	GROUP	SUBGROUP	FORMATION	MEMBER OR SEQUENCE	SEDIMENT STRATIGRAPHY OR BASALT FLOWS	UNIT THICKNESS RANGES (m)		
QUATERNARY	Holocene				SURFICIAL UNITS	LOESS; SAND DUNES; ALLUVIUM ALLUVIAL FANS; LANDSLIDE; TALUS; COLLUVIUM	<3[a]	BUFFER ZONE	DEFENSE WASTE PROGRAM OPERATIONS SYSTEM
QUATERNARY	Pleistocene			Hanford	TOUCHET BEDS / PASCO GRAVELS		≤5[a] / ≤64[a]	BUFFER ZONE	DEFENSE WASTE PROGRAM OPERATIONS SYSTEM
TERTIARY	Pliocene					PLIO-PLEISTOCENE UNIT	0-26[a]	BUFFER ZONE	DEFENSE WASTE PROGRAM OPERATIONS SYSTEM
TERTIARY	Miocene			Ringold		UPPER RINGOLD	0-33[a]	BUFFER ZONE	DEFENSE WASTE PROGRAM OPERATIONS SYSTEM
TERTIARY	Miocene			Ringold		MIDDLE RINGOLD	55-100[a]	BUFFER ZONE	DEFENSE WASTE PROGRAM OPERATIONS SYSTEM
TERTIARY	Miocene			Ringold		LOWER RINGOLD	0-17[a]	BUFFER ZONE	DEFENSE WASTE PROGRAM OPERATIONS SYSTEM
TERTIARY	Miocene			Ringold		BASAL RINGOLD	6-60[a]	BUFFER ZONE	DEFENSE WASTE PROGRAM OPERATIONS SYSTEM
TERTIARY	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Saddle Mountains Basalt	ELEPHANT MOUNTAIN MEMBER	ELEPHANT MOUNTAIN FLOW	0-39.0	BUFFER ZONE	DEFENSE WASTE PROGRAM OPERATIONS SYSTEM
TERTIARY	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Saddle Mountains Basalt	ELEPHANT MOUNTAIN MEMBER	RATTLESNAKE RIDGE INTERBED	0-34.4	BUFFER ZONE	DEFENSE WASTE PROGRAM OPERATIONS SYSTEM
TERTIARY	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Saddle Mountains Basalt	POMONA MEMBER	POMONA FLOW	0-59.0	BUFFER ZONE	DEFENSE WASTE PROGRAM OPERATIONS SYSTEM
TERTIARY	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Saddle Mountains Basalt	POMONA MEMBER	SELAH INTERBED	0-30.8	BUFFER ZONE	DEFENSE WASTE PROGRAM OPERATIONS SYSTEM
TERTIARY	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Saddle Mountains Basalt	ESQUATZEL MEMBER	GABLE MOUNTAIN FLOW	0-36.3	BUFFER ZONE	DEFENSE WASTE PROGRAM OPERATIONS SYSTEM
TERTIARY	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Saddle Mountains Basalt	ESQUATZEL MEMBER	COLD CREEK INTERBED	0-36.6	BUFFER ZONE	DEFENSE WASTE PROGRAM OPERATIONS SYSTEM
TERTIARY	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Saddle Mountains Basalt	UMATILLA MEMBER	SILLUSI FLOW (DISCONTINUOUS); UMATILLA FLOW	20.7-73.2	BUFFER ZONE	DEFENSE WASTE PROGRAM OPERATIONS SYSTEM
TERTIARY	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Saddle Mountains Basalt	UMATILLA MEMBER	MABTON INTERBED	25.6-51.8	BUFFER ZONE	DEFENSE WASTE PROGRAM OPERATIONS SYSTEM
TERTIARY	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Wanapum Basalt	PRIEST RAPIDS MEMBER	LOLO FLOW	39.3-55.2	UPPER SECONDARY ISOLATION ZONE	COMMERCIAL WASTE PROGRAM REPOSITORY ISOLATION ZONE
TERTIARY	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Wanapum Basalt	PRIEST RAPIDS MEMBER	ROSALIA FLOW	16.5-33.5	UPPER SECONDARY ISOLATION ZONE	COMMERCIAL WASTE PROGRAM REPOSITORY ISOLATION ZONE
TERTIARY	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Wanapum Basalt	PRIEST RAPIDS MEMBER	QUINCY INTERBED (DISCONTINUOUS)	0-0.5	UPPER SECONDARY ISOLATION ZONE	COMMERCIAL WASTE PROGRAM REPOSITORY ISOLATION ZONE
TERTIARY	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Wanapum Basalt	ROZA MEMBER	ROZA FLOW (2 COOLING UNITS)	42.1-59.4	UPPER SECONDARY ISOLATION ZONE	COMMERCIAL WASTE PROGRAM REPOSITORY ISOLATION ZONE
TERTIARY	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Wanapum Basalt	ROZA MEMBER	SQUAW CREEK INTERBED (DISCONTINUOUS)	0-0.9	UPPER SECONDARY ISOLATION ZONE	COMMERCIAL WASTE PROGRAM REPOSITORY ISOLATION ZONE
TERTIARY	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Wanapum Basalt	FRENCHMAN SPRINGS MEMBER	SENTINEL GAP FLOW	50.9-64.6	UPPER SECONDARY ISOLATION ZONE	COMMERCIAL WASTE PROGRAM REPOSITORY ISOLATION ZONE
TERTIARY	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Wanapum Basalt	FRENCHMAN SPRINGS MEMBER	SAND HOLLOW FLOWS (2 FLOWS)	32.6-64.4	UPPER SECONDARY ISOLATION ZONE	COMMERCIAL WASTE PROGRAM REPOSITORY ISOLATION ZONE
TERTIARY	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Wanapum Basalt	FRENCHMAN SPRINGS MEMBER	SILVER FALLS FLOWS (1 TO 3 FLOWS)	19.8-47.9	UPPER SECONDARY ISOLATION ZONE	COMMERCIAL WASTE PROGRAM REPOSITORY ISOLATION ZONE
TERTIARY	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Wanapum Basalt	FRENCHMAN SPRINGS MEMBER	GINKGO FLOWS (2-3 FLOWS)	68.0-100.9	UPPER SECONDARY ISOLATION ZONE	COMMERCIAL WASTE PROGRAM REPOSITORY ISOLATION ZONE
TERTIARY	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Wanapum Basalt	FRENCHMAN SPRINGS MEMBER	UNNAMED INTERBED (DISCONTINUOUS)	0-3.7	UPPER SECONDARY ISOLATION ZONE	COMMERCIAL WASTE PROGRAM REPOSITORY ISOLATION ZONE
TERTIARY	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Wanapum Basalt	FRENCHMAN SPRINGS MEMBER	PALOUSE FALLS FLOW	9.1-25.0	UPPER SECONDARY ISOLATION ZONE	COMMERCIAL WASTE PROGRAM REPOSITORY ISOLATION ZONE
TERTIARY	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Wanapum Basalt	FRENCHMAN SPRINGS MEMBER	VANTAGE INTERBED	0-9.1	UPPER SECONDARY ISOLATION ZONE	COMMERCIAL WASTE PROGRAM REPOSITORY ISOLATION ZONE
TERTIARY	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Grande Ronde Basalt	SENTINEL BLUFFS SEQUENCE	FLOW 1	5.3-25.6	PRIMARY ISOLATION ZONE	COMMERCIAL WASTE PROGRAM REPOSITORY ISOLATION ZONE
TERTIARY	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Grande Ronde Basalt	SENTINEL BLUFFS SEQUENCE	FLOW 2	15.9-34.9	PRIMARY ISOLATION ZONE	COMMERCIAL WASTE PROGRAM REPOSITORY ISOLATION ZONE
TERTIARY	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Grande Ronde Basalt	SENTINEL BLUFFS SEQUENCE	ROCKY COULEE FLOW	40.2-57.0	PRIMARY ISOLATION ZONE	COMMERCIAL WASTE PROGRAM REPOSITORY ISOLATION ZONE
TERTIARY	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Grande Ronde Basalt	SENTINEL BLUFFS SEQUENCE	LEVERING FLOW (DISCONTINUOUS)	0-28.0	PRIMARY ISOLATION ZONE	COMMERCIAL WASTE PROGRAM REPOSITORY ISOLATION ZONE
TERTIARY	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Grande Ronde Basalt	SENTINEL BLUFFS SEQUENCE	COHASSETT FLOW	65.8-81.4	PRIMARY ISOLATION ZONE	COMMERCIAL WASTE PROGRAM REPOSITORY ISOLATION ZONE
TERTIARY	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Grande Ronde Basalt	SENTINEL BLUFFS SEQUENCE	BIRKETT FLOW	34.7-43.3	PRIMARY ISOLATION ZONE	COMMERCIAL WASTE PROGRAM REPOSITORY ISOLATION ZONE
TERTIARY	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Grande Ronde Basalt	SENTINEL BLUFFS SEQUENCE	FLOW 7	9.0-18.2	PRIMARY ISOLATION ZONE	COMMERCIAL WASTE PROGRAM REPOSITORY ISOLATION ZONE
TERTIARY	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Grande Ronde Basalt	SENTINEL BLUFFS SEQUENCE	FLOW 8	11.6-24.4	PRIMARY ISOLATION ZONE	COMMERCIAL WASTE PROGRAM REPOSITORY ISOLATION ZONE
TERTIARY	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Grande Ronde Basalt	SENTINEL BLUFFS SEQUENCE	McCOY CANYON FLOW	32.3-45.0	PRIMARY ISOLATION ZONE	COMMERCIAL WASTE PROGRAM REPOSITORY ISOLATION ZONE
TERTIARY	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Grande Ronde Basalt	SCHWANA SEQUENCE	UMTANUM FLOW	60.5-75.0	PRIMARY ISOLATION ZONE	COMMERCIAL WASTE PROGRAM REPOSITORY ISOLATION ZONE
TERTIARY	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Grande Ronde Basalt	SCHWANA SEQUENCE	VERY HIGH-Mg FLOW	0-22.5	LOWER SECONDARY ISOLATION ZONE	COMMERCIAL WASTE PROGRAM REPOSITORY ISOLATION ZONE
TERTIARY	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Grande Ronde Basalt	SCHWANA SEQUENCE	AT LEAST 3 FLOWS[b]	93.5[a]	LOWER SECONDARY ISOLATION ZONE	COMMERCIAL WASTE PROGRAM REPOSITORY ISOLATION ZONE
TERTIARY	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Grande Ronde Basalt		N_2-R_2 PALEOMAGNETIC CONTACT GREATER THAN 10 FLOWS	>1,750 TO BASE OF BASALT	LOWER SECONDARY ISOLATION ZONE	COMMERCIAL WASTE PROGRAM REPOSITORY ISOLATION ZONE

ELLENSBURG FORMATION

NOTE: TO CONVERT METERS TO FEET, MULTIPLY BY 3.28
[a]THICKNESS RANGE FOR THE REFERENCE REPOSITORY LOCATION ONLY.
[b]VALUE IS A MINIMUM ONLY (ONLY ONE BOREHOLE PENETRATED TO BASE OF LOWER BUFFER ZONE).

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Figure 1.2-20. Stratigraphic units found within the controlled area study zone. This figure shows greater detail for the Sentinel Bluffs sequence than Figure 1.2-3.

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1.2.2.1 Columbia River Basalt Group rocks at the controlled area study zone

Within the controlled area study zone, three formations of the Columbia River Basalt Group have been penetrated: Grande Ronde, Wanapum, and Saddle Mountains Basalts (see Fig. 1.2-20). The Imnaha and Picture Gorge Basalts of the Columbia River Basalt Group have not been penetrated within the controlled area study zone and are not expected to be present due to their limited distributions to the south and southeast (see Fig. 1.2-2b and 1.2-2c).

Previous reports, which present stratigraphic and lithologic data on Columbia River basalt and interbedded sediments for the controlled area study zone are Myers/Price et al. (1979, pp. III-1 to III-103), Reidel and Fecht (1981, pp. 3-1 to 3-45), Long and Landon (1981, pp. 4-1 to 4-45), Long and Davidson (1981, pp. 5-1 to 5-55), Moak (1981, pp. 6-1 to 6-17), Long and WCC (1984, pp. I-12 to I-43).

Correlations of flows are based on physical, chemical, and paleomagnetic properties and on their stratigraphic position and thickness (Reidel and Fecht, 1981, pp. 3-1 to 3-45; Long and Landon, 1981, pp. 4-1 to 4-45). Although general information on stratigraphic position and flow thickness is not as definitive as that obtained using the other analytical techniques, these parameters are useful for correlating between closely spaced boreholes (less than approximately 10 km (6.2 mi)). Chemical and paleomagnetic properties of basalt have been found to provide the most reliable means to support both regional and local correlations (Swanson et al., 1979a, p. G19; Long and Landon, 1981, p. 4-2).

Geophysical logs also are used in the development of the stratigraphy. Typical geophysical log responses are shown in Figure 1.2-21. While geophysical log responses generally do not provide definitive correlatable signatures for individual basalt flows or interbeds, they are used to obtain unit contacts and intraflow structure characteristics. They are also used to correlate flows between rotary-drilled boreholes from which drill core is not obtained.

1.2.2.1.1 Grande Ronde Basalt

The Grande Ronde Basalt is of primary stratigraphic importance to the BWIP because it contains the Cohassett flow (the candidate horizon for a basalt mined geologic disposal system at the Hanford Site) and the primary isolation zone. During the horizon identification study (Long and WCC, 1984), basalt flows were evaluated and ranked on the basis of depth, thickness, intraflow structure, fracture characteristics, bulk chemical composition, mineralogy, and petrography. Five boreholes within the reference repository location (RRL-2, -6, and -14; DC-3 and -4) (see Fig. 1.2-7), which were available at the time of the study, were used for the evaluation. Much of the Grande Ronde Basalt data discussed in this section have been derived from this study. A more regional discussion of Grande Ronde Basalt is contained in Section 1.2.1.2.1.3.

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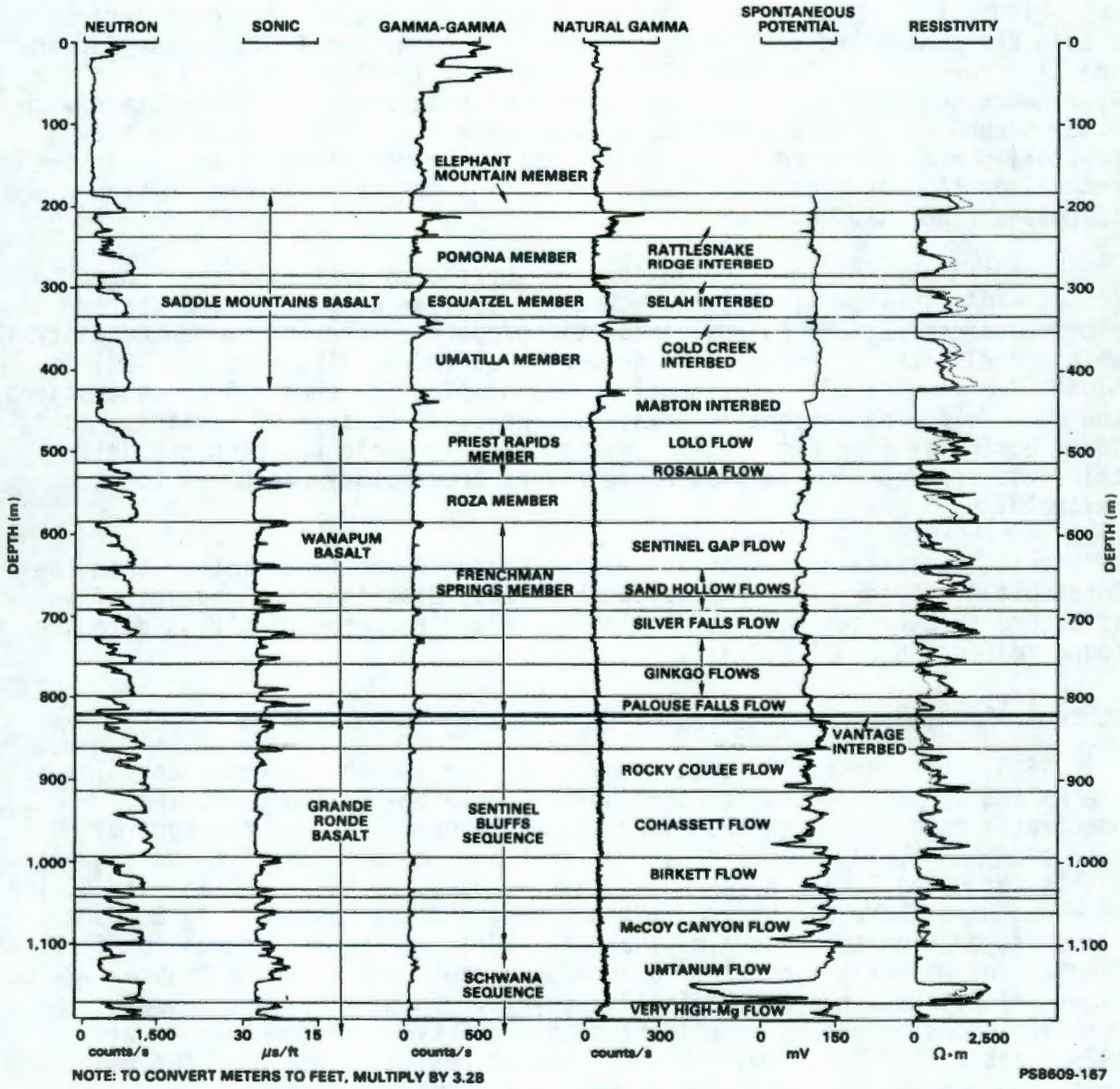

Figure 1.2-21. Example borehole geophysical logs for borehole RRL-2A.

Stratigraphically, within the controlled area study zone, the Grande Ronde Basalt contains the Schwana and the Sentinel Bluffs sequences (see Fig. 1.2-20). The thickness of the Grande Ronde Basalt is estimated to be in excess of 3,050 m (10,006 ft), based on data from Berkman et al. (1986).

Figure 1.2-22 is a fence diagram showing individual flow correlations within the controlled area study zone for the upper two flows of the Schwana and all flows of the Sentinel Bluffs sequence. The lower four flows of the N_2 Schwana sequence are not shown because of uncertainty of correlation with other boreholes (only 1 borehole, DC-16A, penetrates these flows in the controlled area study zone). Isopach maps of Grande Ronde flows within the central portion of the controlled area study zone are presented in Landon and Bjornstad (1986, Appendix C).

Uncertainty in flow correlations for boreholes that have been cored (DC-4, -16A; RRL-2, -6; -14, and McGee) is low, as both major and trace element concentrations and paleomagnetic properties are known. Uncertainty in unit correlations in rotary drilled boreholes (DC-3, -19, -20, and -22) is higher due to lack of representative chip samples for chemical concentrations and no core for paleomagnetic analysis. However, because of proximity to cored boreholes (see Fig. 1.2-7), use of stratigraphic position and unit thickness enables flow-to-flow correlations from rotary boreholes to be reliable.

Detailed descriptions of individual Grande Ronde flows (other than the Cohassett flow) for other than flow thickness, distribution, and intraflow structure thicknesses are not available. Plans for acquiring this data are found in Section 8.3.1.2.3.3.1.

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Schwana Sequence

Within the controlled area study zone, the Schwana sequence contains both the R_2 and N_2 magnetostratigraphic units. Only one borehole (DC-16A) penetrates into the upper two flows of the R_2 unit. Within the controlled area study zone, five flows of the N_2 unit are found in the Schwana sequence. Within the Pasco Basin, seven boreholes (DC-6, DC-7, DC-12, DC-15, and DC-16A; DH-4 and DH-5) have penetrated this horizon, and the number of N_2 Schwana flows ranged from three to nine (Landon, 1985). Thickness ranges for flows of the Schwana within the controlled area study zone are shown on Figure 1.2-20. Flows of this sequence are typically aphyric. Chemically this sequence contains flows belonging to all three chemical types of (Swanson et al., 1979b, Table 2)--high, low, and very-high magnesium. The upper two flows of this sequence are the very-high magnesium and Umtanum flows.

Sentinel Bluffs Sequence

The Sentinel Bluffs sequence within the controlled area study zone contains eight to nine flows (Landon and Bjornstad, 1986, Table 2), all of the high magnesium chemical type of Swanson et al. (1979b, Table 2). The Sentinel Bluffs sequence contains the Cohassett flow, which is the proposed repository

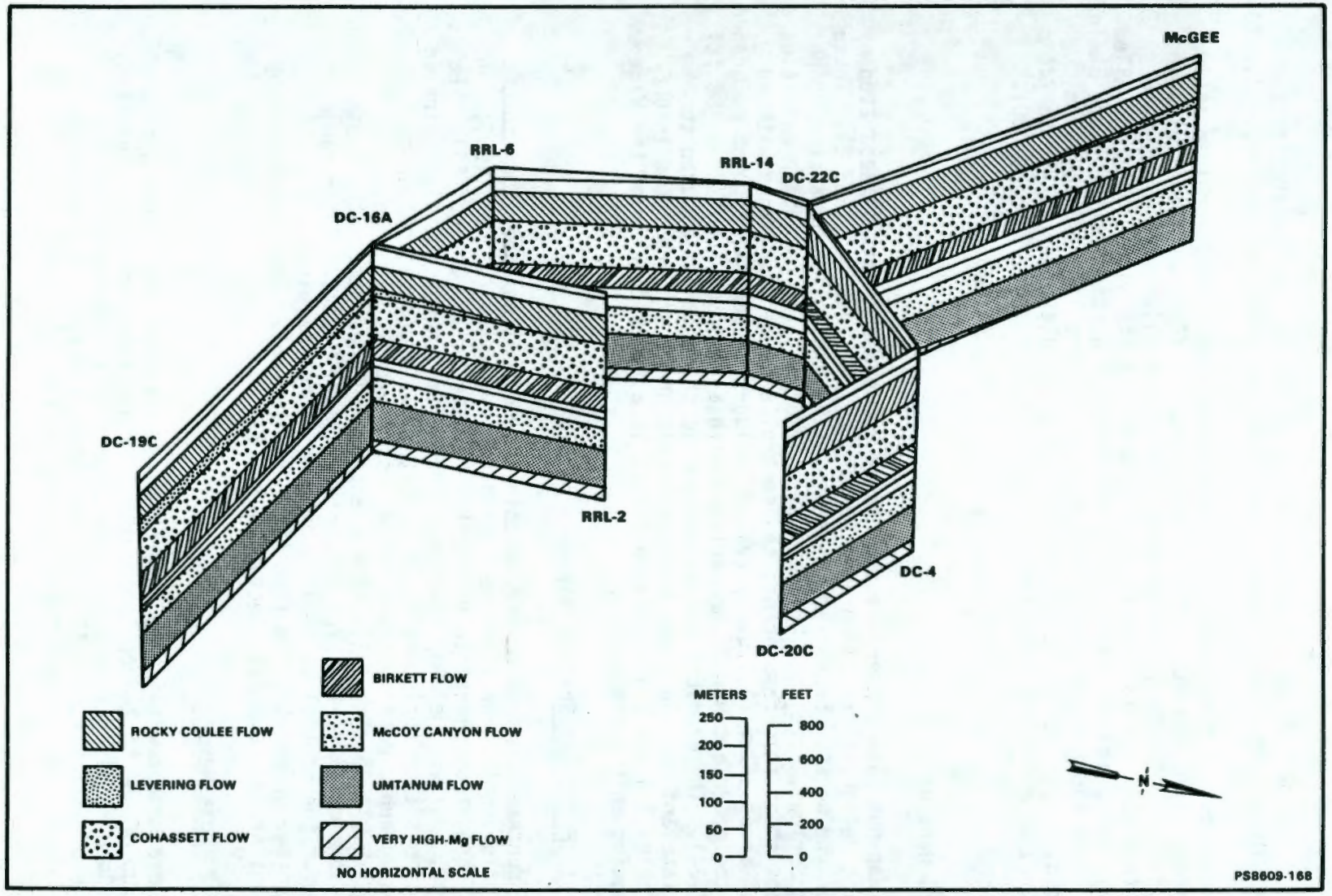

Figure 1.2-22. Fence diagram of the Grande Ronde Basalt in the controlled area study zone. Figure shows only flow correlations and does not illustrate geologic structure. (See Fig. 1.2-7 for borehole locations.)

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horizon. All flows of this sequence belong to the N_2 magnetostratigrahic unit. Thickness ranges for flows of this sequence are shown on Figure 1.2-20.

Correlations of the Cohassett flow are based on stratigraphic position and thickness (Long and WCC, 1984). The Cohassett flow, as illustrated in Figure 1.2-23, is thickest in the area of the controlled area study zone (ranging from approximately 66 to 81 m (216 to 267 ft) within the controlled area study zone), and it thins in the southeastern portion of the Pasco Basin. The top of the flow in the controlled area study zone lies 671 to 943 m (2,200 to 3,093 ft) below the ground surface at an elevation of 416 to 746 m (1,365 to 2,447 ft) below sea level (Landon and Bjornstad, 1986, p. 30).

1.2.2.1.2 Wanapum Basalt

The Wanapum Basalt overlies the Grande Ronde Basalt and is separated by the Vantage Member of the Ellensburg Formation (see Section 1.2.3.2). Three members of the Wanapum Basalt are present in the controlled area study zone: Frenchman Springs, Roza, and Priest Rapids Members. The formation maintains a fairly consistent thickness across the controlled area study zone with an average of about 357 m (1,170 ft) (value includes interbeds from top of Grande Ronde to top of Priest Rapids Member) and with a range of about 26 m (86 ft) (Fig. 1.2-24). The chemical and paleomagnetic characteristics used to differentiate and correlate the Wanapum Basalt units are presented in DOE (1986a, Tables 3-3 and 3-4). Figure 1.2-25 is a fence diagram of the Wanapum Basalt showing unit correlations.

1.2.2.1.2.1 Frenchman Springs Member

The Frenchman Springs Member, within the controlled area study zone, consists of seven to nine flows belonging to five units (Landon, 1985). The five units are, from oldest to youngest: Palouse Falls, Ginkgo, Silver Falls, Sand Hollow, and Sentinel Gap basalts. These five groups are discriminated by chemical composition (principally Cr, P_2O_5, TiO_2, and MgO); paleomagnetic data; stratigraphic position; and, to a lesser extent, lithology (Beeson et al., 1985, Table 1). The Frenchman Springs Member thickness variation is similar to that for the total Wanapum Basalt. Total range of thickness for the controlled area study zone is approximately 16 m (53 ft) with an average of about 233 m (766 ft) (Fig. 1.2-26). Detailed mineralogic descriptions are discussed in Section 4.1.1.3.

1.2.2.1.2.2 Roza Member

The Roza Member within the controlled area study zone consists of one flow made up of one to two cooling units. Within the controlled area study zone, the Roza Member has an average thickness of approximately 52 m (172 ft) and a range of approximately 17 m (57 ft) (Fig. 1.2-27). The member is characterized by large plagioclase phenocrysts (up to 1.5 cm (0.6 in.))

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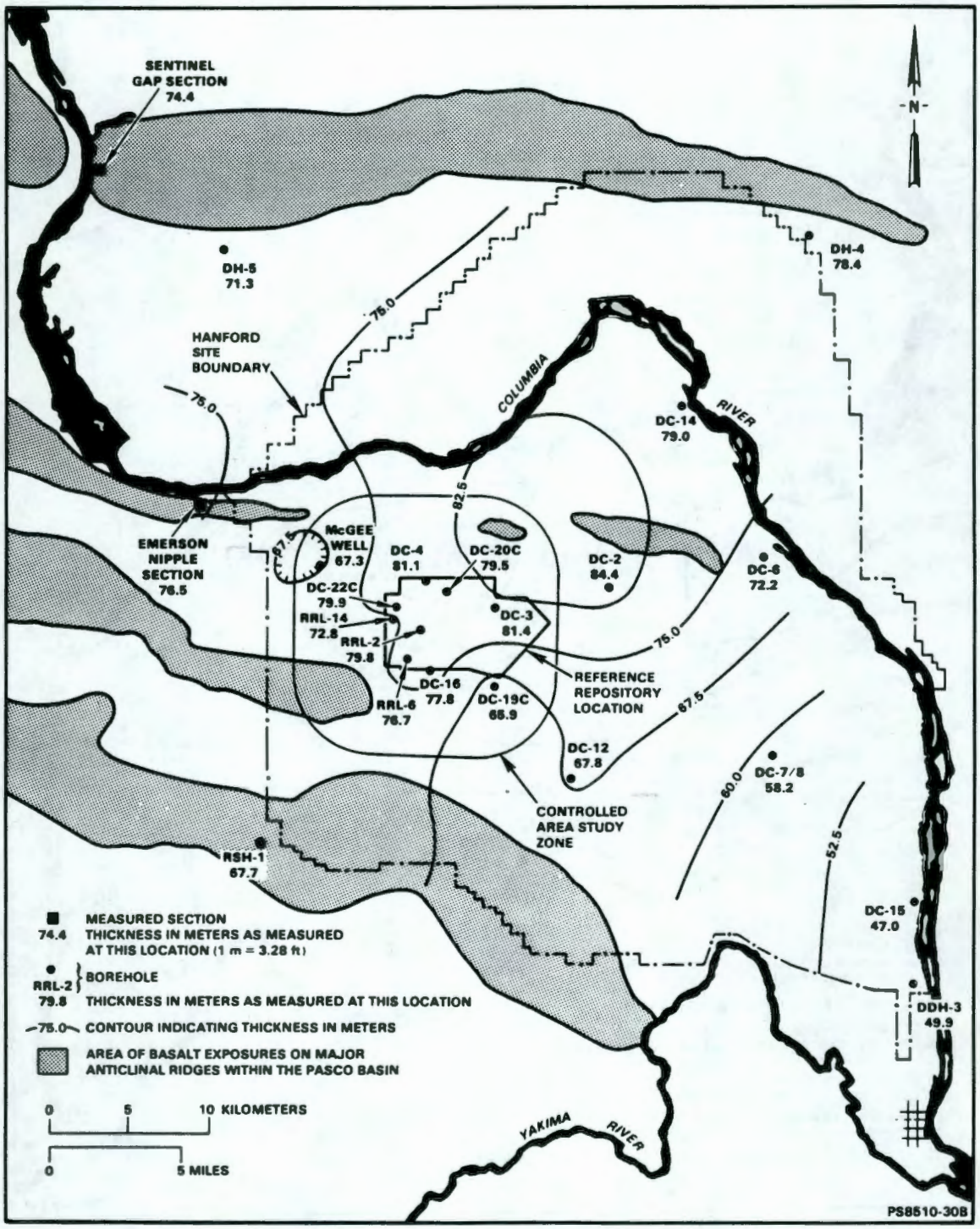

Figure 1.2-23. Isopach map of the Cohassett flow.

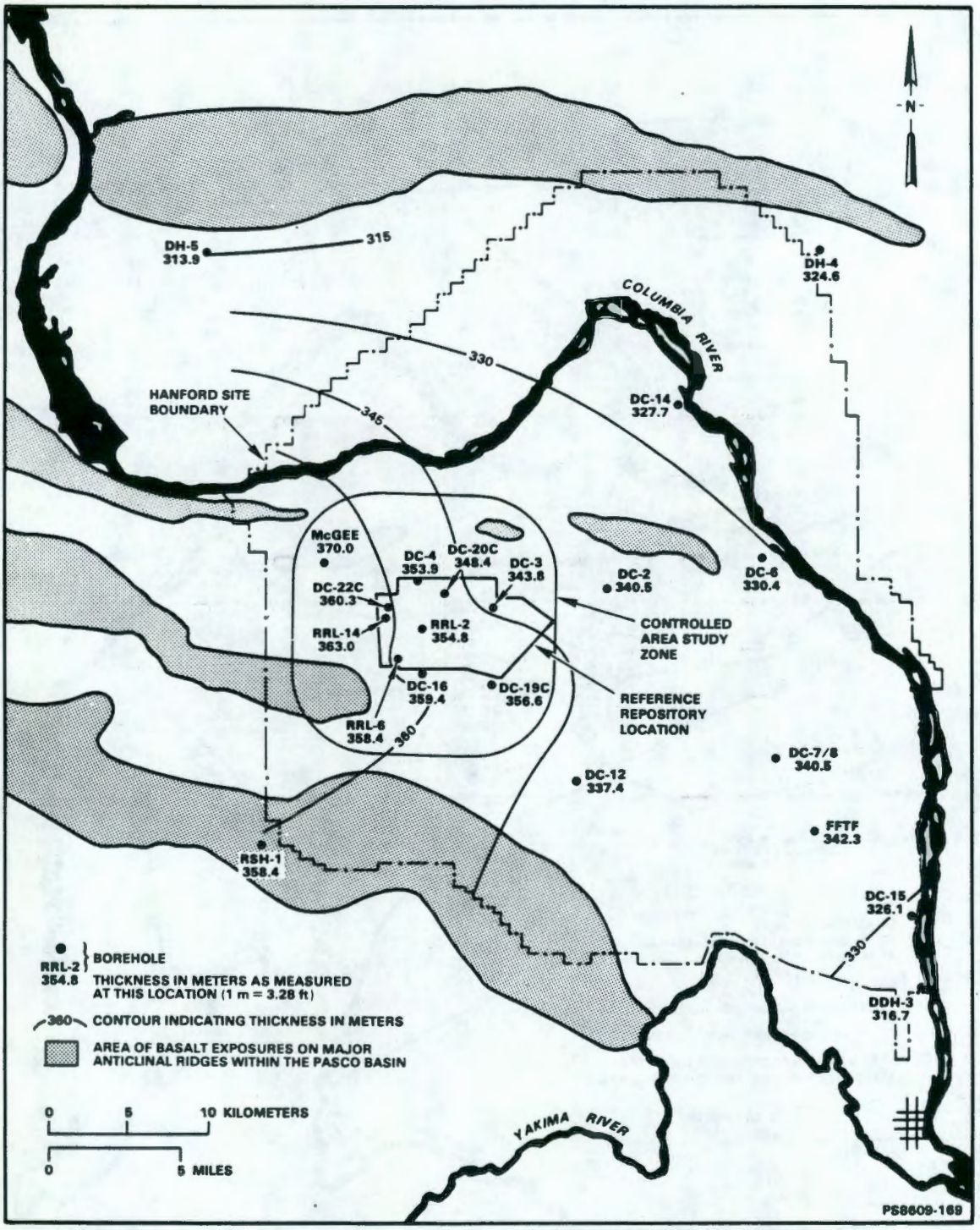

Figure 1.2-24. Isopach map of the Wanapum Basalt.

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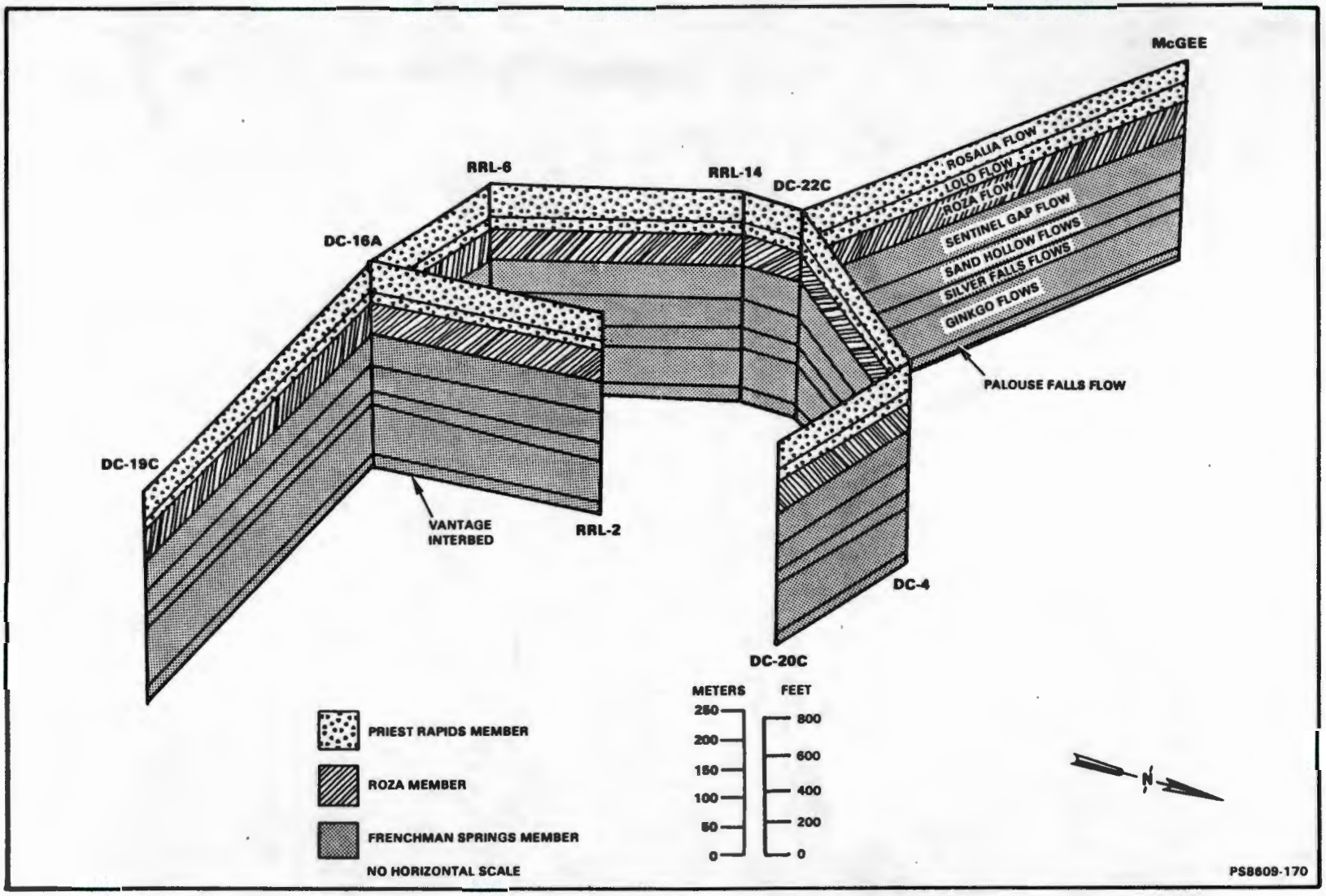

Figure 1.2-25. Fence diagram of the Wanapum Basalt in the controlled area study zone. Figure shows only flow correlations and does not illustrate geologic structure. (See Fig. 1.2-7 for borehole locations.)

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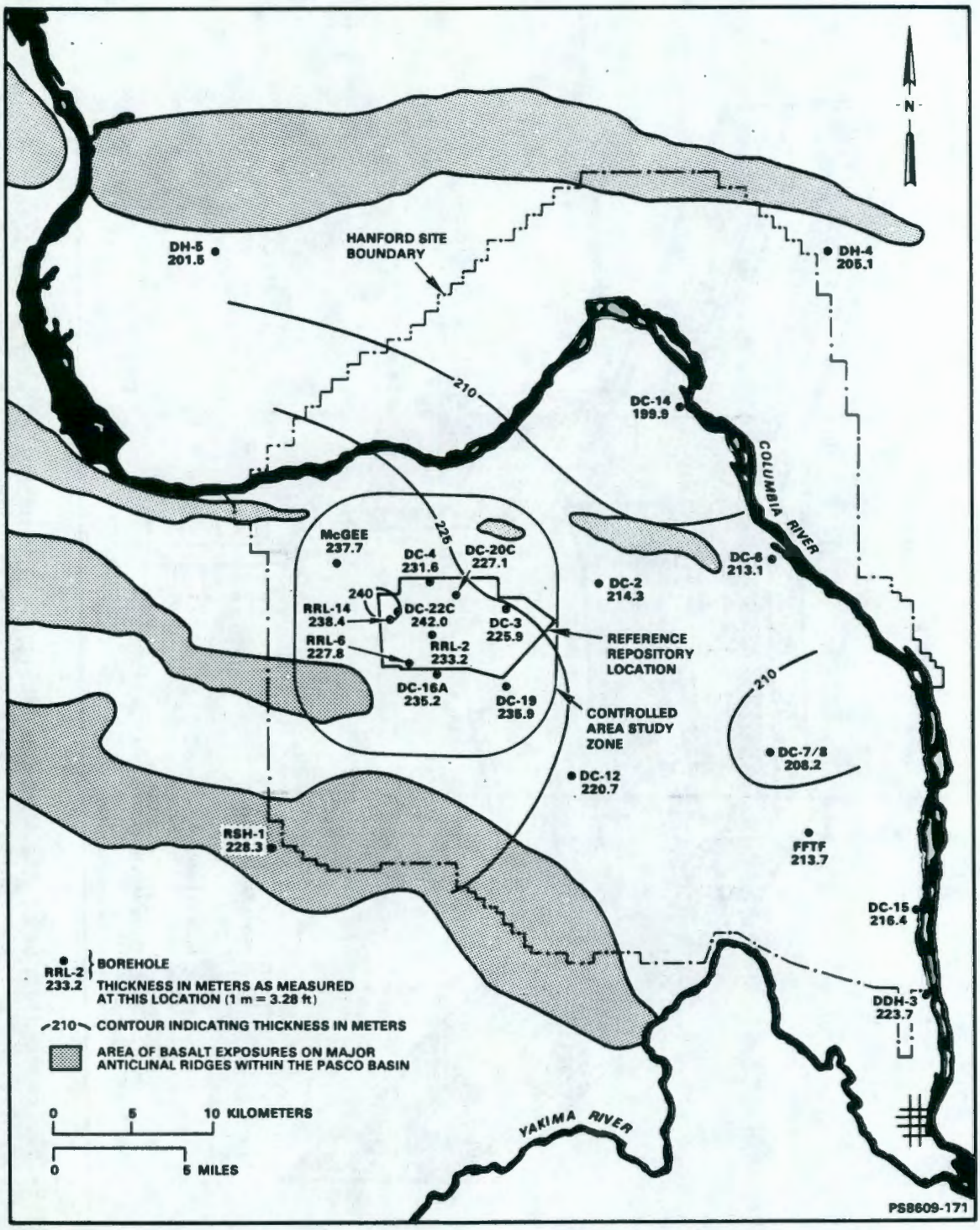

Figure 1.2-26. Isopach map of the Frenchman Springs Member.

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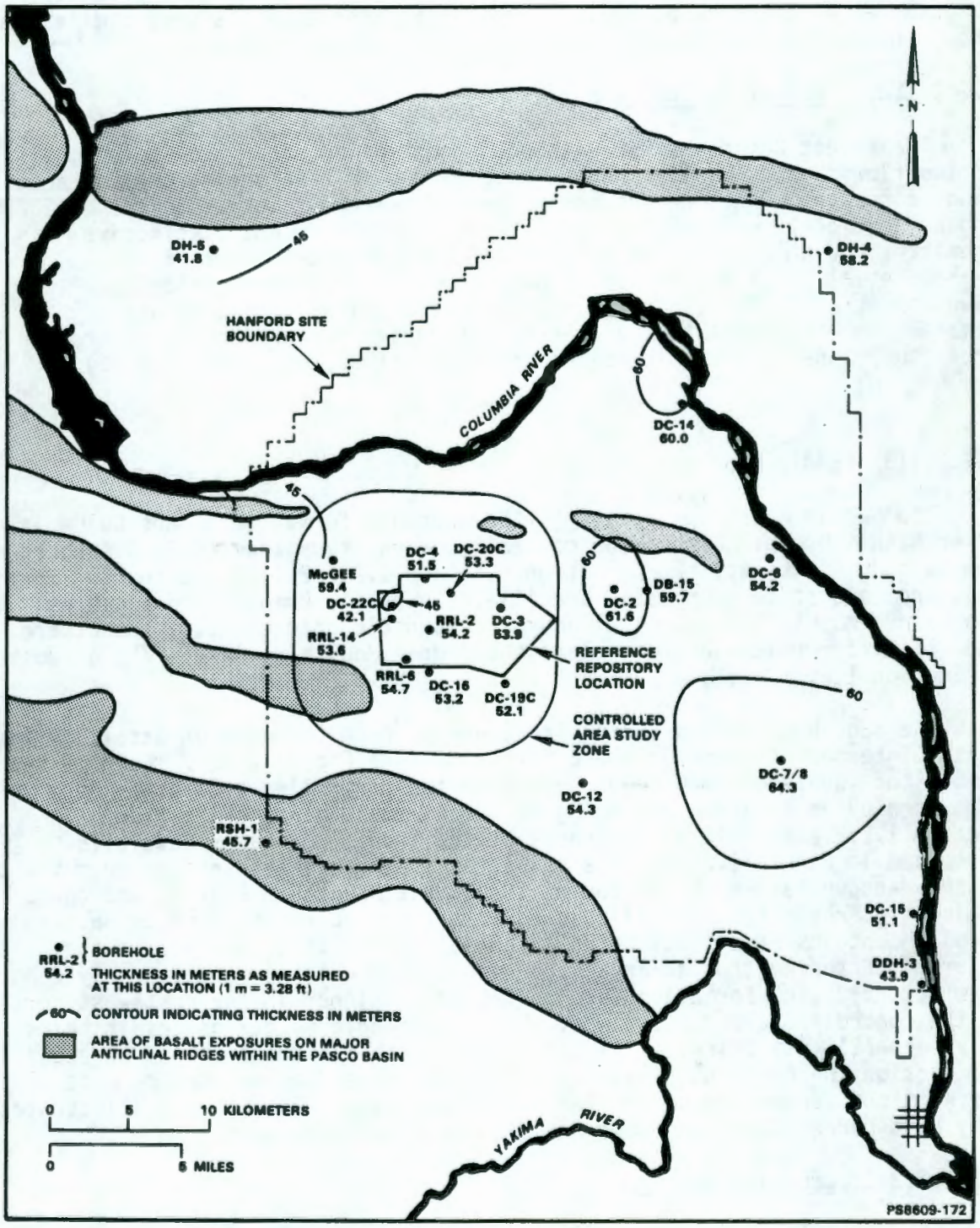

Figure 1.2-27. Isopach map of the Roza Member.

(Reidel and Fecht, 1981 p. 3-11) and transitional paleomagnetic polarity (Swanson et al., 1979a, p. G34). Chemically, the member is very similar to the Frenchman Springs Member (Swanson et al., 1979a, p. G34).

1.2.2.1.2.3 Priest Rapids Member

The Priest Rapids Member within the controlled area study zone consists of two flows: the Rosalia and the Lolo flows. Within the controlled area study zone, the Priest Rapids member has an average thickness of 71 m (232 ft) and a range of 12 m (40 ft) (Fig. 1.2-28). Each flow has distinctive chemistry and belongs to the Rosalia and Lolo chemical types of Swanson et al., (1979a, p. G37). Both flows have reversed polarity (Swanson et al., 1979a, p. G37), and both are sparsely plagioclase phyric. A more complete description of the Priest Rapids Member for the controlled area study zone is given in Reidel and Fecht (1981, pp. 3-13 to 3-16).

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1.2.2.1.3 Saddle Mountains Basalt

The Saddle Mountains Basalt is the youngest formation of the Columbia River Basalt Group. Within the controlled area study zone, only 4 members of the 14 that constitute the formation (Section 1.2.1.2.1.5) are found. They are, from oldest to youngest: Umatilla, Esquatzel, Pomona, and Elephant Mountain Members. The chemical and paleomagnetic characteristics that are used to differentiate and correlate the Saddle Mountains Basalt are discussed in Section 1.2.1.2.1.5.

The Saddle Mountains Basalt is separated from the Wanapum Basalt by the Mabton Interbed of the Ellensburg Formation (see Fig. 1.2-20). Each of the members of the Saddle Mountains Basalt in the controlled area study zone is separated by an interbed belonging to the Ellensburg Formation (see Section 1.2.2.2.1). Total thickness of the Saddle Mountains Basalt is presented in Figure 1.2-29. The values used here are thicknesses from the top of the Wanapum Basalt to the top of the Saddle Mountains Basalt, and thus, include interbeds from the Ellensburg Formation. Like the Wanapum Basalt, Saddle Mountains Basalt maintains a fairly uniform thickness across the majority of the controlled area study zone, with a total range of only about 19 m (62 ft). The formation is significantly thinner in the northwest portion of the controlled area study zone, where the Saddle Mountains Basalt thins to only 64 m (211 ft) thick. This thinning is probably due to both nondeposition and erosion in the area. Figure 1.2-30 is a fence diagram showing unit correlations across the controlled area study zone. This figure illustrates only unit correlations and does not display structure.

1.2.2.1.3.1 Umatilla Member

The Umatilla Member is the lowermost member of the Saddle Mountains Basalt. Within the controlled area study zone, it consists of one to two (Umatilla and Sillusi) flows and has an average thickness of 68 m (223 ft) with a range of 39 m (127 ft) (Fig. 1.2-31), except in the northwest corner of

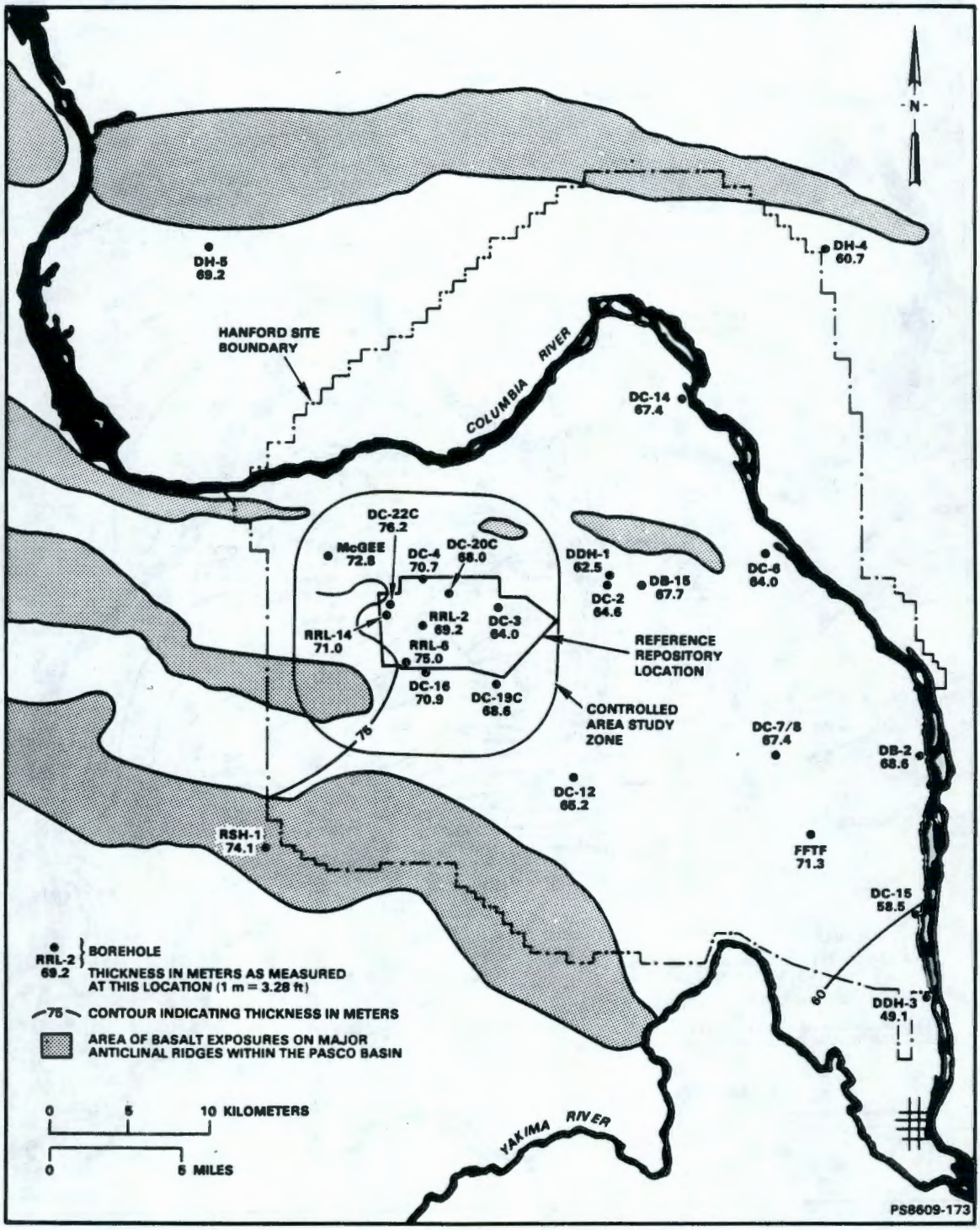

Figure 1.2-28. Isopach map of the Priest Rapids Member.

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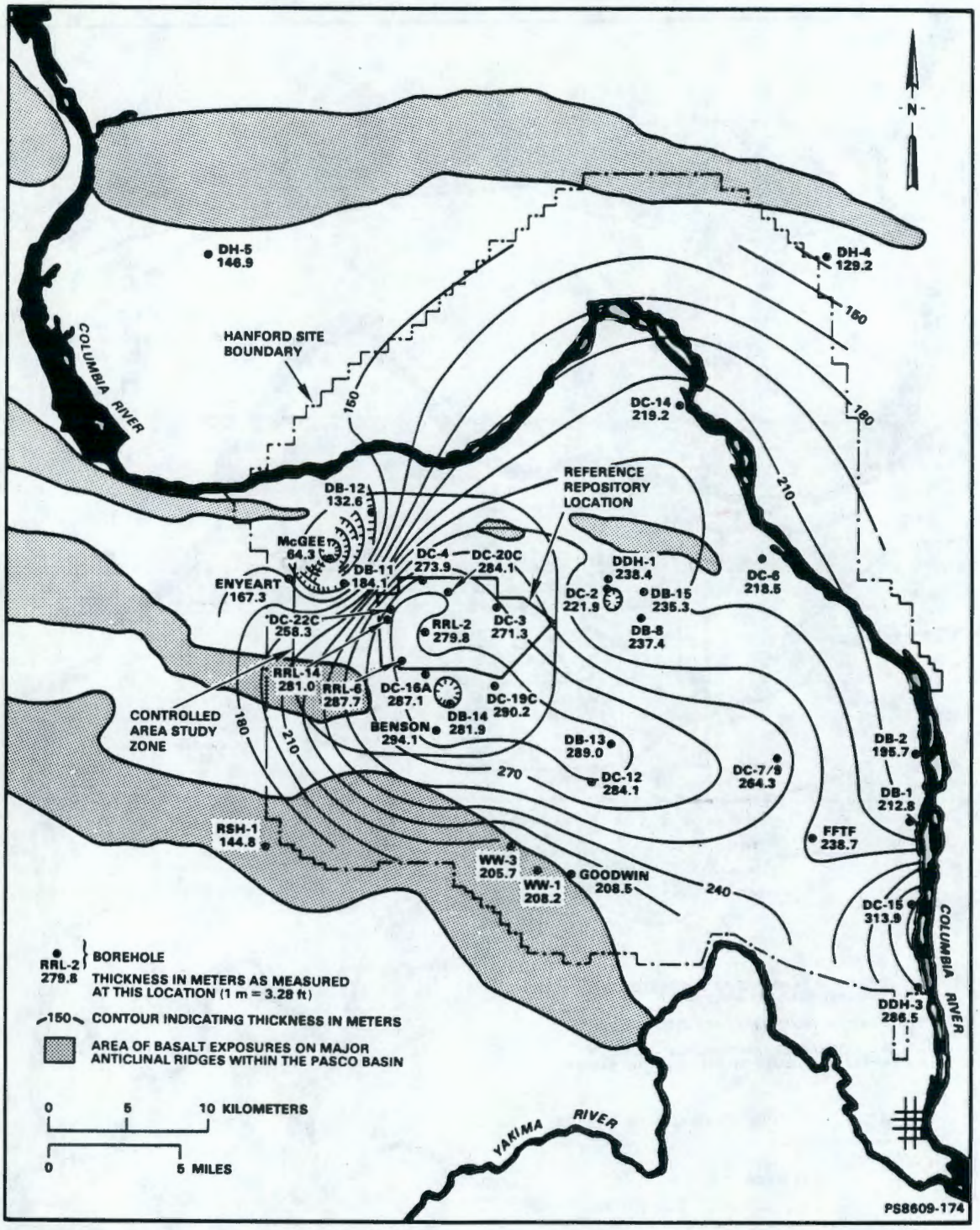

Figure 1.2-29. Isopach map of the Saddle Mountains Basalt.

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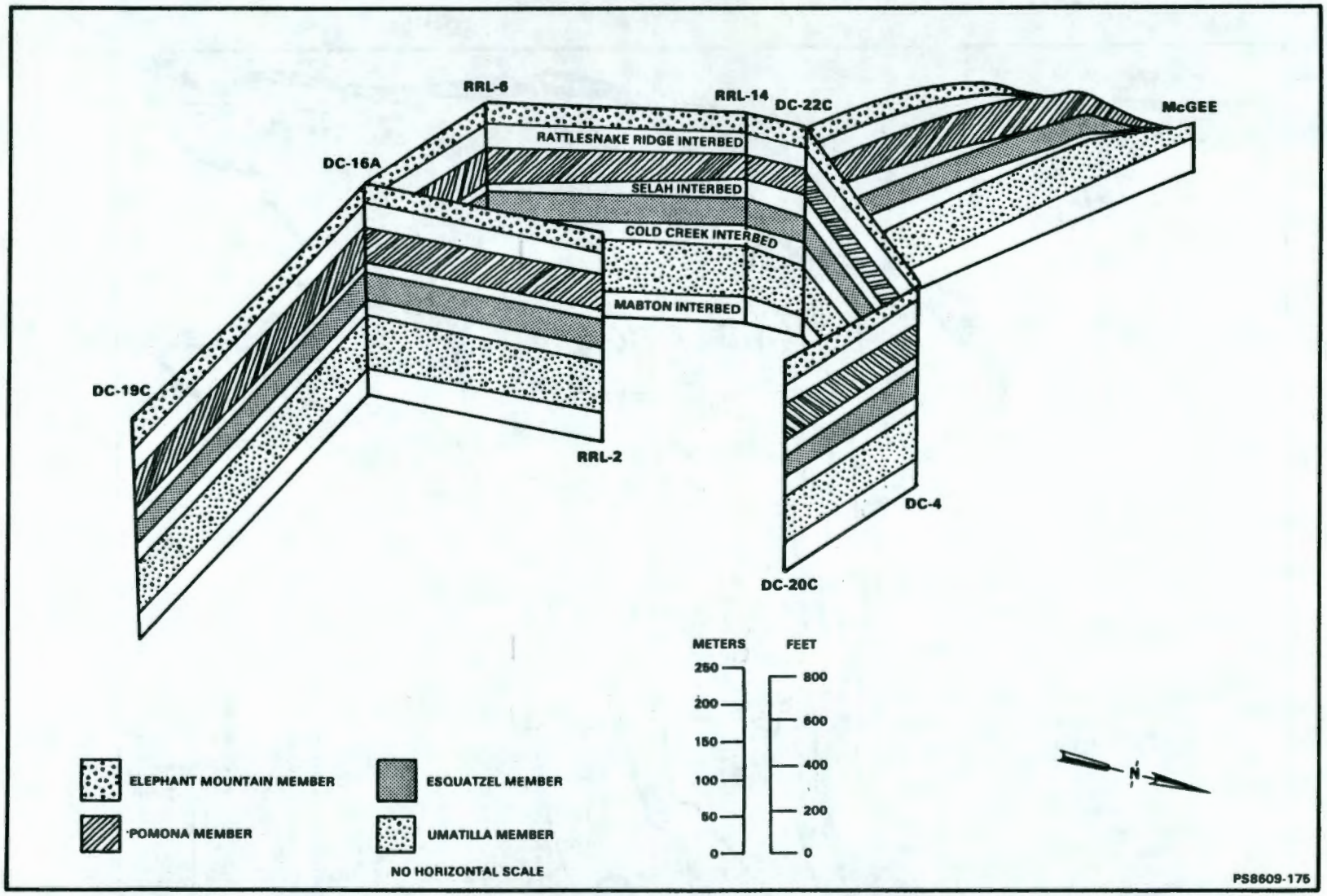

Figure 1.2-30. Fence diagram of the Saddle Mountains Basalt in the controlled area study zone. Figure shows only flow correlations and does not illustrate geologic structure. (See Fig. 1.2-7 for borehole locations.)

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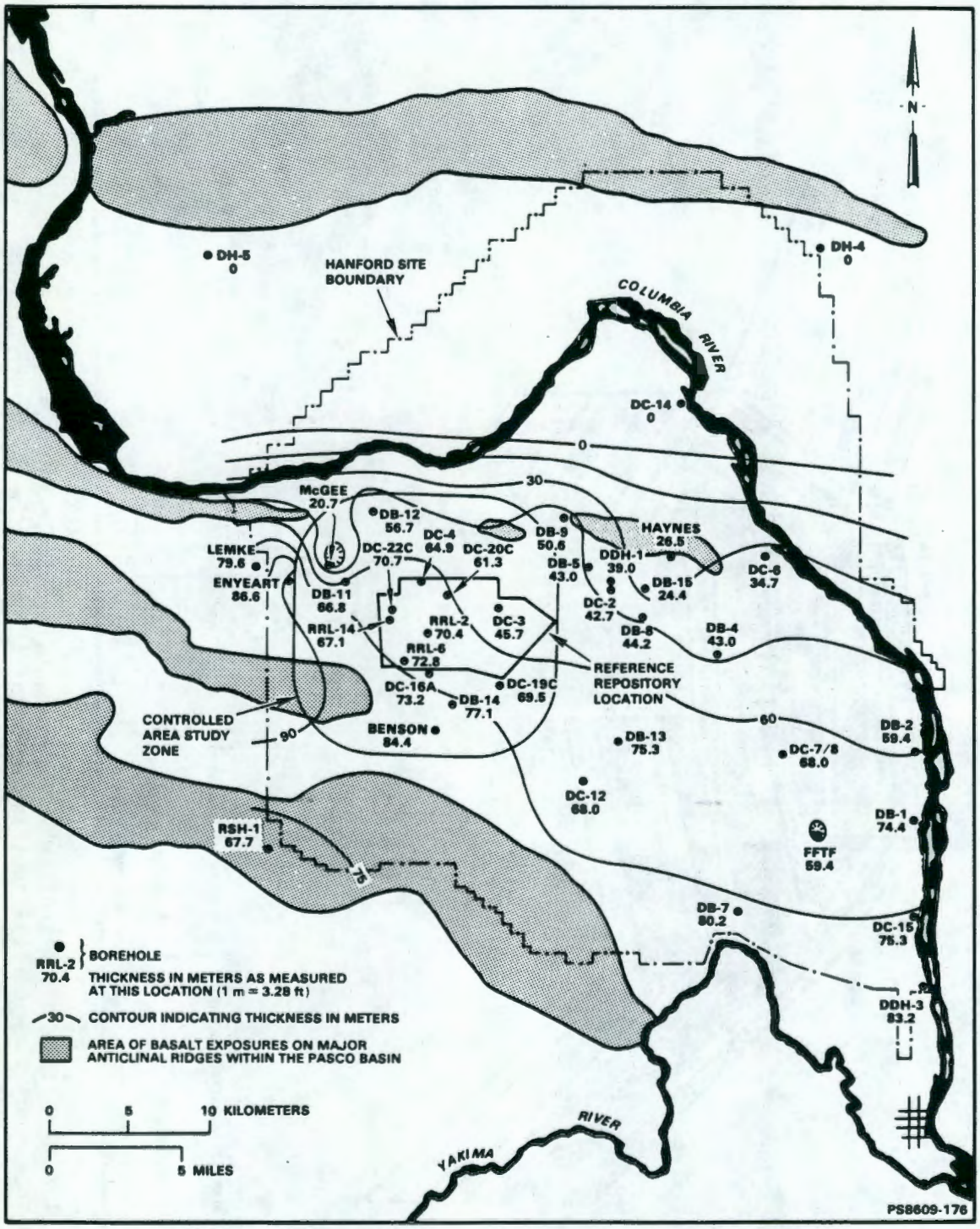

Figure 1.2-31. Isopach map of the Umatilla Member.

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the controlled area study zone at McGee borehole, where the member is only 21 m (68 ft) thick. This unit belongs to the Umatilla chemical type of Wright et al. (1973, p. 377). Magnetically this unit has normal polarity (see Fig. 1.2-1). The unit is fine-grained with very sparse plagioclase phenocrysts and often has a glassy appearance.

1.2.2.1.3.2 Esquatzel Member

The Esquatzel Member lies above the Umatilla Member and is separated from it by the Cold Creek Interbed of the Ellensburg Formation. The member is identified by its chemical composition (Swanson et al., 1979a, Table 2). The flow consists of one flow in the controlled area study zone and has an average thickness of 32 m (105 ft) and a range of 14 m (47 ft) (Fig. 1.2-32). The flow is absent in the northwest portion of the controlled area study zone due to its emplacement onto the developing Umtanum Ridge Structure (Reidel and Fecht, 1981, pp. 3-24). The Esquatzel Member is of normal paleomagnetic polarity (see Fig. 1.2-1) with a fine-grained, sparsely plagioclase-phyric texture.

1.2.2.1.3.3 Pomona Member

The Pomona Member overlies the Esquatzel Member and is separated from it by the Selah interbed of the Ellensburg Formation. The Pomona Member consists of a single flow in the controlled area study zone and has an average thickness of 43 m (142 ft) with a range of 22 m (73 ft) (Fig. 1.2-33). The flow is absent in the northwest corner of the controlled area study zone due to nondeposition or to erosion. The member is recognized on the basis of chemical composition (Pomona chemical type) (Wright et al., 1973 pp. 371-385); reversed paleomagnetic polarity (see Fig. 1.2-1); and fine-grained, plagioclase-phyric texture.

1.2.2.1.3.4 Elephant Mountain Member

The Elephant Mountain Member is the uppermost Columbia River basalt unit in the controlled area study zone and consists of a single flow. Across the controlled area study zone, the flow, where present, has an average thickness of 28 m (91 ft) with a range of 20 m (67 ft) (Fig. 1.2-34). The member thins to the northwest and is absent in the northwest portion of the controlled area study zone. This flow is medium- to fine-grained with abundant microphenocrysts of plagioclase. The composition of the flow falls into the Elephant Mountain chemical type of Wright et al. (1973, pp. 371-385). This flow has reversed magnetic polarity (see Fig. 1.2-1).

1.2.2.1.4 Intraflow structures at the controlled area study zone

As discussed previously in Section 1.2.1.2.2, intraflow structures are internal macroscopic features of a basalt flow. They include flow-top,

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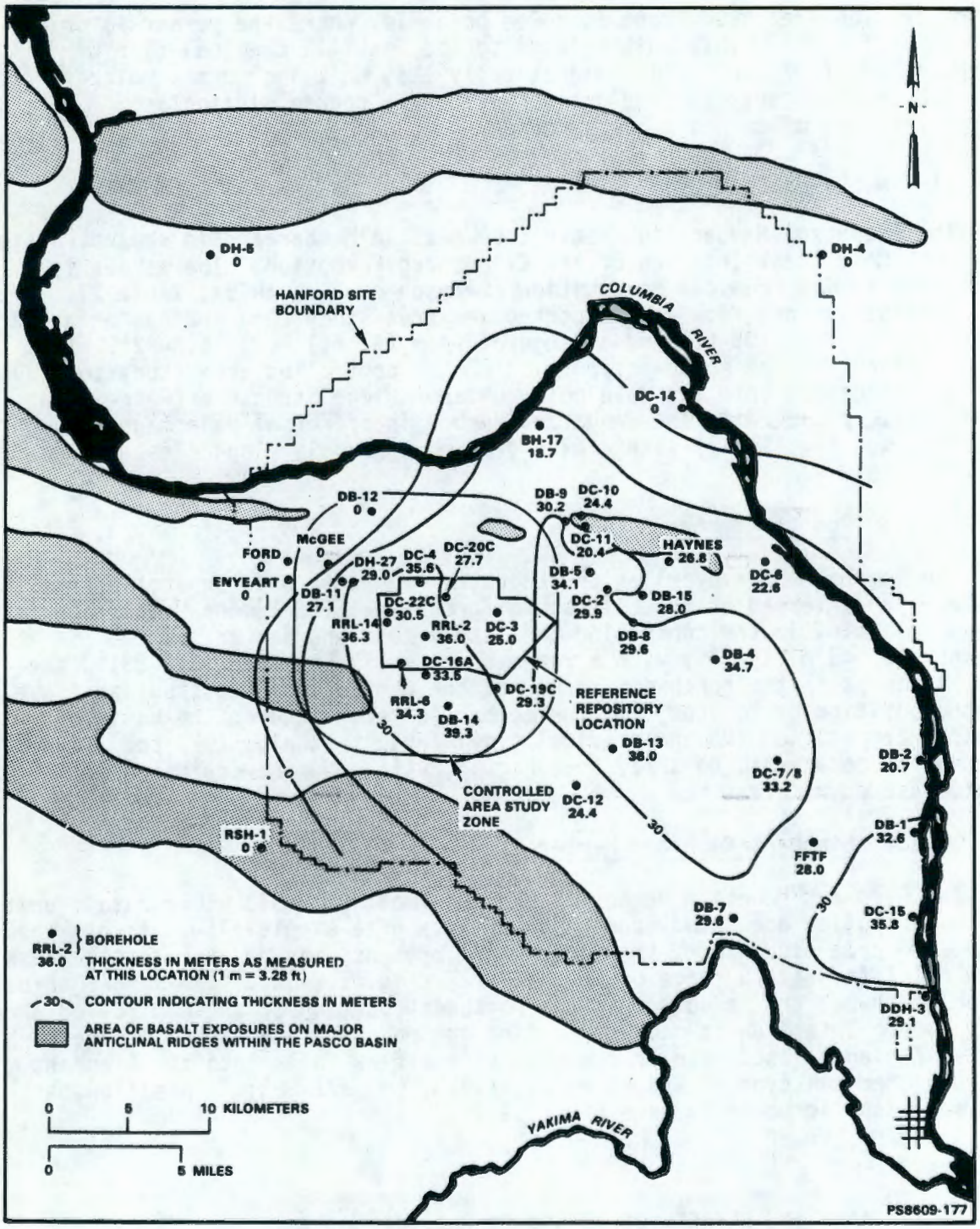

Figure 1.2-32. Isopach map of the Esquatzel Member.

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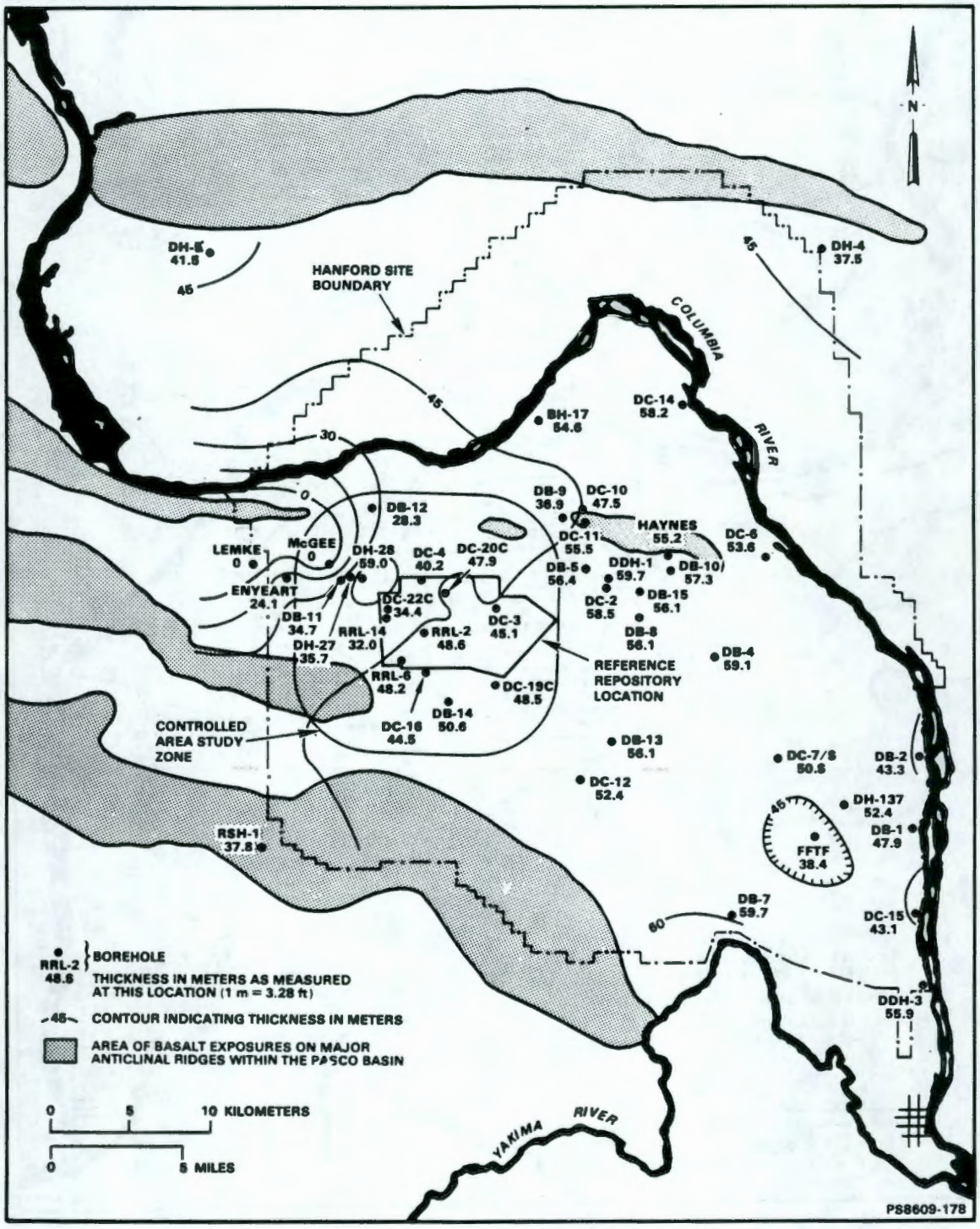

Figure 1.2-33. Isopach map of the Pomona Member.

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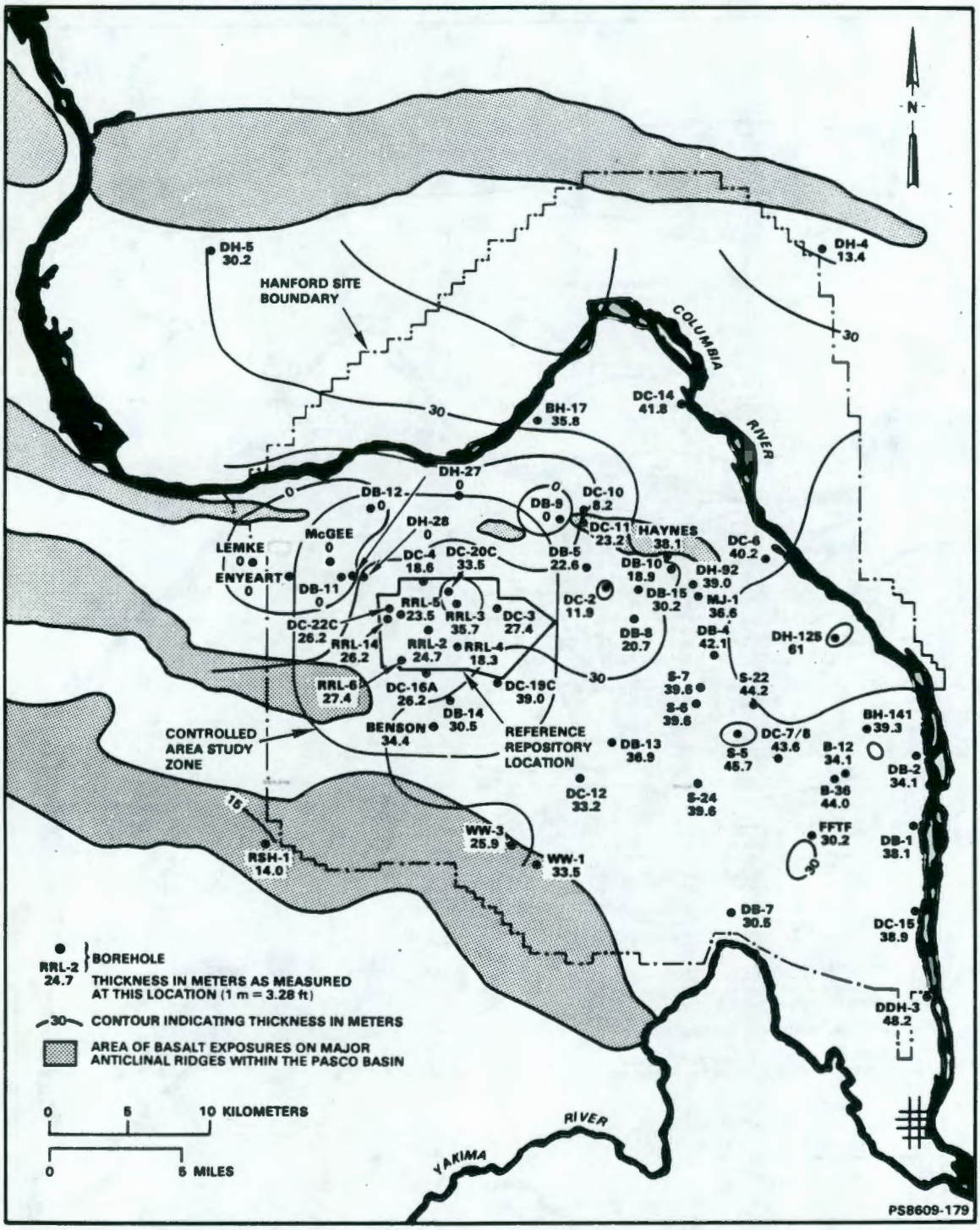

Figure 1.2-34. Isopach map of the Elephant Mountain Member.

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flow-interior, and flow-bottom features. The variety of intraflow structure features is illustrated in Figure 1.2-12.

In the following discussion, thickness ranges and general descriptions will be presented for intraflow structures in Grande Ronde Basalt flows of the primary isolation zone (see Fig. 1.2-20) in the controlled area study zone. Intraflow structure thickness ranges for Wanapum flows of the upper secondary isolation zone and Grande Ronde Basalt flows of the lower secondary isolation zone (see Fig. 1.2-20) are briefly mentioned. In addition, a detailed description of the Cohassett flow within the controlled area study zone will be discussed. Such discussions will provide a summary of the intraflow structure characteristics that are currently known for the host rock, its surrounding primary isolation zone, and the upper and lower secondary isolation zones.

Detailed intraflow structure studies of the repository isolation system in the controlled area study zone are important for the reasons given below.

- Intraflow structures of the candidate horizon represent zones of potential rock strength variations and potential hydrologic property variations. As such, the study of intraflow structures is critical to repository design and construction activities.

- Intraflow structures in the primary isolation zone and the upper and lower secondary isolation zones represent layers of aquifers (generally flow tops/flow bottoms) and aquitards (generally flow interiors) that are important to modeling potential radionuclide migration from a repository. Variations in lithologic characteristics, thickness, and lateral continuity of intraflow structures are important parameters to such modeling efforts.

- Intraflow structures provide the next greater level of detail to a three-dimensional stratigraphic model of the controlled area study zone. Such a model is necessary to an integrated geologic description and understanding of the subsurface of the controlled area study zone (see Section 8.3.1.2.3).

1.2.2.1.4.1 Grande Ronde Basalt flows in the primary isolation zone

Nine to ten Grande Ronde Basalt flows occur in the primary isolation zone in the controlled area study zone. Thickness of flow-top material, flow-bottom material, and thickness and position of internal zones of vesiculation and (or) vugs have been determined and are presented in Landon (1985). These interpretations are based on analysis of borehole drill core and geophysical logs from rotary-drilled boreholes for which no drill core exists. For four of these flows (the Umtanum, McCoy Canyon, Cohassett and Rocky Coulee flows) additional interpretations concerning the occurrence of colonnade and entablature, as well as flow top, flow bottom, and vesicular and vuggy zones, have been made based on analysis of borehole drill core (Cross and Fairchild,

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1985). Techniques have not yet been developed for the interpretation of colonnades and entablatures from geophysical logs from rotary-drilled boreholes (see Section 8.3.1.2.3.3.2).

Colonnade and entablature interpretations from drill core are based on color changes in the core; relative primary fracture abundance; and, to some extent, petrographic textural differences. Previous work by Swanson (1967, pp. 1087-1092), Long (1978, pp. 56-65), Long et al. (1980), Long and Davidson (1981, pp. 5-40 to 5-45) and Long and WCC (1984, pp. I-100 to I-109) has demonstrated that petrographic textural differences exist between colonnade and entablature (see Section 1.2.1.2.2.1). Based on this work, petrographic textures of samples from core are useful in distinguishing between entablature and colonnade. There is an overlap in megascopic and microscopic lithologic textures between colonnade and entablature, which at times makes classification difficult. More work is needed to develop a rigorous classification system suitable for determining intraflow structures in drill core based on petrographic textures. Determination of entablature and colonnade from drill core has a greater degree of uncertainty than do interpretations at outcrop. Planned outcrop studies (see Section 8.3.1.2.3.3.2) will aid in developing a rigorous classification system, which will improve the ability to interpret colonnades and entablatures in flows in the subsurface.

Lateral continuity of intraflow structures in Grande Ronde Basalt flows have been demonstrated for flow top, flow interiors, and some vesicular zones (Long and Davidson, 1981, pp. 5-45 to 5-49; Long and WCC, 1984, pp. I-53 to I-67). The presence of such features in each borehole in the controlled area study zone implies that they are laterally continuous over this area. Intraflow structures will continue to be studied in all flows in the primary isolation zone in all future boreholes drilled in the controlled area study zone (see Section 8.3.1.2.3.3.2). Intraflow structures also will be studied in all upper and lower secondary isolation zone flows penetrated by future boreholes. Additional borehole intraflow structure studies are important because they indicate the thicknesses and positions of the intraflow structures, which are needed to reduce uncertainty.

Outcrop studies of intraflow structures at Sentinel Gap, Emerson Nipple, and north of the Pasco Basin (see Fig. 1.2-7) (Long and Davidson, 1981) provide preliminary information on thickness variation and lateral continuity of intraflow structures in several Grande Ronde Basalt flows. Sentinel Gap and Emerson Nipple are the closest locations to the site of outcrops of applicable Grande Ronde Basalt flows, including the host rock. The outcrop studies demonstrate that intraflow structures in some flows are laterally continuous for distances of up to 10 km (6.2 mi) or more and change in thickness gradually (Long and Davidson, 1981). The studies also demonstrate that certain intraflow structures, such as the flow top in the Umtanum flow, are quite variable in thickness (Long and Davidson, 1981; Long and WCC, 1984, pp. I-53 to I-67). Outcrop studies are valuable in that they allow direct observation and measurement of the occurrence, thickness variation, and lateral continuity of intraflow structures. Such information, when combined with borehole data, is useful for making predictions and geostatistical

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estimations of the occurrence of intraflow structures among boreholes in the controlled area study zone. More work at outcrop exposures (see Section 8.3.1.2.3.3.2) will provide a better reference data base for developing subsurface intraflow structure models for Grande Ronde Basalt flows in the controlled area study zone.

Thickness ranges of flow top, flow interior, and flow bottom in primary isolation zone flows in the controlled area study zone are presented in Table 1.2-1. Outcrop studies of these Grande Ronde Basalt flows on the margins of the Pasco Basin and borehole studies from the controlled area study zone have shown that flow tops display many of the features observed in basalt flows elsewhere on the Columbia Plateau. Pahoehoe and aa features are observed to a certain extent in the upper portions of some flow tops.

The Umtanum, McCoy Canyon, Cohassett, and Rocky Coulee flows range in flow-interior thickness from 16.8 to 75.6 m (55 to 248 ft). It is apparent that the thickest flow interior exists for the Cohassett flow. With the exception of the Umtanum flow, the interior of these flows contains discontinuous and laterally continuous vesicular and vuggy zones. The Umtanum flow in the controlled area study zone consistently shows no vesiculation in the flow interior. Flow interior in the six relatively thin primary isolation zone flows ranges from 0 to 29.6 m (0 to 97 ft) in thickness (see Table 1.2-1). (Note that two flows may be entirely composed of flow top at some borehole sites.) It is evident that in thinner flows the interior can be quite variable in thickness, owing mostly to variations in flow top rather than flow bottom thicknesses.

Grande Ronde flows in the controlled area study zone display most of the upper interior features observed elsewhere on the Columbia Plateau. It appears that tiered entablature and colonnade in the Rocky Coulee, Cohassett, and McCoy Canyon flows in the controlled area study zone may be more common in the Pasco Basin than at other locations on the Columbia Plateau. Vesicle cylinders have only been observed in the Type I Grande Ronde Basalt flows studied in outcrop in and near the Pasco Basin. Grossly diktytaxitic texture is most prevalent in the Type I flows, but some diktytaxitic texture is observed in all flows. Vesicle sheets are most common in Type I flows but have been observed in all Grande Ronde Basalt flows. Vesicular zones in the flow interior are typically found in the thicker Grande Ronde Basalt flows (Type II and Type III) in the controlled area study zone. Relatively thin (generally less than 1 m (3.2 ft)), laterally continuous (up to 500 to 1,000 m (1,640 to 3,280 ft)) zones of platy fracturing have been observed primarily in the thicker Grande Ronde Basalt flows on the margins of the Pasco Basin but have not been identified in boreholes in the controlled area study zone.

Flow bottoms for the six thin flows range from 0 to 4.3 m (0 to 14 ft) in thickness (see Table 1.2-1). In almost every case, the flow bottoms are simply vesicular/vuggy rock. In a few cases they are thin (0.6 m (1.9 ft)), rubbly, or brecciated zones. No pillowed basalts, hyaloclastites, or spiracles have been recognized in these flow bottoms in the controlled area study zone. In the four thicker flows, flow bottom ranges from 0 to 10.7 m (0 to 35 ft) in thickness. The 10.7-m- (35.1-ft-) thick flow bottom is in the

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Table 1.2-1. Thickness ranges of intraflow structures in the primary isolation zone flows in the controlled area study zone

Grande Ronde Basalt flow	Flow top m (ft)	Flow interior m (ft)	Flow bottom m (ft)	Total flow m (ft)
GR-1	1.8-15.2 (6-50)	0-20.1 (0-66)	0-1.2 (0-4)	5.3-25.6 (17.5-84)
GR-2	3.4-12.5 (11-41)	10.7-26.8 (35-88)	0-4.3 (0-14)	15.9-34.9 (52.2-114.5)
GR-3 (Rocky Coulee)	5.2-26.9 (17-88.2)	25.6-46.6 (84-153)	0-7.9 (0-26)	40.2-57.0 (132-187)
GR-4 (Levering) (only in portions of the controlled area study zone)	2.9-16.5 (9.6-54)	1.6-11.0 (5.4-36)	0-1.9 (0-6.1)	0-28.0 (0-92)
GR-5 (Cohassett flow)	4.0-23.2 (13-76)	42.7-75.6 (140-248)	0-0.6 (0-2)	65.8-81.4 (216-267)
GR-6 (Birkett)	13.4-24.4 (44-80)	11.9-29.6 (39-97)	0-06 (0-2)	34.7-43.3 (114-142)
GR-7	1.8-16.5 (6-54)	0-12.5 (0-41)	0-1.8 (0-6)	9.0-18.2 (29.5-59.8)
GR-8	0.9-10.4 (3-34)	3.0-14.6 (10-48)	0-2.2 (0-7.1)	11.6-24.4 (38-80)
GR-9 (McCoy Canyon)	6.1-18.3 (20-60)	22.3-33.5 (73-110)	0-2.4 (0-8)	32.3-45.0 (106-147.5)
GR-10 (Umtanum)	17.1-47.5 (56-156)	16.8-47.9 (55-157)	0-10.7 (0-35)	60.5-75.1 (198.5-246.5)

Source: Landon, 1985. PST87-2005-1.0-20

NOTE: Based on boreholes DC-3, DC-4, RRL-2A, RRL-6, RRL-14, DC-16A, McGee, DC-19C, DC-20C, and DC-22C.

Umtanum flow in borehole DC-19C (see Fig. 1.2-7) and is flow breccia. A flow bottom of 6.1 m (20 ft) was interpreted to exist in the Cohassett flow in borehole RRL-2C.

Only the Cohassett flow has been interpreted for intraflow structures to date in rotary-drilled borehole RRL-2C. Therefore, data for this borehole were not included in Table 1.2-1. Because borehole RRL-2C was rotary drilled and no drill core was produced, interpretations are based on geophysical and borehole video logs. The 6.1-m (20-ft) zone in the Cohassett flow bottom is interpreted as two flow lobes, each having a dense lower half and vesicular upper half. This is based on the neutron-epithermal-neutron log response. In borehole RRL-2A (a core-drilled borehole approximately 150 m (492 ft) south of RRL-2C), there is no flow bottom material in the drill core for the Cohassett flow. This suggests a limited lateral extent to the Cohassett flow bottom observed in RRL-2C. Flow bottoms in the four thick flows occur as rubble or breccia in about half the cases and vesicular/vuggy in the remaining cases. Over 75% of the flow bottom zones in the 10 Grande Ronde flows are 2 m (6.5 ft) or less in thickness.

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1.2.2.1.4.2 Flows in the upper and lower secondary isolation zones

Intraflow structure data from flows in the upper and lower secondary isolation zones of the primary isolation system (see Fig. 1.2-20) in the controlled area study zone will be used in modeling the migration of radionuclides from the repository. Intraflow structures that may accentuate radionuclide migration are the flow tops and flow bottoms, whereas flow interiors may act as impediments to radionuclide migration. The thickness ranges of flow tops, flow interiors, and flow bottoms of Wanapum Basalt flows that compose the upper secondary isolation zone, and those Grande Ronde Basalt flows in the lower secondary isolation zone are given in Table 1.2-2. Thickness ranges for Saddle Mountains Basalt members and (or) flow units in the buffer zone are also included for completeness.

Flow tops in most of the flows show a high degree of variability. The apparent greater variability of flow tops in these flows versus the primary isolation zone flows is unexplained. In general, the flow tops in the upper and lower secondary isolation zone flows are a combination of an upper rubbly to brecciated zone underlain by vesiculation.

Thin discontinuous zones of flow bottom have been found for all flows somewhere in the controlled area study zone. The thickest flow bottom in the upper and lower secondary isolation zone flows is 11 m (36 ft) in a Silver Falls flow in the Frenchman Springs Member. Flow bottom thickness in these flows is much the same as for the Grande Ronde Basalt flows in the primary isolation zone. They are, perhaps, only slightly thicker. The flow bottoms are typically vesicular/vuggy basalt; however, rubbly to brecciated flow bottom does occur in some flows.

Flow interiors in the upper and lower secondary isolation zone flows are highly variable. Most of these flows are relatively thin, so their intraflow structure thickness variations are like the thin Grande Ronde Basalt flows in the primary isolation zone. The thicker upper and lower secondary isolation zone flows appear somewhat more variable in flow interior thickness than the interior of the thick Grande Ronde Basalt flows of the primary isolation zone. Additionally, many of the flow interiors of both thick and thin upper and lower secondary isolation zone flows contain zones of vesicular/vuggy basalt. Variability of upper secondary isolation zone flow interiors appears to be primarily related to variability of flow tops rather than flow bottoms.

Information concerning flow tops, flow interiors, and flow bottoms of Grande Ronde Basalt flows in the lower secondary isolation zone is limited in the controlled area study zone. Most boreholes in the controlled area study zone only penetrate the very high magnesium flow and part of the flow immediately beneath it. The only borehole in the controlled area study zone for which information on intraflow structures exists to date for the deeper lower secondary isolation zone flows is DC-16A (see Fig. 1.2-7).

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Table 1.2-2. Thickness of flow top, flow interior, and flow bottom in flows of the secondary isolation zones and the buffer zone in the controlled area study zone

	Flow top m (ft)	Flow interior m (ft)	Flow bottom m (ft)
Elephant Mountain Member	1.2-14.6 (4-48)	5.3-25.0 (17.5-82)	0-4.9 (0-16)
Pomona Member	4.3-31.7 (14-104)	2.7-36.9 (9-121)	0-6.9 (0-22.5)
Esquatzel Member	1.5-15.8 (5-52)	17.1-28.0 (56-92)	0-2.4 (0-8)
Umatilla Member	2.4-23.8 (8-78)	21.3-67.4 (70-221)	0-1.8 (0-6)
Priest Rapids Member Lolo flow	1.2-13.4 (4-44)	31.1-50.0 (102-164)	0-3.4 (0-11)
Rosalia flow	1.2-15.8 (4-52)	6.4-17.4 (21-57)	0-0.3 (0-1)
Roza Member (up to two cooling units)	3.0-18.9 (10-62)	4.0-48.8 (13-160)	0-4.3 (0-14)
Frenchman Springs Member Sentinel Gap Flow	6.4-18.9 (21-62)	32.0-56.5 (105-185.5)	0.2-1.8 (0.5-6)
Sand Hollow flow(s) (up to two flows)	1.8-15.5 (6-51)	4.0-29.3 (13-96)	0-0.9 (0-3)
Silver Falls flows (up to three flows)	2.7-21.3 (9-70)	0-22.6 (0-74)	0-11.0 (0-36)
Ginkgo flow(s) (up to three flows)	2.4-31.7 (8-104)	0-34.4 (0-113)	0-6.6 (0-21.5)
Palouse Falls flow	2.9-11.0 (9.6-36)	4.6-14.0 (15-46)	0-8.5 (0-28)
Grande Ronde Basalt very high magnesium flow	3.7-14.5 (12-47.7)	7.9-18.0 (26-59)	0-3.7 (0-12)
GR-12[a]	4.0-17.4 (13-57)	25.3 (83)	0.2 (0.8)
GR-13[a]	2.5 (8.2)	47.5 (156)	0.2 (0.7)
GR-14[a]	4.1 (13.3)	34.1 (112)	0.0 (0)
GR-15[a]	6.1 + (20 +)		

Source: Landon, 1985.

[a]No ranges, from borehole DC-16A only.

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Flow top, flow interior, and flow bottom thicknesses will continue to be interpreted for all future boreholes drilled in the controlled area study zone (see Section 8.3.1.2.3.3.2). If the lower secondary isolation zone needs to be characterized, even to a minimum, then a few existing boreholes will need to be deepened or a few future controlled area study zone boreholes will have to be drilled to the N2-R2 paleomagnetic horizon. More detailed intraflow structure studies of upper and lower secondary isolation zone flows will be conducted if the project requires the additional data for these flows.

1.2.2.1.4.3 Cohassett flow

The internal characteristics of the Cohassett flow within the controlled area study zone are similar to other Columbia River basalt flows in that there is a flow top, a flow interior, and a discontinuous flow bottom zone. The flow interior of the Cohassett flow contains a laterally extensive zone of vesicular basalt and exhibits alternating tiers of entablature and colonnade, making it a Type II flow. These intraflow structure features are illustrated in Figure 1.2-35. Detailed descriptions of intraflow structure arrangement in boreholes, for the Cohassett flow, can be found in Cross and Fairchild (1985, pp. 41-60).

The Cohassett flow top thickness ranges from 4.0 to 23.2 m (13 to 76 ft) across the controlled area study zone (Table 1.2-1 and Fig. 1.2-36). The flow top typically comprises flow-top breccia and rubble overlying vesicular and vuggy rock. Field studies in progress at Sentinel Gap indicate that flow-top thickness variations of approximately 10 m (33 ft) occur over distances of about 100 m (330 ft). Borehole spacings are too distant to indicate such variations in flow top. Flow-top breccia and rubble in boreholes and outcrop typically make up one half of the total flow top thickness, with vesicular and vuggy rock constituting the remainder (Cross and Fairchild, 1985, pp. 41-60). The breccia and rubble are typically composed of subangular clasts 1 to 6 cm (0.4 to 2.4 in.) in diameter with occasional clasts to about 40 cm (16 in.). The clasts occupy 60% to 70% of the rock mass in a matrix filled with clay, silica, zeolite, or basalt. Vesicles and vugs range from 2% to a maximum of 40% of the rock mass. Vesicles vary in size from 1 to 9 mm (0.04 to 0.35 in.) and vugs range from 1 to 5 cm (0.4 to 2 in.) in size. In core, both vesicles and vugs are unfilled or partially filled with clay, silica, or zeolites.

The interior of the flow ranges from 42.7 to 75.6 m (140 to 248 ft) thick within the controlled area study zone (Table 1.2-1 and Fig. 1.2-37). A laterally extensive vesicular zone is found within the interior of the Cohassett flow. This zone is defined as having greater than 2 vol% vesicles. The flow interior above this vesicular zone and below the base of the flow top ranges from approximately 16.2 to 22.3 m (53 to 73 ft) within the controlled area study zone. The flow interior below the vesicular zone and above the flow bottom ranges from 29.0 to 45.4 m (95 to 149 ft). The interior of the flow is fractured from contraction during cooling of the basalt flow. Of the cooling joints observed in cores from this flow, nearly all (99.4%) are completely filled with clays, silica, or zeolite (Lindberg, 1986) (see also Section 1.2.2.1.5).

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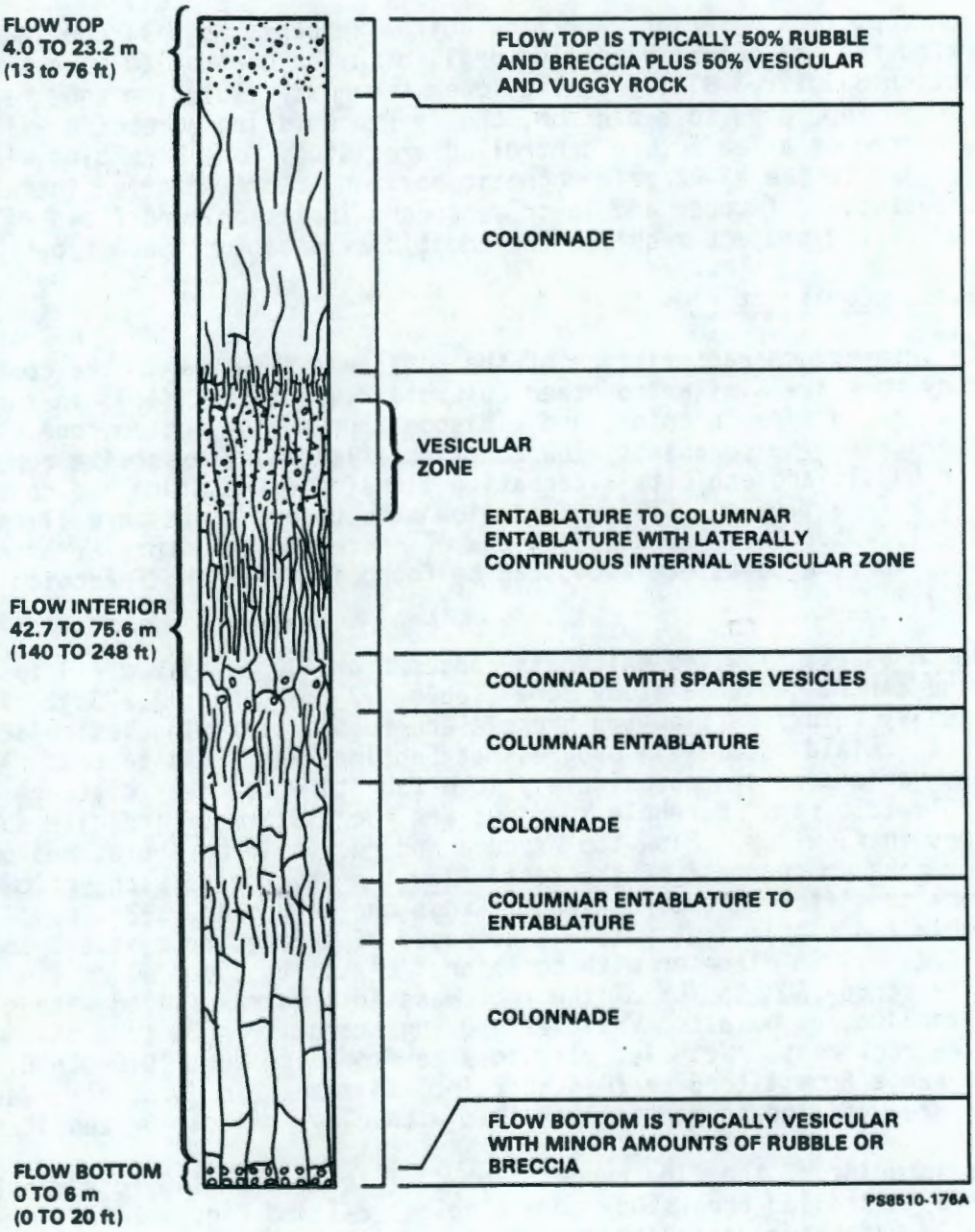

Figure 1.2-35. Typical intraflow structures of the Cohassett flow within the controlled area study zone (arrangement shown is similar to borehole RRL-2A). Ranges of values are for the controlled area study zone. The Cohassett flow total thickness ranges from 73 to 81 m (240 to 266 ft) within the controlled area study zone.

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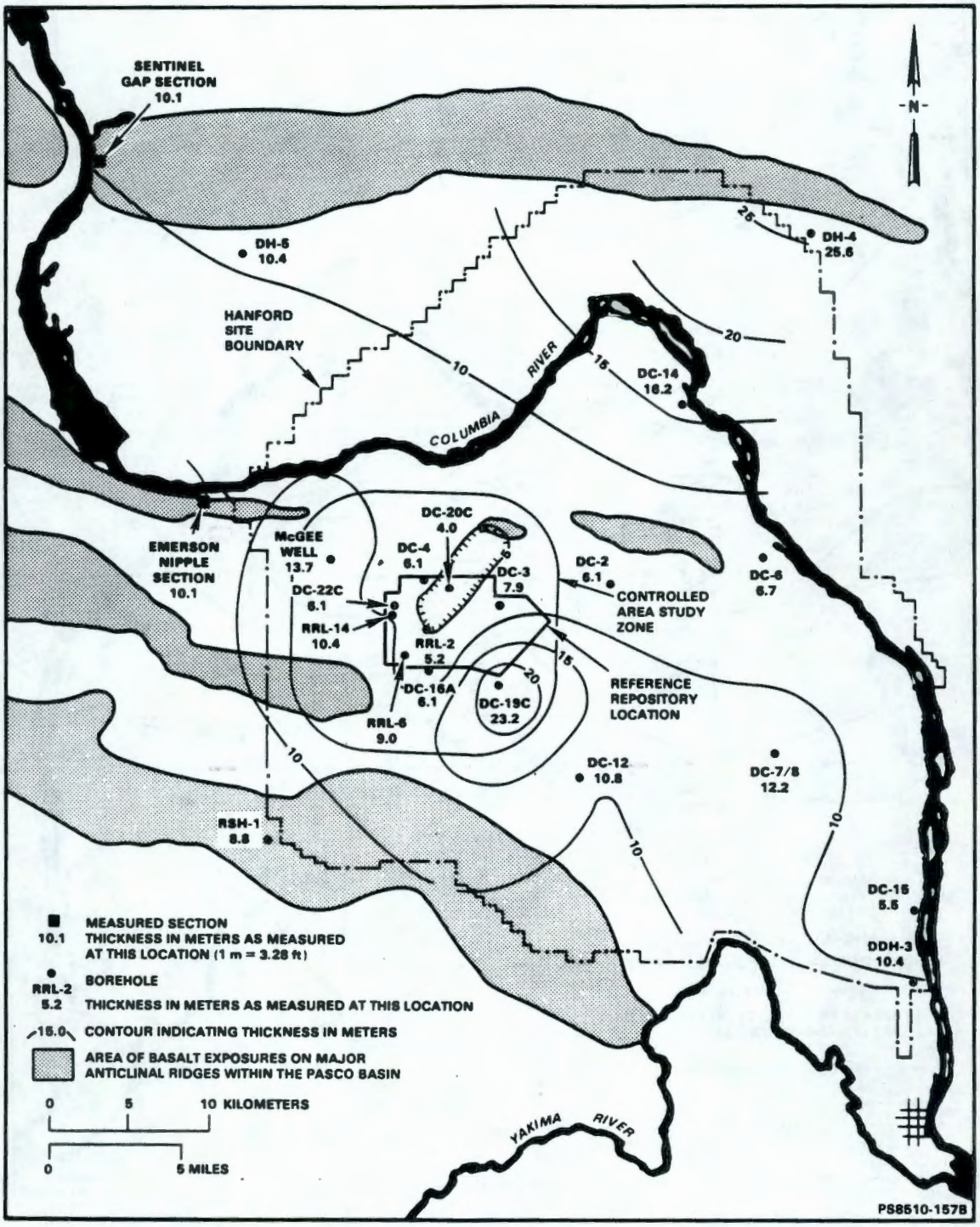

Figure 1.2-36. Isopach map of the Cohassett flow top.

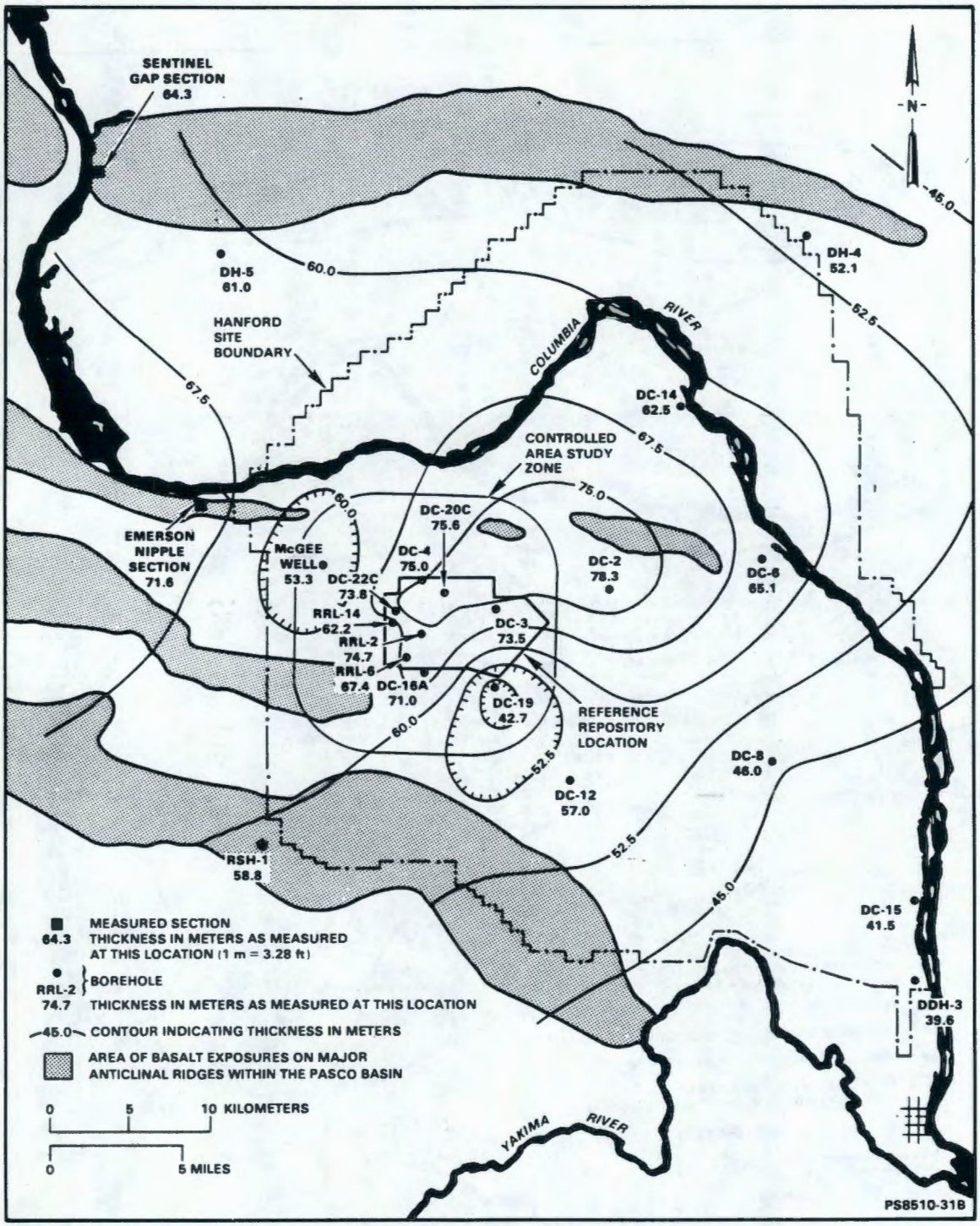

Figure 1.2-37. Isopach map of the total flow interior of the Cohassett flow.

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Entablature-colonnade tiers occur within the interior of the Cohassett flow (Cross and Fairchild, 1985, pp. 41-60). These tiers have not yet been correlated from borehole to borehole within the controlled area study zone because of high uncertainty in correlation criteria. Improvement of the techniques for determination of entablature and colonnade in drill core may refine the current interpretations and result in the ability to make correlations in the Cohassett flow between boreholes that have low associated uncertainties (Section 8.3.1.2.3.3.2). Studies of Grande Ronde Basalt flows on the margins of the Pasco Basin indicate that intraflow structure tiers in the Grande Ronde Basalt flows may correlate for distances of several kilometers.

The vesicular zone in the Cohassett flow is located approximately 18 m (60 ft) below the base of the flow top. The vesicular zone is characterized by its well defined, upper planar boundary where abundant vesiculation ends, and only scattered vesicles occur above this discrete position in the flow. Column-defining fractures pass uninterrupted through the vesicular zone and into the overlying nonvesiculated rock. The base of the vesicular zone is characterized by a gradational decrease in vesiculation downward in the flow. Recent work (McMillan et al., 1985) suggests that the position of the vesicular zone in the flow is related to upward migration of vapor bubbles encountering a downward progressing solidification front. This would explain the relatively planar upper surface. McMillan et al. (1985) suggest that the Cohassett flow vesicular zone occurs at approximately the same relative position in the flow, given the flow's total thickness at each location. The vesicular zone is typically within a columnar-entablature portion of the flow interior.

Thickness of the vesicular zone ranges from 0 to 15.9 m (0 to 52 ft) (Fig. 1.2-38) within the controlled area study zone. Other than at borehole DC-19C in the southeast corner of the controlled area study zone (where the zone is absent), the vesicular zone thickness ranges from 3.0 to 15.9 m (10 to 52 ft) across the controlled area study zone. The vesicular zone is interpreted to be continuous throughout much of the Pasco Basin (see Fig. 1.2-38). This zone is composed of vesiculation that occupies from 2% to 25% of the rock volume, and vugs similarly constitute from 2% to 20%. Vesicle size ranges from 1 to 9 mm (0.04 to 0.35 in.), with an average size of approximately 5 mm (0.20 in.). Vugs range from 1 to 3 cm (0.4 to 1.2 in.), with an average size of approximately 1 cm (0.4 in.). Vesicles typically predominate in abundance in comparison to vugs. When vesicular and vuggy rock occur together, the average open space is approximately 15%.

Preliminary results of detailed core logging suggest that vesicles and vugs within this zone are completely or predominately filled approximately 50% of the time. When filled, the principal infilling material is clay (probably smectite) with minor amounts of silica and zeolites (see Section 4.1.1.3). Basalt is sometimes found as a primary filling in the vesicles and vugs and is the result of the flow solidification. Vesicles and vugs are not connected except where transected by fractures. The amount of vesicles in the vesicular

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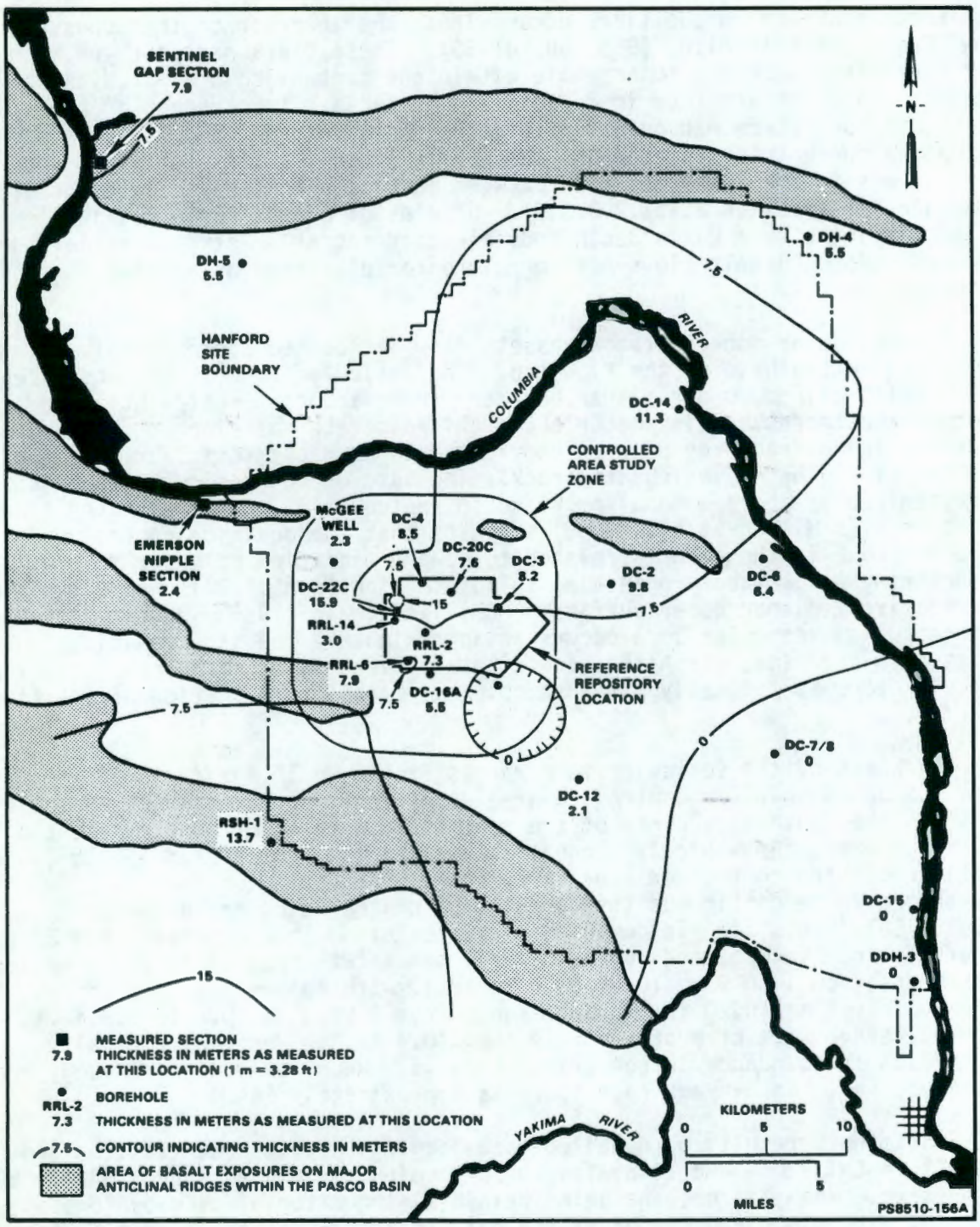

Figure 1.2-38. Isopach map of the internal vesicular zone in the Cohassett flow.

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zone commonly increases in abundance upward from the base; the largest abundance of vesiculation and vugginess is commonly found at the top of the zone. An internal stratification of vesicles and vugs also may occur in this zone. Brecciated rock that occurs in flow tops has not been observed within the vesicular zone.

At borehole DC-19C, flow top and flow interior thicknesses for the Cohassett flow are different than those elsewhere within the controlled area study zone (see Fig. 1.2-36 and 1.2-37). At this location, the Cohassett flow is 19.5 m (64 ft) thinner than at all remaining locations within the controlled area study zone, except McGee borehole (see Fig. 1.2-23). Additionally, the Cohassett flow top is thicker at DC-19C than has been encountered in all other locations in the controlled area study zone (see Fig. 1.2-36). This flow top is interpreted as the typical Cohassett flow top, with the addition of a vesicular flow lobe on top of the flow. Together, these yield a thicker flow top. Interior thickness at this location is 42.7 m (140 ft), and no internal vesicular zone is present (see Fig. 1.2-37). The absence of the internal vesicular zone is interpreted to be related to the thinner flow thickness (see Fig. 1.2-23) (McMillan et al., 1985). The internal vesicular zone of the Cohassett flow in the vicinity of borehole DC-19C may either gradually disappear laterally as the flow thins, or it may merge with the vesiculation associated with the flow top. The thickness of the interior of the flow in borehole DC-19C is comparable to the interior below the vesicular zone in all other boreholes within the controlled area study zone, except for the McGee borehole.

The flow bottom of the Cohassett flow is typically a thin zone of vesicular basalt. Brecciated flow bottom has not been observed within the controlled area study zone for the Cohassett flow, although two occurrences of rubbly flow bottom 1 m (3 ft) or less in thickness have been observed. Vesicles in the flow bottom are 1 to 8 mm (0.04 to 0.32 in.) in diameter and represent approximately 2% to 15% of the rock mass. Flow bottom thickness of the Cohassett flow ranges from 0 to 0.6 m (2 ft) in the controlled area study zone with the exception of rotary-drilled borehole RRL-2C (see Fig. 1.2-7), where the presence of two flow lobes with vesicular tops is considered to be flow bottom with a total thickness of 6 m (20 ft) (see Section 1.2.2.1.4.1).

Intraflow structure studies in progress at outcrops at Sentinel Gap (see Fig. 1.2-7) have shown that spiracles exist in the base of the Cohassett flow in this vicinity. Approximately five spiracles were observed in a single 20-m (66-ft) long exposure. The largest of these spiracles was approximately 2.5 m (8 ft) tall by 1.5 m (5 ft) wide. Such features as spiracles, pillow-palagonite, hyaloclastite, or other inferred water interaction features have not been identified in the Cohassett flow either in the controlled area study zone or at other locations in the Pasco Basin. The presence of spiracles in the Cohassett flow on the margins of the Pasco Basin and their limited size and extent suggest they could possibly occur in the controlled area study zone and be undetected by current borehole spacing. However, the apparent absence of any appreciable flow bottom in the Cohassett flow in any boreholes in the controlled area study zone suggests that water or saturated sediments were not common in the area of the controlled area study zone when the Cohassett flow was emplaced.

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Future boreholes in the controlled area study zone will provide additional samples to further describe the probability of occurrence of areas where significant interaction between the cooling basalts and water has occurred. However, additional borehole observations are unlikely to yield much additional data on discrete features such as spiracles. Outcrop observations, and to a lesser extent Exploratory Shaft Facility investigations, are the best source of data on the spatial distribution of spiracles and related discrete features in the Cohassett flow and other primary isolation zone flows.

1.2.2.1.5 Cooling joint characteristics at the reference repository location

Detailed, quantifiable cooling joint data from the controlled area study zone are necessary for geologic characterization, which is input for repository design studies, shaft and borehole seal design and placement, and hydrologic modeling efforts.

The existing cooling joint data base for the controlled area study zone is from borehole geologic and fracture logs of drill core. No outcrop data exist from within the controlled area study zone. These data have been collected for different purposes using four somewhat different methodologies. As discussed in Section 1.2.1.2.3, the possibility exists that a few joints not of primary cooling origin have been included in the data, although the impact of this is considered to be negligible.

The first set of data was collected from 1977 to 1983 using basalt core geomechanical data logs. These data are from five boreholes (DC-4, -16, RRL-2, -6, -14) within the controlled area study zone. In four of the boreholes (DC-4, -16, RRL-2, -6) all three of the basalt formations were logged for fractures. In the fifth (RRL-14), only the Grande Ronde Basalt was fracture logged, as this was the only formation cored in this borehole. Data collected using this log included frequency, orientation, width, roughness, and infilling type. Strike and dip of the joint was oriented to an arbitrary line. This set of data was not collected randomly and is probably useful only for qualitative analysis.

A second set of data was collected specifically to quantify cooling joint width and infilling type. These data were collected only from the Rocky Coulee, Cohassett, McCoy Canyon, and Umtanum flows of the Grande Ronde Basalt in boreholes RRL-2, -6, -14, and DC-16. These data were collected randomly and are of good quality for statistical use.

Meints (1986) collected a third set of data on joint orientations and joint spacing from boreholes within the controlled area study zone but only for the Museum and Rocky Coulee flows.

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The fourth set of data are detailed geologic logs of boreholes DC-16 and McGee. These logs contain data on joint abundance, width, dip, roughness, and infilling type. The remaining deep boreholes within the controlled area study zone (RRL-2, -6, -14, and DC-4) are to be relogged in the near future to increase the data base (see Section 8.3.1.2.3.3.3.2).

Analyses of the core data within the controlled area study zone have provided information on seven cooling joint parameters: frequency, width, orientation, percent infilling by secondary minerals, infilling type, core-break frequency, and wall-rock alteration. Data on persistance and roughness from boreholes within the controlled area study zone have not yet been analyzed. Analysis of these parameters is discussed in Section 8.3.1.2.3.3.3. Available data for each parameter are discussed separately below.

1.2.2.1.5.1 Frequency

Cooling joint abundance data from basalt core geomechanical data logs within the controlled area study zone show similar results as the data collected from core samples outside the controlled area study zone (see Section 1.2.1.2.3). Frequencies plotted against position in the flow are shown in Long and WCC (1984, pp. I-80 and I-82) for the Cohassett and Umtanum flows. Like the data from core samples outside the controlled area study zone, the frequency data from within the controlled area study zone generally do not delineate intraflow structures or basalt flows. However, in a very general manner, frequency averages appear to be lower in the basal colonnade of the Umtanum flow in borehole RRL-2 than in the majority of the entablature (Long and WCC, 1984, p. I-82). Cooling joint frequency versus position in flow for the Cohassett flow in borehole RRL-2 is plotted in Figure 1.2-39. This figure illustrates that, in general, cooling joint frequency data from core holes cannot be used to delineate intraflow structures.

The average joint frequencies in core samples collected more recently suggest a correlation with intraflow structure types. In the Cohassett flow at the McGee well and DC-16A core hole, the following average joint frequencies were observed (Rockwell, 1987, Table 5).

Feature	McGee Well	DC-16A
Entablature	38.4 joints/m	36.6 joints/m
Columnar entablature	23.3 joints/m	28.1 joints/m
Vesicular zone	14.4 joints/m	15.8 joints/m
Colonnade	20.5 joints/m	14.1 joints/m

The vesicular zone included in these statistics is the one occurring in the Cohassett flow interior; it does not include vesicular zones that are associated with the flow top or bottom. In both core holes, the Cohassett flow intraflow structures have average joint frequencies that are comparable to those found at outcrop (Section 1.2.1.2.3.1). That is, the entablature has the highest frequency, the colonnade the lowest, and the columnar entablature is intermediate. The vesicular zone average joint frequencies were included

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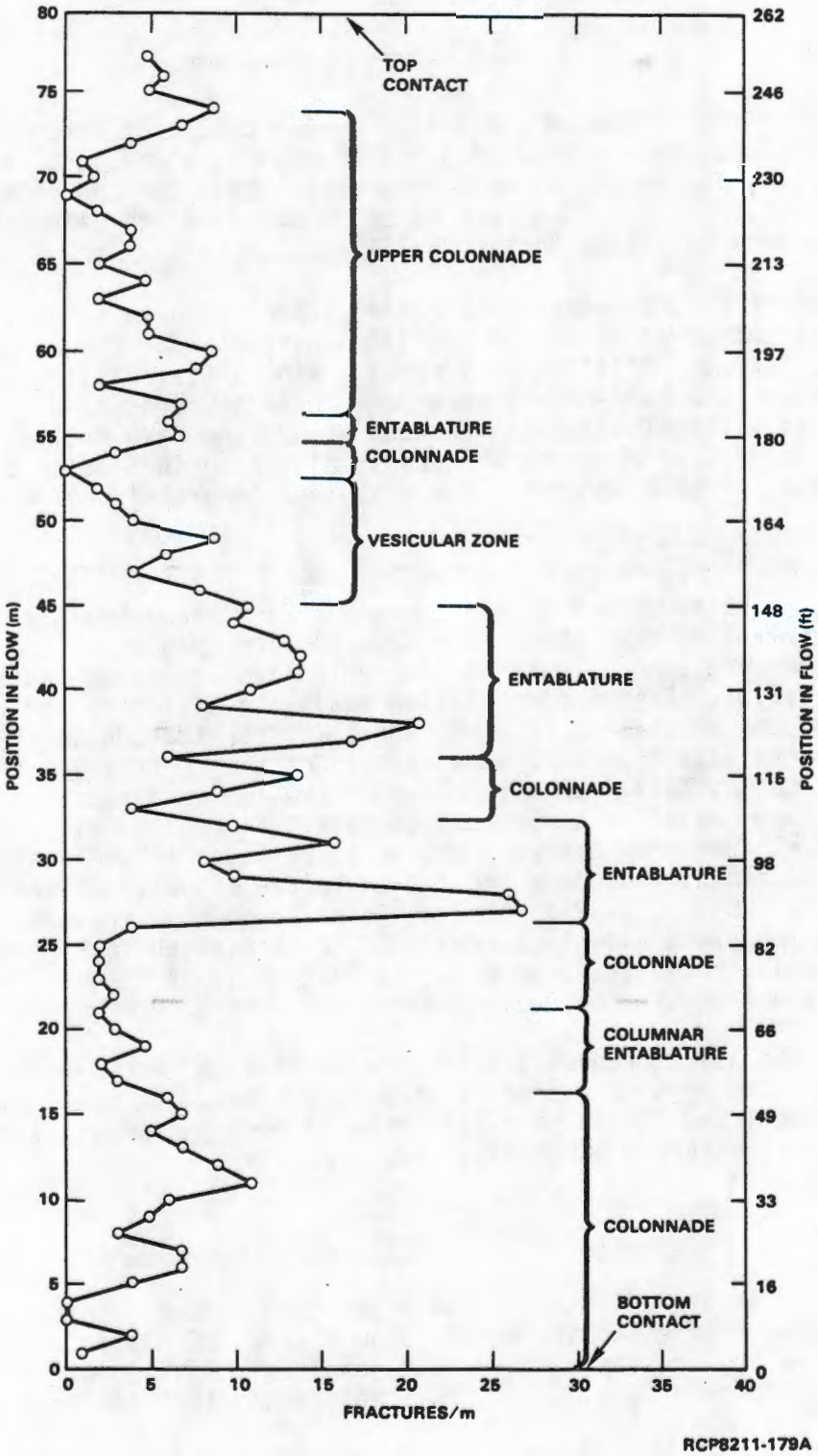

Figure 1.2-39. Plot of fracture abundance versus position in flow for the Cohassett flow in borehole RRL-2. Identification of colonnade and entablature is based on observation of petrographic characteristics of the basalt core. Fracture abundance data may or may not reflect intraflow structure characteristics and associated fracture abundances as observed in surface exposures.

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for comparison. It is not known why the vesicular zone has such a low joint frequency, since the zone usually is found within a columnar entablature. However, the zone has been observed crossing intraflow structure boundaries.

The cooling joint frequency data of the Cohassett flow from the McGee and DC-16A core holes, like data from other vertical core holes, may contain sampling bias. As stated in Section 1.2.1.2.3.1, vertical boreholes are more likely to sample moderately dipping to horizontal joints than vertical joints. Cosine correction programs can be written that correct for orientation bias in vertical borehole data, but they rely on previous knowledge of the orientation of joint sets or the attitude of each joint. To date, little is known about joint sets in basalts, and core has been difficult to orient. As a result, frequency correction programs have not been used, and the frequencies given earlier for the Cohassett flow in the McGee and DC-16A core holes have not been corrected. Should joint sets be identified, the cosine correction techniques will be used (see Section 8.3.1.2.3.3.3.2).

1.2.2.1.5.2 Orientation

The most recent and reliable data on cooling joint orientation is from Meints (1986, pp. 39-96 and 128-227). The orientations of cooling joints of the Museum and Rocky Coulee flows from cores mostly inside the controlled area study zone (one core was outside, DH-5) were plotted on lower hemisphere stereo projections. The drill core was oriented using the paleomagnetic inclination and declination of the core. Each plot (as determined by flow type and borehole) was inspected for preferred clustering of fracture poles. The individual plots displayed a highly variable scattering of poles without any preferred clustering, regardless of whether the borehole was located within or outside of the assigned controlled area study zone boundary. Because the individual plot did not show distinct fracture patterns, it is suggested that there is a significant amount of local variability in cooling joint orientation in core as well as at outcrop.

The individual plots were combined into two master core plots (Fig. 1.2-40), based on flow designation, and were considered to represent the subsurface cooling joint sample population. These plots show a greater concentration of poles with moderate to low dips without a preferred strike. The vertical orientation of the boreholes would account for sampling a lower amount of high angle to vertical joints. The purpose of the master core plots was to statistically compare surface and core jointing populations for similarities. The randomness of the master core plots was not statistically checked by comparing the plots with a known random population plot. Cooling joint orientation in core shows a high degree of variability but cannot be termed random unless the above check is made.

1.2.2.1.5.3 Width

Cooling joint width was measured on 3,200 randomly selected cooling joints in core samples from the Rocky Coulee, Cohassett, McCoy Canyon, and Umtanum flows from boreholes RRL-2, -6, -14, and DC-16 (Lindberg, 1986, pp. 1-36). Approximately 200 cooling joints were measured in each of the 16 basalt flow/borehole combinations. The widths were measured with a

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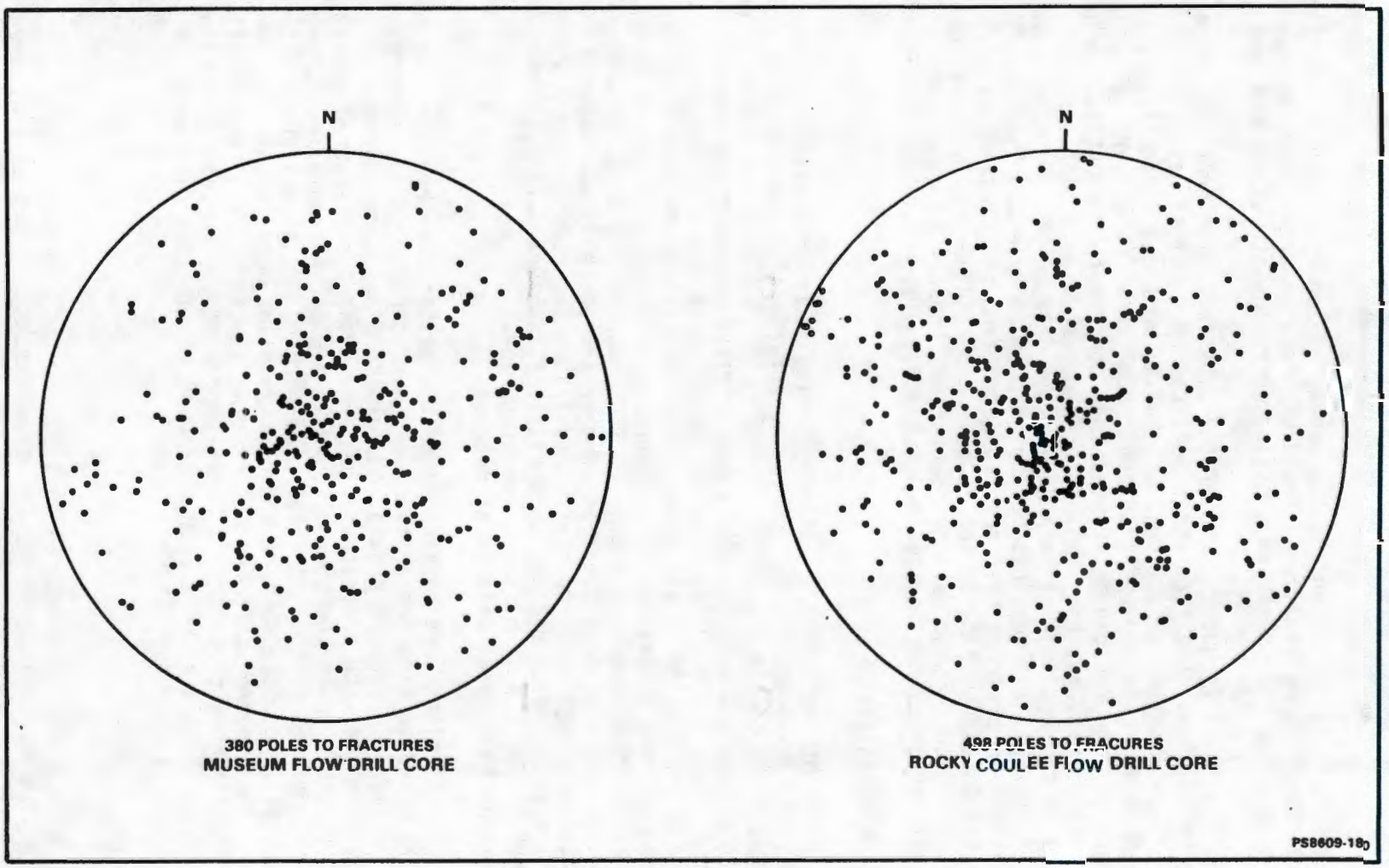

Figure 1.2-40. Lower hemisphere pole projections for the Museum and Rocky Coulee flows from the combination of all fracture orientations measured in drill cores from boreholes DC-2, DC-4, DC-12, DC-16, DH-5, RRL-2, and RRL-6.

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binocular microscope and a precision of 0.01 mm (0.0004 in.). The distribution of cooling joint width was characterized within each of the 16 samples by calculating sample means, standard deviation, and cumulative frequency distributions of the width data in natural log-transform and untransformed format.

Results of the study on cooling joint widths (Lindberg, 1986, pp. 13-25) indicate that there is no significant difference between intraflow structures (colonnades and entablatures) or between flows. There appears to be only one population of cooling joint widths, and that population exhibits local variation related to spatial position (Fig. 1.2-41). The distributions overlap extensively, indicating that they may be represented by a single composite sample of all 3,200 cooling joint widths of the study. The composite sample has a distribution that is log-normal with an untransformed mean and standard deviation of 0.226 and 0.489 mm (0.009 and 0.019 in.) and a log-transformed mean and standard deviation of -1.945 and 0.896 log mm (-5.18 and -2.34 log in.).

Width studies have not addressed differences in cooling joints measured in vertically drilled boreholes versus horizontally drilled boreholes. A vertical sampling direction (i.e., a vertical borehole) may cause bias because the sampling direction parallels the orientation of column-defining joints. Column-subdividing joints and column-defining joints may have different distributions, depending on the direction that the data are collected.

1.2.2.1.5.4 Percentage of filled cooling joints

In the same data set used to study cooling-joint width, an estimate was made of the volume percent of secondary minerals in each joint (Lindberg, 1986, pp. 36-54). (An estimate of the infilling types was made also and is discussed in Section 4.1.1.3). Cooling joints with voids were found to be rare. Only 19 (or 0.6%) of approximately 3,200 joints contained void space. Furthermore, all 19 fractures containing voids were partially filled with secondary minerals and had widths that were comparable to cooling joints that were completely filled. The small number of cooling joints with voids makes statistical analysis difficult. However, the data suggest that fractures with voids may occur in clusters but are not concentrated in certain flows or intraflow structures (Lindberg, 1986, pp. 36-54).

1.2.2.1.5.5 Infilling types

Most cooling joints are filled predominantly with clay; zeolite and silica occur less commonly (Lindberg, 1986, pp. 45-51). Wider joints are more likely to have greater percentages of zeolite and silica than narrow joints. Types of joint infilling are discussed in greater detail in Section 4.1.1.

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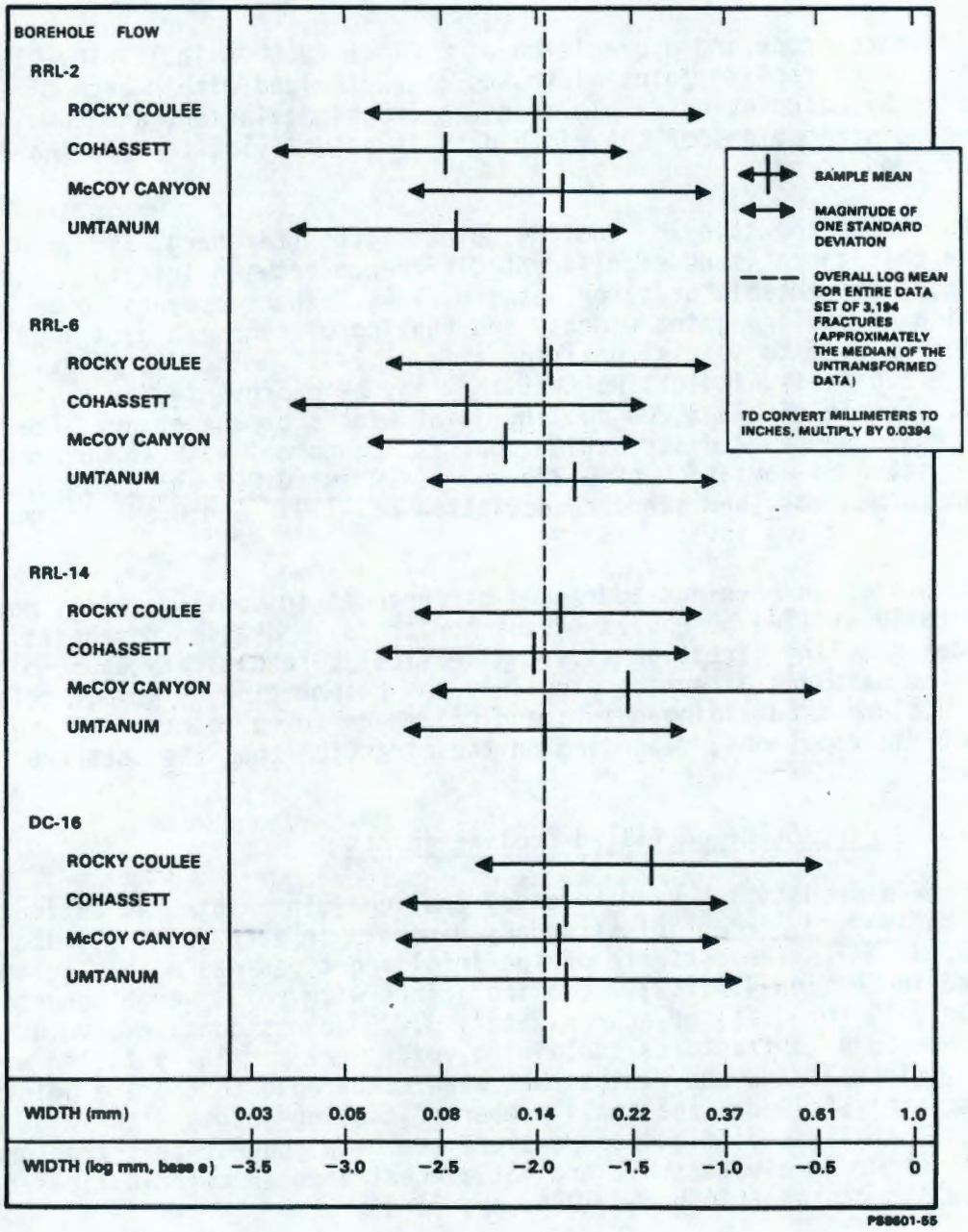

Figure 1.2-41. Comparison of the fracture width distributions of 16 cooling joint samples. Each sample contains approximately 200 cooling joints. The vertical line associated with each arrow pair is the sample mean, and the arrows represent the magnitude of one standard deviation. The long, vertical, dashed line is the overall log mean for the entire data set of 3,194 fractures (approximately the median of the untransformed data). Note that the distributions overlap extensively (taken from Lindberg, 1986, p. 35).

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1.2.2.1.5.6 Core-break frequency

Core samples of the Cohassett flow were found to break, for the most part, along existing cooling joints rather than across intact basalt. This is not surprising because the secondary mineral most commonly filling the joints is clay. Therefore, like rock quality designation (RQD), core-break frequency can provide data about rock strength.

Core-break frequency was calculated for the Cohassett flow by averaging the break frequencies in McGee and DC-16A core samples (Rockwell, 1987). The highest core-break frequency (14/m) was found to be in the entablatures of the DC-16A core hole, and the lowest frequency (5/m) occurred in the colonnades and columnar-entablatures of the McGee core samples. The DC-16A core samples display a lot more disking than McGee core samples, although disking fractures were not included in these counts. Therefore, there appears to be two factors that affect core-break frequency: intraflow structure type (or cooling joint frequency) and the amount of disking (degree of in situ stress). Entablatures are more likely to have more core breaks (they also have more cooling joints per meter), and core hole samples displaying a greater amount of disking (more in situ stress) will show considerably more core breaks (Rockwell, 1987). The ratio of intact joints to total joint count may provide a means of detecting the damaged rock zone in the Exploratory Shaft Facility openings (see Table 8.3.1.2-4).

1.2.2.1.5.7 Wall-rock alteration

The thickness of wall-rock alterations was measured on cooling joints in the Cohassett flow portion of McGee and DC-16A core samples (Rockwell, 1987). The joints were differentiated on the basis of intraflow structure type and were tabulated in four alteration thickness categories: (1) no visible alteration, (2) 0 to 0.5 mm (0 to 0.02 in.), (3) 0.5 to 1.0 mm (0.02 to 0.04 in.), and (4) greater than 1.0 mm (0.04 in.).

The intraflow structure type displaying the greatest amount of wall-rock alteration was the vesicular zone (internal vesicular zone). For instance, the vesicular zone in DC-16A core had the following percentages of joints in the alteration thickness categories:

Wall-rock alteration thickness	Percent	
No visible alteration	11%	
0-0.5 mm (0-0.02 in.)	24%	
0.5-1.0 mm (0.02-0.04 in.)	19%	
>1.0 mm (0.04 in.)	46%	(thickest alteration was 11 mm (0.43 in.)
	100%	

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The intraflow structure displaying the least amount of wall-rock alteration was the entablature immediately below the vesicular zone in DC-16A. The percentages in each alteration thickness category are:

Wall-rock alteration thickness	Percent
No visible alteration	89%
0-0.5 mm (0-0.02 in.)	10%
0.5-1.0 mm (0.02-0.04 in.)	1%
>1.0 mm (0.04 in.)	0% (thickest alteration was 1.0 mm (0.04 in.)
	100%

Greater wall-rock alteration is displayed in Cohassett flow intraflow structures adjacent to flow top and flow bottom, as well as the internal vesicular zone (Rockwell, 1987). Without more information about the history and origin of alteration associated with cooling joints, it is impossible to determine why the vesicular zone has more joint wall-rock alteration than other intraflow structure types in the flow interior.

Additional data must be gathered and analyzed with respect to all parameters discussed to properly characterize cooling joints from flows within the controlled area study zone. Plans for the collection of additional data and analysis are discussed in Section 8.3.1.2.3.3.3.

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1.2.2.2 Sedimentary deposits at the site

This section summarizes the characteristics of the interbedded and suprabasalt sediments within and immediately adjacent to the reference repository location. A more regional discussion of the sediments on the Columbia Plateau was presented previously (see Section 1.2.1.3). Within the reference repository location, the interbedded sediments belong to the Ellensburg Formation while the suprabasalt units are represented by the Ringold Formation, a Plio-Pleistocene unit, the early "Palouse" soil, and the Hanford Formation. These are overlain locally with alluvium, colluvium, loess, and dune sand.

1.2.2.2.1 Ellensburg Formation

The Ellensburg Formation in the controlled area study zone consists of five continuous basalt interbeds (see Fig. 1.2-20) and several discontinuous interbeds. Three of the continuous interbeds are contained within the Saddle Mountains Basalt. They are Cold Creek, Selah, and Rattlesnake Ridge interbeds, in order of decreasing age. A fourth interbed, the Mabton, lies

between the Saddle Mountains and Wanapum Basalts. The fifth and lowest continuous interbed within the controlled area study zone is the Vantage Member (Swanson et al., 1979a, pp. G24-G25), which separates the Wanapum and Grande Ronde Basalts. The Vantage horizon is significant, since it lies within the repository isolation zone and would be the closest interbed to the proposed repository. The Vantage horizon (Fig. 1.2-42) is thickest northwest of the controlled area study zone and thins southeastward. The thickness in the controlled area study zone averages about 2.7 m (9 ft).

The Ellensburg Formation within the controlled area study zone consists mostly of quartzitic to arkosic sandstone and mudstone with minor conglomerate containing abundant plutonic and metamorphic clasts (Reidel and Fecht, 1981, pp. 3-30 to 3-40). Paleosols composed of fine-grained, massive silt and clay are common. Layers of airfall tuff often lie within paleosols, indicating Cascade volcanism was active during Columbia River basalt time.

Detailed studies of the interbeds are lacking within the controlled area study zone. Petrographic, stratigraphic, and sedimentologic descriptions by Schmincke (1964, pp. 178-359) (discussed in Section 4.1.1) were performed on interbeds outside the central Cold Creek syncline and, therefore, may not be representative of interbeds within the controlled area study zone. The provenance of the interbeds within the central Columbia Plateau, indicated by the quartzitic to arkosic nature of the deposits, is believed associated with the ancestral Columbia and Snake Rivers. Various lithologic studies are planned (Sections 8.3.1.2.3.3.1.1 and 8.3.1.2.5.3.1) to further characterize the Ellensburg Formation within the controlled area study zone and vicinity. These are to include comprehensive facies analyses, as well as mineralogic and hydrologic properties, of interbeds both within the controlled area study zone and the Pasco Basin.

The Ellensburg Formation sediments generally have higher hydraulic conductivities than the interiors of basalt flows and show large variations in thickness, texture, mineralogy, and sedimentary structure. These parameters may affect groundwater flow through the Wanapum and Saddle Mountains Basalts.

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1.2.2.2.2 Suprabasalt sediments

The suprabasalt sediments within and adjacent to the reference repository location were derived from a variety of sedimentary environments, although the fluvial-lacustrine Ringold Formation and glaciofluvial Hanford Formation dominate the preserved stratigraphic record (Brown, 1959, p. 6; Routson and Fecht, 1979, p. 10; Tallman et al., 1981, p. 2-1; Bjornstad, 1984, 1985). A total of seven lithofacies correlate over most of the reference repository location (Bjornstad, 1985). The characteristics used to differentiate these units are summarized in Table 1.2-3. Three-dimensional facies relationships among the different units are represented in Figure 1.2-43. The suprabasalt sediments are thickest (up to 230 m (750 ft)) beneath Cold Creek bar and they thin and pinch out toward Yakima Ridge (Fig. 1.2-44).

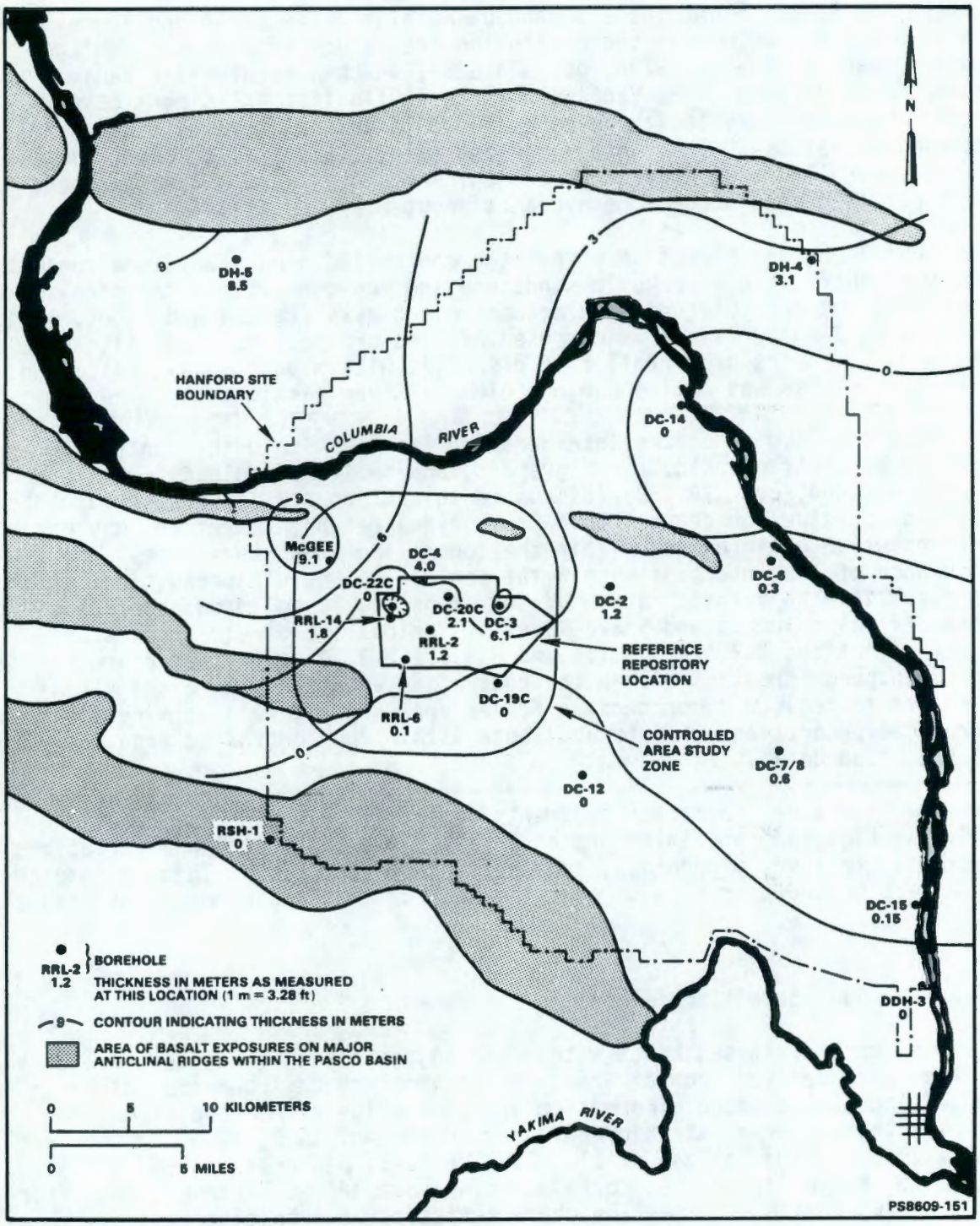

Figure 1.2-42. Vantage interbed isopach map.

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Table 1.2-3. Characteristics used to distinguish suprabasalt units within and adjacent to the reference repository location (sheet 1 of 2)

Formation	Hanford Formation		Plio-Pleistocene unit		Ringold Formation				
Unit	Pasco Gravels	Touchet Beds	Fanglom-erate	Paleosol	Upper	Middle	Lower	Basal	
Subunit								Fine-grained	Coarse-grained
Thickness within RRL	≤5 m (15 ft)	64 m (210 ft)	0 m (0 ft)	26 m (85 ft)	0 - 33 m (0-108 ft)	55 - 100 m (180-328 ft)	0 - 17 m (0-56 ft)	0 - 20 m (0-66 ft)	6 - 46 m (20-151 ft)
Texture	Sandy gravel to gravelly sand	Sand to mud	Muddy sandy gravel	Mud to sand	Sand to mud; occassional gravel	Sandy gravel	Mud	Mud to sand	Gravelly sand to sandy gravel
Sedimentary Structure									
Primary	Large-scale foreset bedding	Graded bed-ding; planar to ripple lamination	Crude sub-horizontal bedding	NP	Planar-tabular cross bedding; ripple lamination	Crude sub-horizontal bedding	Moderately to well-laminated	Ripple lamination	Planar lamination; crude sub-horizontal bedding
Secondary	Occasional caliche	Load structures; clastic dikes; occasional caliche	Intercalated caliche layers	Pedogenic platy to massive calcrete; bioturbation	Load structures	NP	NP	Pedogenic blocky illuviation; caliche stringers and nodules; bioturbation	NP
Roundness of gravel (mode/range)	Subrounded/ angular to well rounded	NA	Subangular/ angular to subangular	NA	Well-rounded/ subrounded to well rounded	Well rounded/ subrounded to well rounded	NA	NA	Well rounded/ subrounded to well rounded
Sorting	Poor	Poor to moderate	Poor	Poor	Moderate to well	Moderate to well	Well	Poor to well	Moderate to well
Natural gamma activity	Low	Moderate to high	Low	Moderate to high	Moderate to high	Low	High to very high	Low to high	Low to moderate

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Table 1.2-3. Characteristics used to distinguish suprabasalt units within and adjacent to the reference repository location (sheet 2 of 2)

Formation	Hanford Formation		Plio-Pleistocene unit		Ringold Formation				
Unit	Pasco Gravels	Touchet Beds	Fanglom-erate	Paleosol	Upper	Middle	Lower	Basal	
Subunit								Fine-grained	Coarse-grained
Basalt content									
Framework (%)	50 - 90	NA	90 - 100	NA	20 - 40	20 - 40	NA	NA	10 - 50
Matrix (%)	10 - 30	10 - 30	75 - 100	0 - 10	5 - 20	5 - 20	NP	0-75	5 - 20
$CaCO_1$ (relative abundance/ occurrence)	Moderate/ rinds on gravel; reworked caliche clasts	Moderate/ fine-grained and disseminated	Low-high/inter-calated pedogenic layers	High/ advanced pedogensis; massive to platy	Low/ occassional coatings or cement	Low/ occassional coatings or cement	NP	Low to high/ caliche stringers and nodules	Low/ occassional coatings or cement
Environment of deposition	Glaciofluvial (high-energy)	Glaciofluvial (low-energy)	Fluvial/ colluvial (side-stream facies)	Subaerial	Fluvial (low-energy)	Fluvial (high-energy)	Lacustrine and (or) fluvial (low-energy)	Fluvial (low-energy to subaerial)	Fluvial (high-energy)

NOTE: NA - Not applicable.
NP - Not present.
RRL - Reference repository location.

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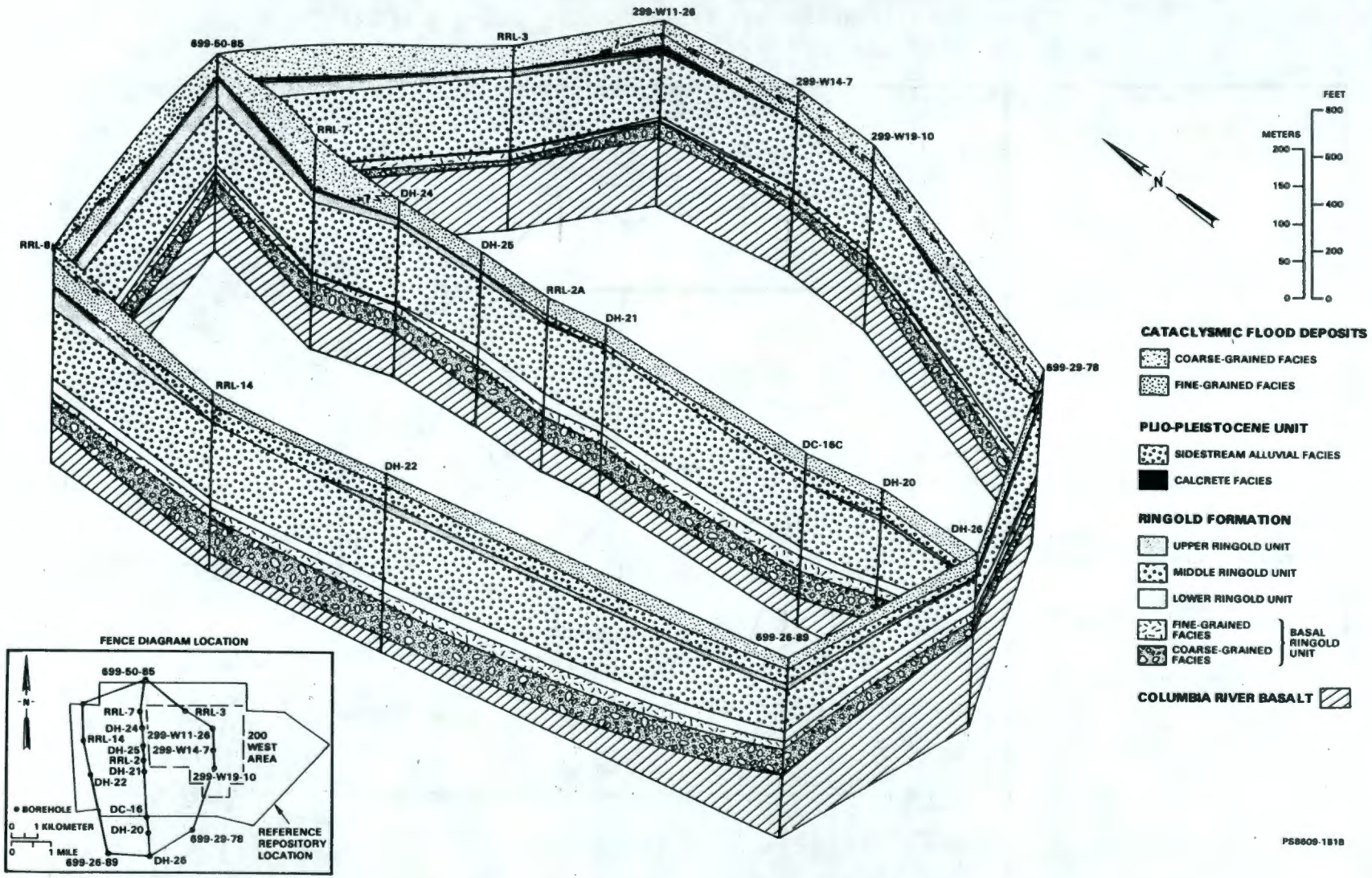

Figure 1.2-43. Fence diagram of the suprabasalt sediments within a portion of the controlled area study zone.

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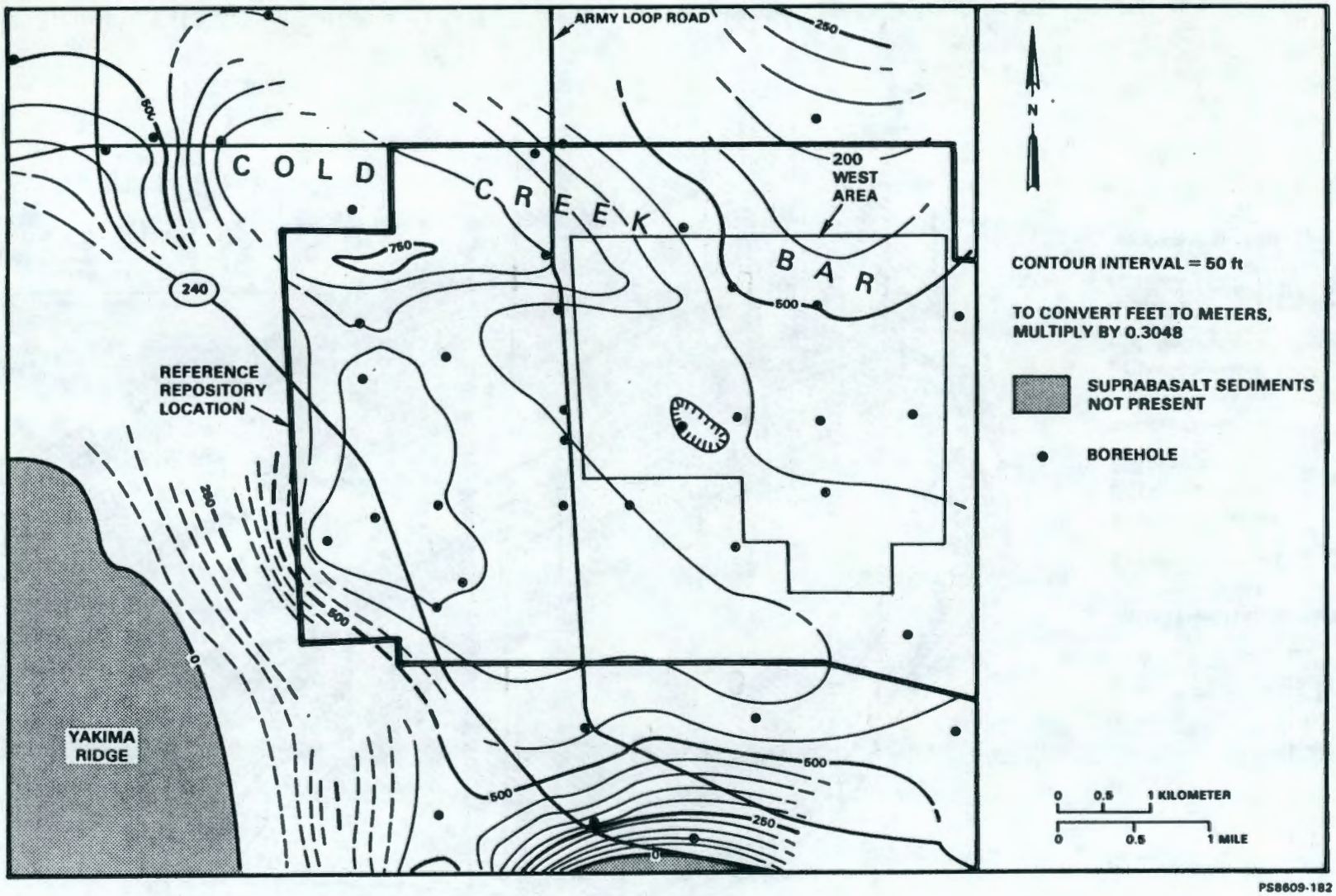

Figure 1.2-44. Isopach map of the suprabasalt sediments.

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1.2.2.2.2.1 Ringold Formation

The Ringold Formation, which overlies the Elephant Mountain Member of the Saddle Mountains Basalt within the central Cold Creek syncline, ranges in thickness from about 110 to 215 m (350 to 700 ft). The Ringold Formation is not exposed at the surface, and the following description is from borehole observations. The Ringold Formation in the central Cold Creek syncline is subdivided into four units, principally on the basis of texture. Brown (1959, p. 6) classified the Ringold Formation into three textural lithofacies: lower, middle, and upper units. Later, Tallman et al. (1979, p. 19) and Routson and Fecht (1979, p. 19) identified a fourth unit, the basal Ringold, which was further subdivided by Bjornstad (1984, 1985) into a coarse- and a fine-grained subunit (Fig. 1.2-45 and 1.2-46).

1.2.2.2.2.1.1 Basal Ringold unit.

The basal Ringold unit, up to 60 m (200 ft) thick, generally represents a complete fining-upward fluvial cycle. Within the coarse-grained subunit, gravelly sand is the predominant texture although lenses of sandy gravel and cross-bedded sand occur locally. The depositional environment is interpreted as being a major through-going, braided-river system associated with the ancestral Columbia River, which probably flowed southward through the controlled area study zone across the Rattlesnake Hills and into the Yakima River Basin (Fecht et al., 1985, pp. 30-34). Cycles marked by secondary fining-upward sequences are common within the basal Ringold coarse-grained subunit but occur locally and are not usually correlative from one borehole to another.

Overlying the coarse-grained subunit is the fine-grained subunit, a conformable sequence of ripple-laminated micaceous mud and sand that represents the transition to a lower-energy fluvial environment perhaps as a result of diversion of the main channel eastward toward Wallula Gap (Fecht et al., 1985, pp. 31-34). Both the coarse-grained and fine-grained basal Ringold subunits are thickest toward the axis of the Cold Creek syncline (see Fig. 1.2-45 and 1.2-46).

The fine-grained subunit includes, and is capped by, a well-developed paleosol sequence (Bjornstad, 1985). This interval consists of a massive, bioturbated, olive-colored, clay-rich illuvial horizon. Subhorizontal stringers of light-colored, Stage II-III (Gile et al., 1966, p. 352) pedogenic calcium carbonate occur toward the base of the paleosol (Fig. 1.2-47). The thickness (as much as 10 m (35 ft)) and multiple stages of development within this zone suggest this paleosol sequence consists of several or more superposed relic soils that developed intermittently over a long period of time. Concentrations of well sorted basaltic sand that represent influxes of fluvial sidestream sedimentation are locally present. A thin (generally 2 to 5 cm (1 to 2 in.)) layer of tephra lies at or near the top of the paleosol sequence within most boreholes at the reference repository location.

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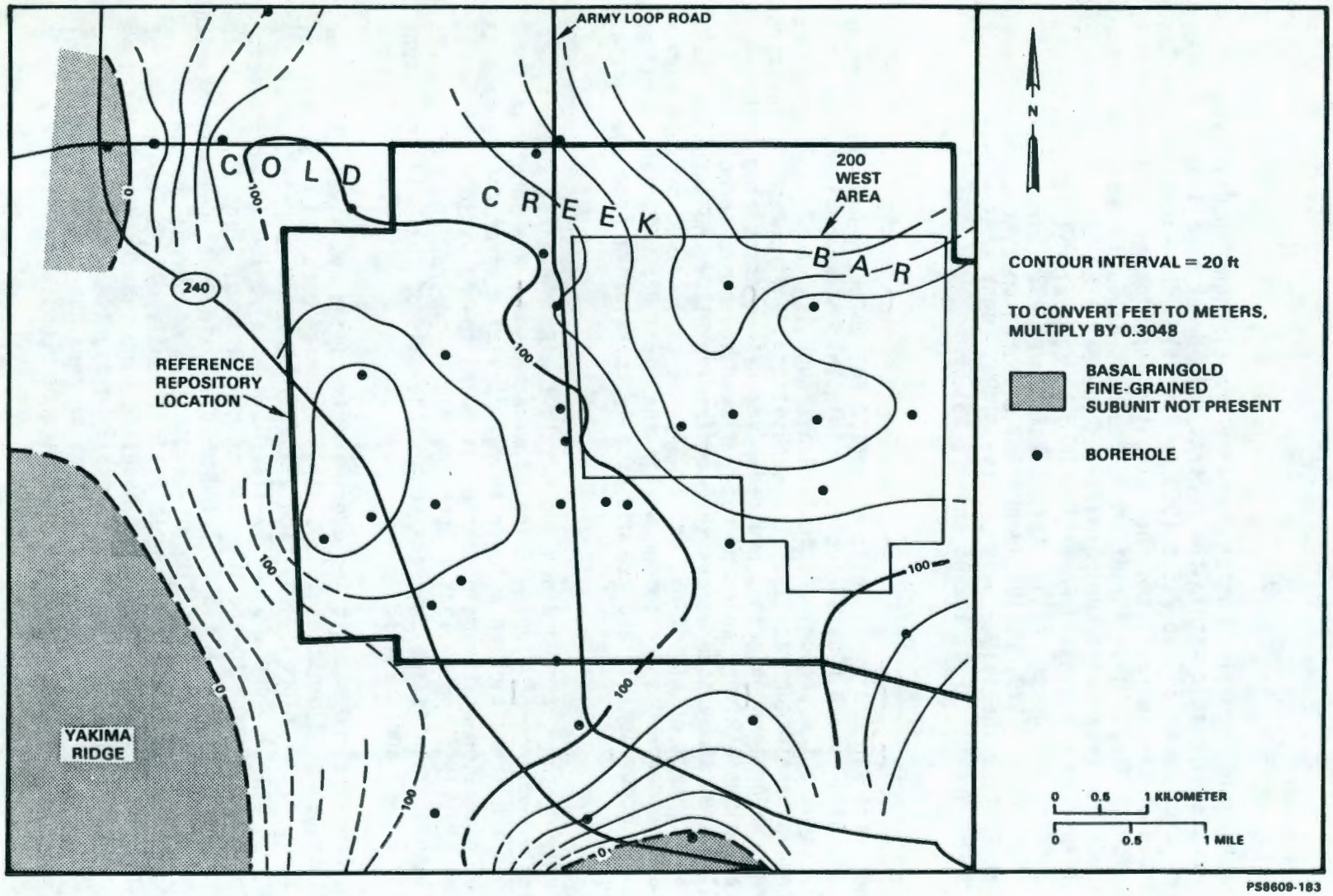

Figure 1.2-45. Isopach map of the basal Ringold coarse-grained subunit.

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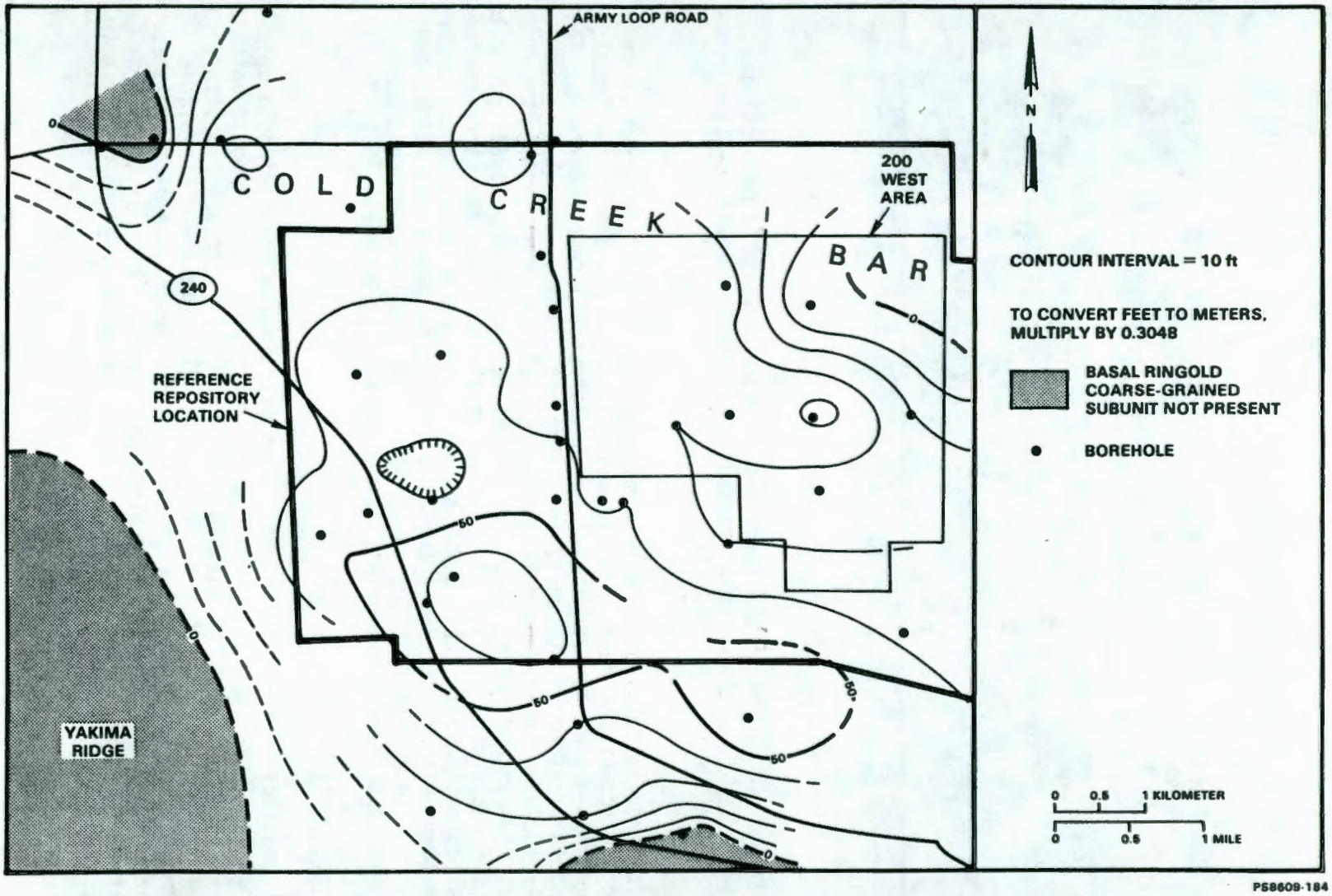

Figure 1.2-45. Isopach map of the basal Ringold fine-grained subunit.

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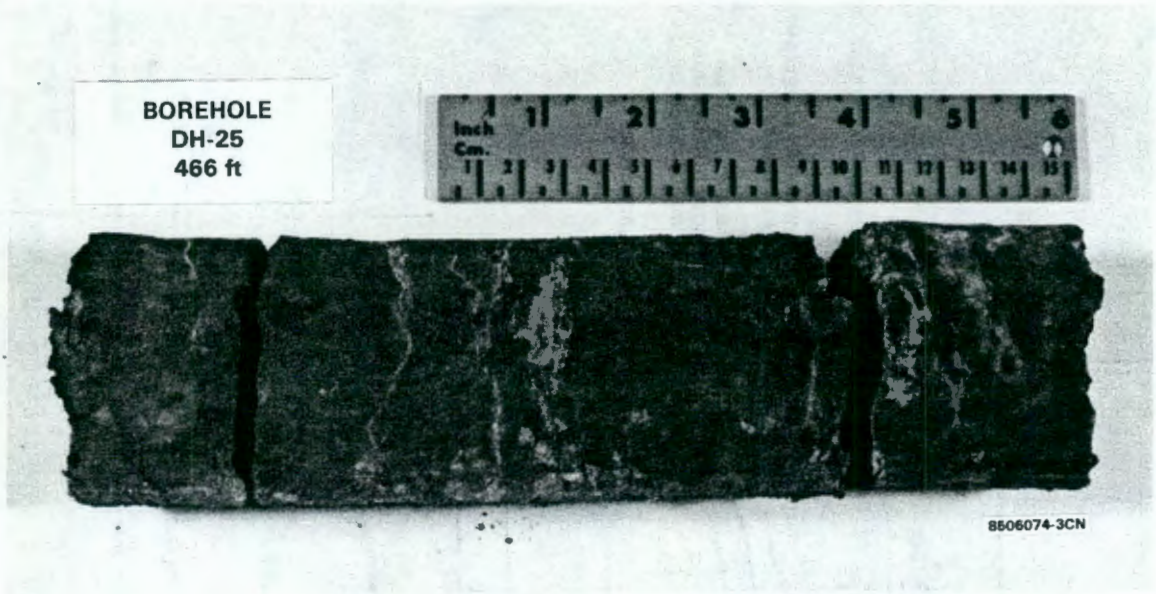

Figure 1.2-47. Core from a segment of the basal Ringold paleosol sequence. Light-colored, subhorizontal layers are pedogenic calcium carbonate within illuviated clay.

The tephra, in combination with a magnetostratigraphic reversal associated with the top of the basal Ringold unit, indicate the top of the basal Ringold unit is a time horizon as well as a lithostratigraphic surface. The basal Ringold fine-grained subunit, including the paleosol sequence, was previously included in the lower Ringold unit (Tallman et al., 1979, pp. 29-32; Routson and Fecht, 1979, pp. 19-20; Tallman et al., 1981, pp. 2-13, 2-17) on the basis of a similar fine-grained texture. However, other characteristics (as outlined in Table 1.2-3 and discussed here) indicate the upper basal and lower Ringold units are two distinct facies (Bjornstad, 1984; 1985). As a result of this modification, the thickness of the basal Ringold unit is greater than that shown previously (Tallman et al., 1979, pp. 2-15 to 2-16).

Lower Ringold unit

Silt and clay of the lower Ringold unit overlie the basal Ringold unit in the central Cold Creek syncline (see Fig. 1.2-43). The lower Ringold unit is thickest (16 m (50 ft)) in the western portion of the reference repository location and pinches out to the east (Fig. 1.2-48). The lower Ringold is disconformable with the underlying basal Ringold paleosol and distinguishable by (1) the presence of primary sedimentary structures, (2) a distinct gray versus olive color, and (3) a significantly higher natural-gamma response in geophysical logs (Bjornstad, 1984).

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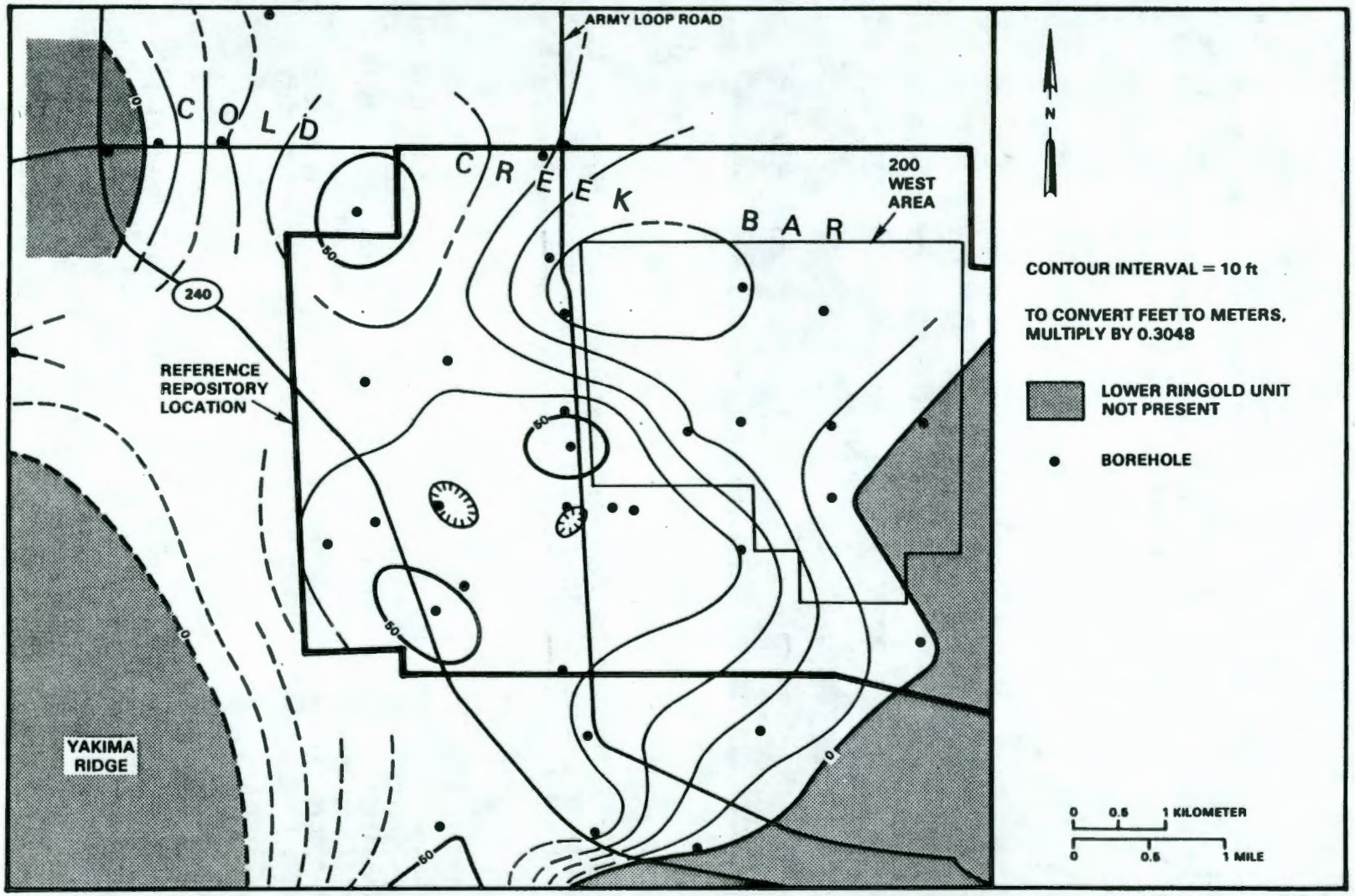

Figure 1.2-48. Isopach map of the lower Ringold unit.

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Sedimentary structures within the lower Ringold grade from thin, rhythmic laminations at the base to generally more massive, irregular, and subhorizontal laminations upward. Occasionally, in thicker sequences of lower Ringold, an interval of pale yellow to gray, even-laminated mud exists in the uppermost lower Ringold unit (Fig. 1.2-49). In boreholes, this interval is also characterized by high natural-gamma activity. Often, this part of the lower Ringold unit is missing, suggesting channeling and subsequent filling associated with the overlying middle Ringold gravel.

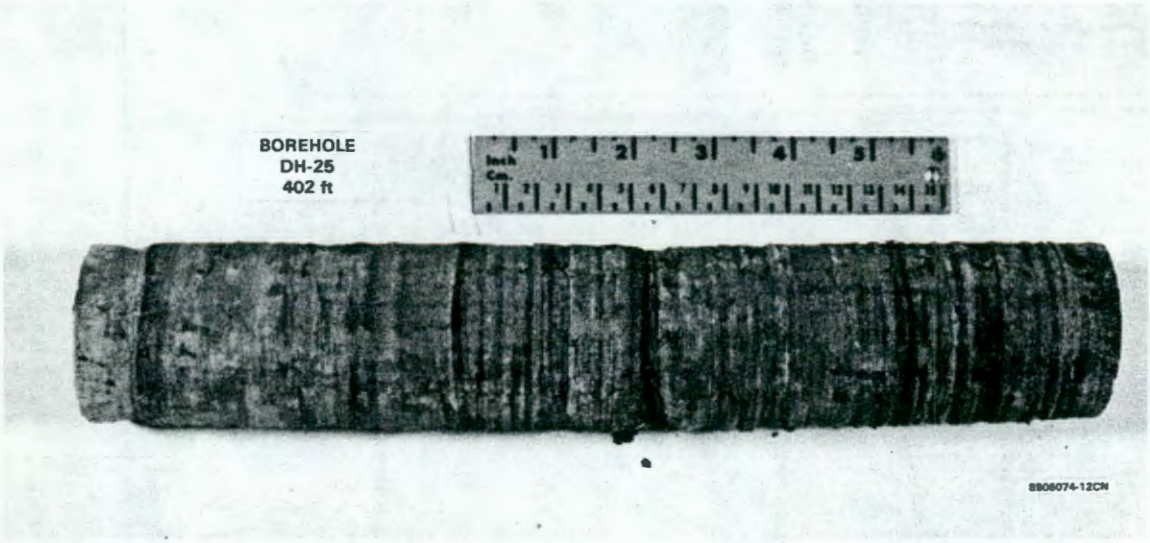

Figure 1.2-49. Core from the uppermost lower Ringold unit. Thin, rhythmic laminations suggest this interval is a lacustrine deposit. Because of erosion, this sequence is sometimes missing from the lower Ringold unit.

The sequence of sedimentary structures observed in the lower Ringold unit indicates low-energy lacustrine and (or) fluvial overbank depositional environments at a time when the area either lay beneath a lake or the main stream channel was located elsewhere within the basin. A multitude of paleomagnetic reversals preserved within the lower Ringold unit (Bjornstad, 1984, Plate 2, 6) suggests the lower Ringold accumulated slowly over many millenia.

Middle Ringold unit

The middle Ringold unit is composed of stream gravels (Tallman et al., 1979, pp. 32-36; Routson and Fecht, 1979, p. 20; Bjornstad, 1984, 1985) and is the thickest of the suprabasalt units (see Fig. 1.2-43 and 1.2-50). These gravels consist mostly of quartzite with lesser amounts of volcanic and plutonic

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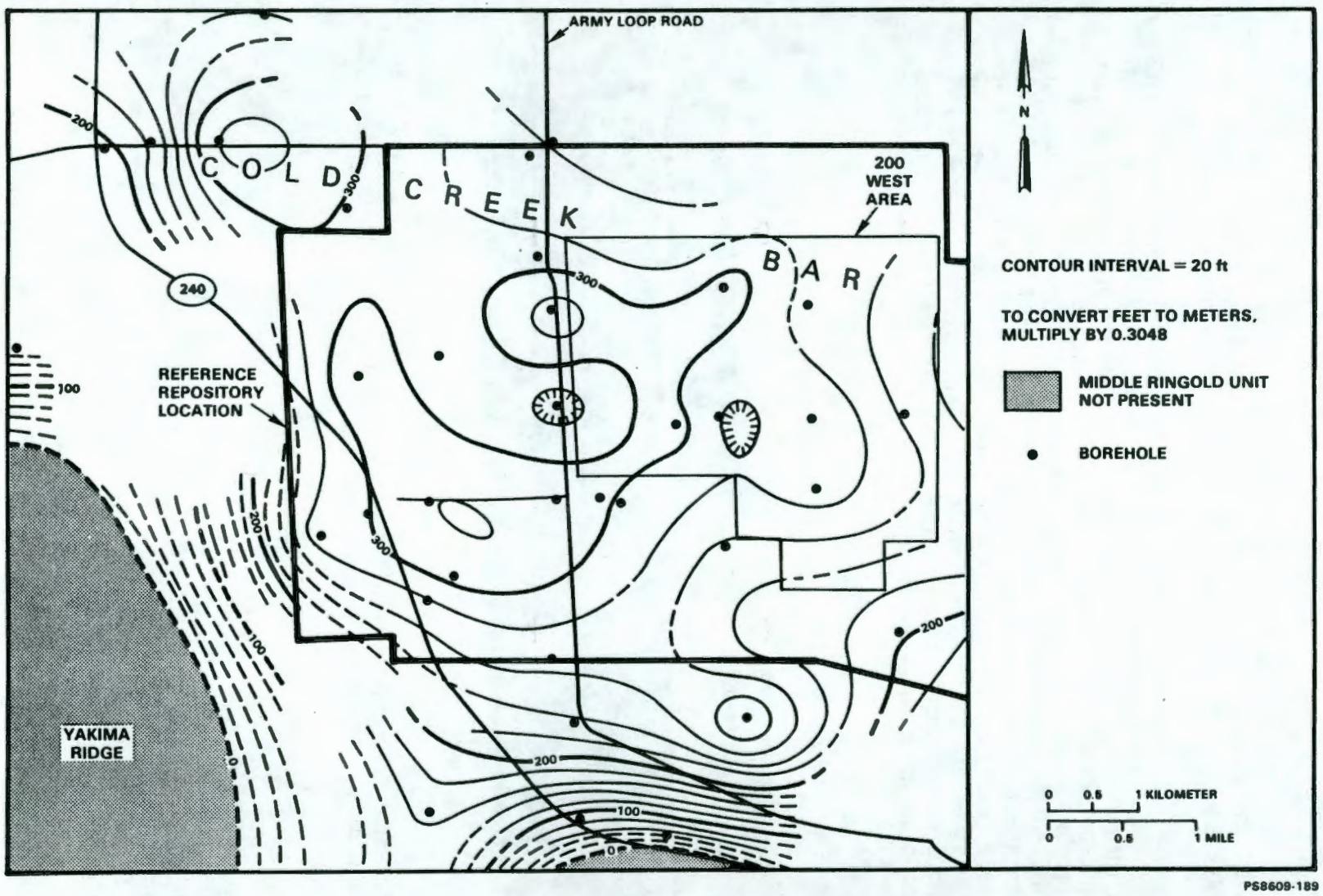

Figure 1.2-50. Isopach map of the middle Ringold unit.

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clasts, which were deposited in a braided-stream environment when the main channel of the ancestral Columbia River reoccupied the Cold Creek syncline. The middle Ringold unit is unconformable with the lower Ringold unit, the latter having up to several meters, locally, of erosional relief.

The middle Ringold unit (Fig. 1.2-51) is texturally and mineralogically similar to the coarse-grained basal Ringold subunit (Tallman et al., 1981, pp. 2-13 through 2-19), except that there is a higher proportion of quartzite to volcanic-porphyry lithologies in the middle Ringold unit. The uniform clast-supported texture of the middle Ringold unit is sometimes interrupted with thin zones of current-laminated sand and mud. The unit probably represents a multitude of sedimentary cycles, whereby the fine facies are missing as a result of beveling by succeeding cycles. The proportion of basalt clasts within the middle Ringold unit increases toward the top, suggesting greater contributions to the fluvial system from side streams toward the close of middle-Ringold time.

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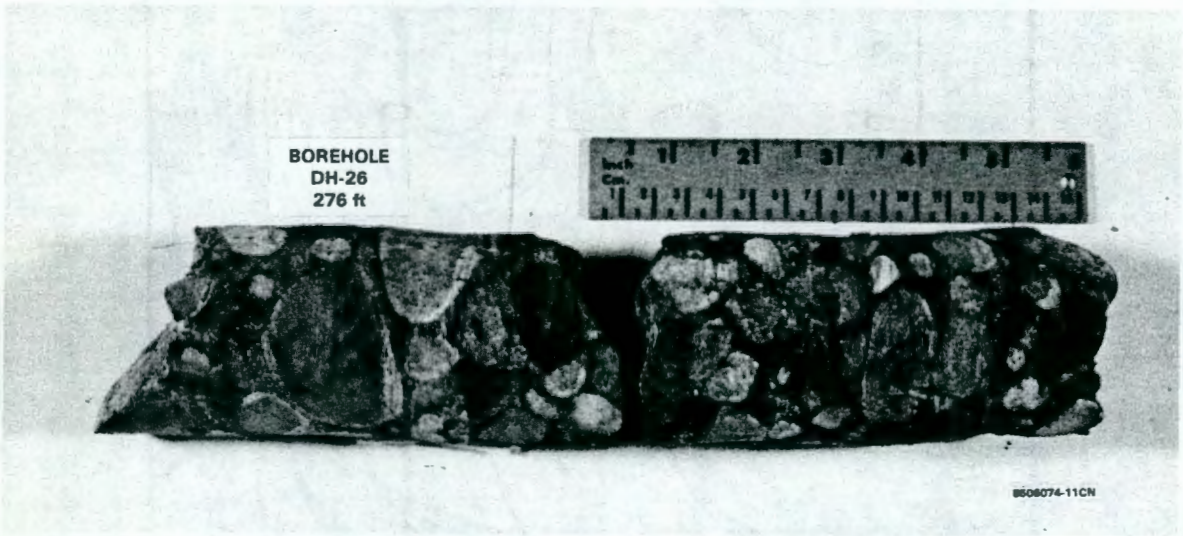

Figure 1.2-51. Core from middle Ringold unit that consists of semiconsolidated, bimodal, clast-supported conglomerate.

Upper Ringold unit

The upper Ringold unit (Tallman et al., 1979, pp. 36-37; Tallman et al., 1981, pp. 2-19, 2-22; Bjornstad, 1984, 1985) conformably overlies the middle Ringold unit within the central Pasco Basin. It consists of alternately bedded and laminated, arkosic sand and mud representative of a low-energy fluvial and lacustrine environment. The large variations in thickness of the upper Ringold unit (Fig. 1.2-52) are primarily due to erosion by post-Ringold fluvial incision and cataclysmic flooding (see Section 1.1.3). The maximum elevation of the upper Ringold unit over the central Pasco Basin was probably much higher at one time. This is indicated by the present elevation (about 275 m (900 ft)) of the upper Ringold unit preserved in the eastern Pasco Basin along the White Bluffs (see Fig. 1.1-9).

1.2.2.2.2.2 Plio-Pleistocene unit

Unconformably overlying the Ringold Formation is a locally derived unit of probable early Pleistocene or, perhaps, latest Pliocene age. This unit is separated into two facies: sidestream alluvium and pedogenic calcrete (Fig. 1.2-43 and 1.2-53). Depending on location, either one or both facies may be present. The sidestream alluvial facies, derived from ancestral Cold Creek and its tributaries, is characterized by relatively thick zones of unweathered basalt clasts, often intercalated with overbank deposits, along with calcareous, pedogenically altered (Stage I to III) (Gile et al., 1966, pp. 349-357) loess and (or) colluvium. Within the reference repository location, the sidestream alluvial facies becomes thinner and finer grained to the northeast where it grades into, or may be interbedded with, a Stage III to IV (Gile et al., 1966, pp. 349-357) pedogenic calcrete (see Fig. 1.2-53), which developed subaerially atop the eroded Ringold surface (Brown, 1959, p. 16; Brown, 1960, pp. 3-8). This unit, present over much of the western Pasco Basin, is a valuable marker horizon because it divides often similar-appearing facies of the Ringold and the Hanford Formations. The Plio-Pleistocene unit appears to correlate with other sidestream alluvial sequences present near the base of the basaltic ridges that bound the Pasco Basin on the north, west, and south.

1.2.2.2.2.3 Early "Palouse" soil

Overlying the Plio-Pleistocene unit in the reference repository location is a fine-grained sand to silt unit believed to be of mostly eolian origin, derived from either older reworked Plio-Pleistocene unit or upper Ringold material (Brown, 1960). Early "Palouse" soil (Tallman et al., 1979, pp. 37-39) is differentiated from the overlying slackwater flood deposits by a greater calcium-carbonate content, massive structure in core samples, and high natural gamma response in geophysical logs (Bjornstad, 1984). This unit is thickest (over 20 m (70 ft)) in the southeastern 200 West Area of the Hanford Site (Brown, 1960, p. 5) and pinches out toward the margins of the basin. The upper contact of this unit is ill-defined and may grade upward and (or) lie intercalated with the Hanford Formation.

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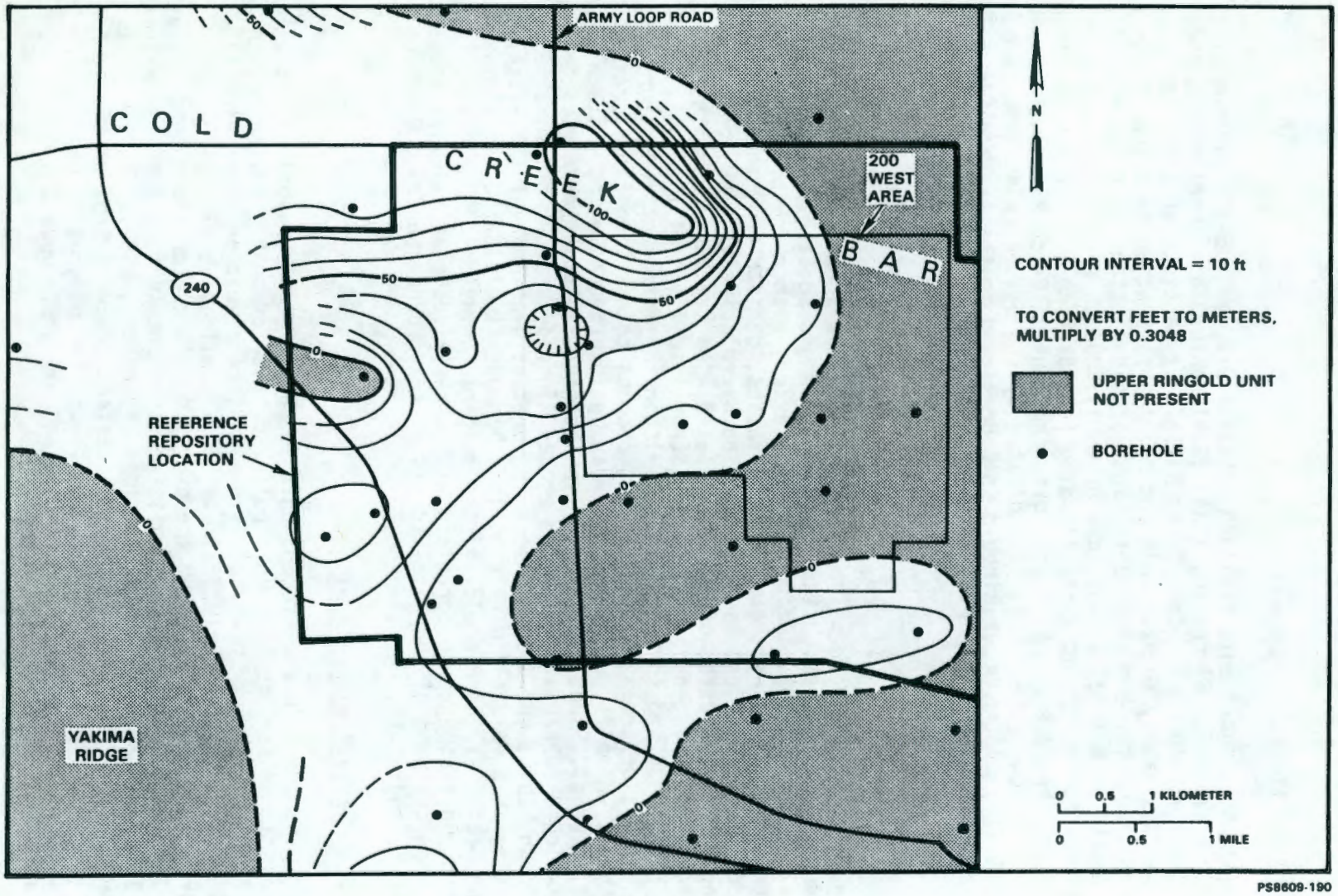

Figure 1.2-52. Isopach map of the upper Ringold unit.

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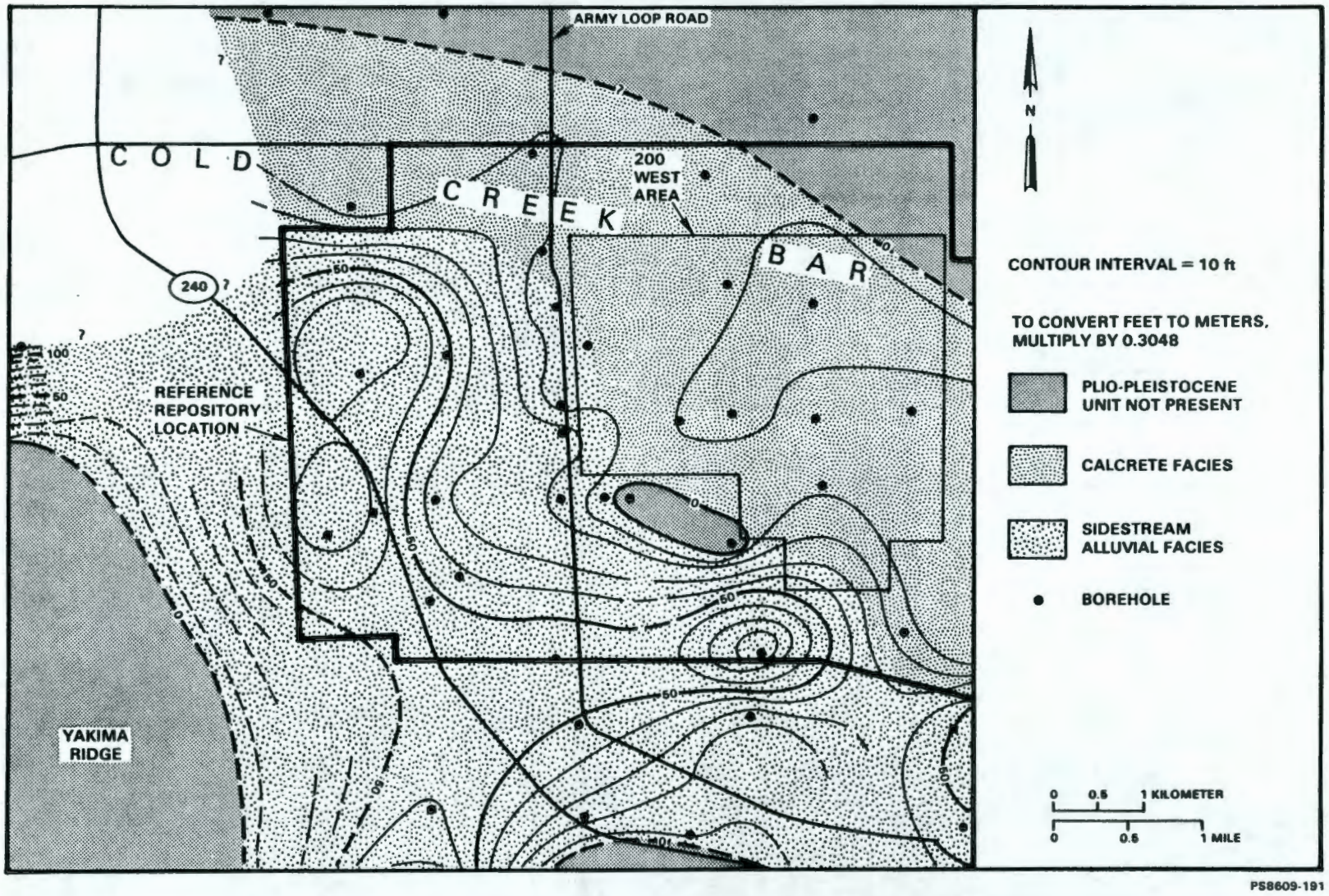

Figure 1.2-53. Isopach and facies map of the Plio-Pleistocene unit.

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1.2.2.2.2.4 Hanford Formation

Pleistocene cataclysmic flood deposits of the Hanford Formation consist of deposits over a wide range in grain size within the controlled area study zone (Tallman et al., 1979, pp. 39-49; Routson and Fecht, 1979, pp. 20-21; Bjornstad, 1984, 1985). Thicknesses also vary from about 5 m (15 ft) or less in the southwest corner of the reference repository location to about 65 m (210 ft) beneath the Cold Creek bar in Figure 1.2-54. The mechanics of cataclysmic flooding are discussed in more detail in Section 1.1.3.3. The combination of erosion, lack of exposure, and rapid lateral facies changes within the Hanford Formation make the accurate correlation of separate flood events difficult. Two facies of the Hanford Formation, the Pasco Gravels and the Touchet Beds, are recognized and discussed below.

Pasco gravels

Pasco Gravels are composed of basaltic, massive- to laminated-coarse sand and (or) large-scale forset-bedded gravel. They are restricted mainly to the Pleistocene flood bars and terraces that developed along high-energy flood channelways (see Section 1.1.3). One such flood bar, the Cold Creek bar (see Fig. 1.1-4), is present in the northern portion of the reference repository location. The Pasco Gravels have been subdivided into the Missoula and pre-Missoula gravels (PSPL, 1981, p. 2R-22 and 2R-23) in the central Pasco Basin, although there is no confirmatory evidence for pre-Missoula gravels in the reference repository location.

Touchet Beds

Touchet Beds are a rhythmically bedded and fine-grained, flood facies deposited away from main flood channelways in slack-water or backflooded areas during flooding (Baker, 1973, pp. 42-47; Waitt, 1980, pp. 653-654). Touchet Beds occur as surficial deposits in the southern and western parts of the Cold Creek syncline and in the subsurface to the north and east where they underlie Pasco Gravels associated with Cold Creek bar.

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1.2.2.2.3 Holocene surficial deposits

Holocene surficial deposits of dune and sheet sand, alluvium, loess, and colluvium locally overlie the Hanford Formation in the controlled area study zone (see Fig. 1.1-5). Cumulative thicknesses of these deposits rarely exceed several meters.

1.2.2.2.4 Correlative suprabasalt horizons

Correlative stratigraphic horizons within the suprabasalt sediments are important for the determination of timing and rates of post-basalt tectonic deformation. At the present time, tephra layers are the only proven time-stratigraphic horizons present within the Pasco Basin. Only one correlative

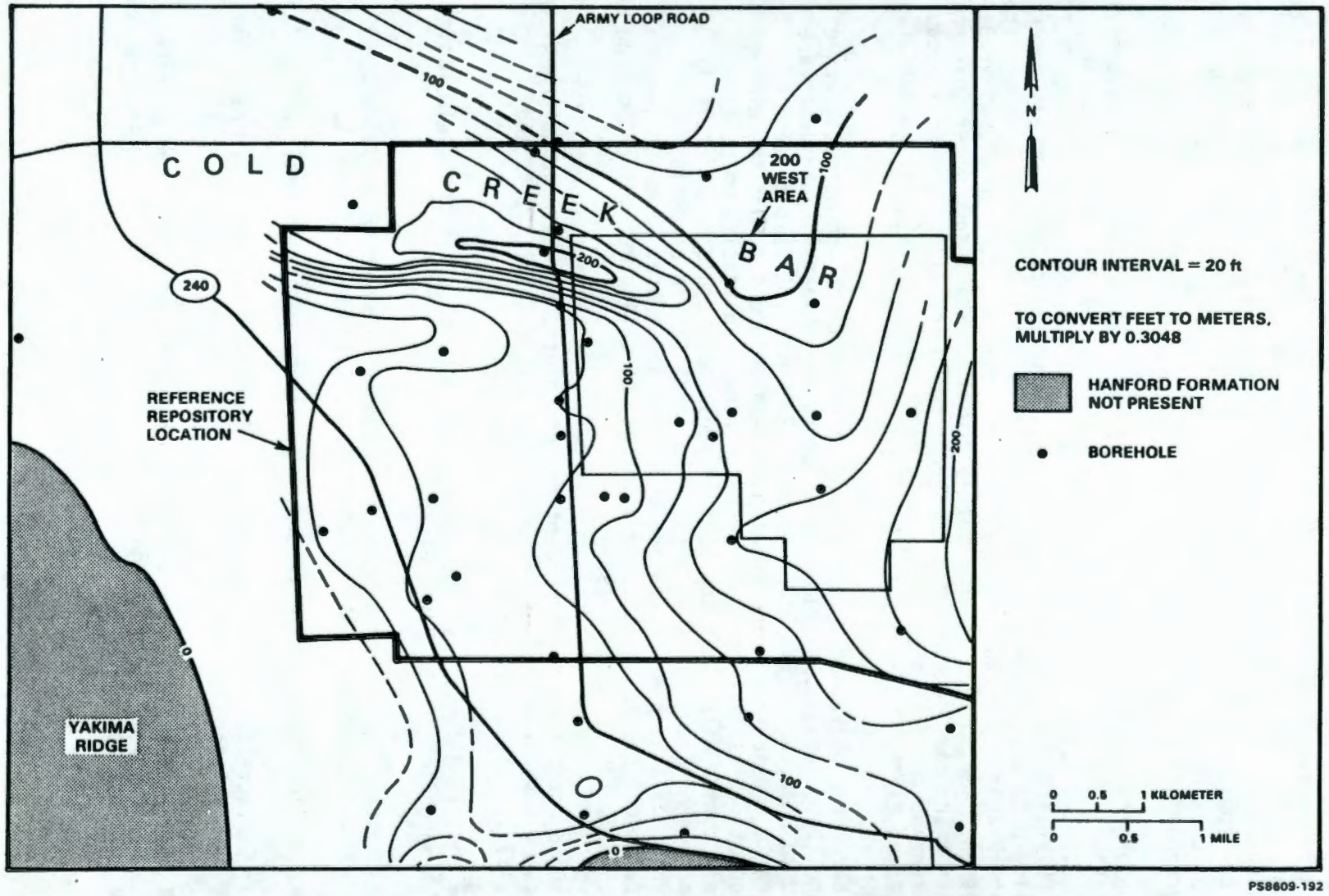

Figure 1.2-54. Isopach map of the Hanford Formation.

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pre-Quaternary tephra has been identified, while at least three exist for the Quaternary. The pre-Quaternary tephra, present at or near the top of the basal Ringold paleosol, is present in most core holes drilled within the reference repository location (see Section 1.2.2.2.2.1). The exact age of this tephra is not known but is inferred to be late Miocene, based on stratigraphic position.

Quaternary tephra horizons include the Mount St. Helens set S couplet, a Glacier Peak couplet (layers G and B), and a Mount Mazama tephra (see Section 1.2.1.3.5.1). These tephra are dated at approximately 13,000, 11,200, and 6,600 yr, respectively. One or more of these tephra are commonly observed in shallow pits and trenches in the Pasco Basin. A fourth tephra layer, the Mount St. Helens set M couplet, dated at less than or equal to 20,000 yr B.P. (Mullineaux, 1986, p. 22) is only rarely present. While many other Quaternary tephra from the Pacific Northwest are reported in the literature (Mullineaux, 1986; Sarna-Wojcicki et al., 1987), most have yet to be positively identified in the Pasco Basin.

Other correlative horizons include (1) contacts between stratigraphic units and (2) paleosols. Stratigraphic contacts between Ringold units are believed to be roughly time stratigraphic (Bjornstad, 1985); however, considerable erosion has occurred atop post-Ringold units, and therefore, these do not represent time-equivalent surfaces. Paleosols, which are relatively common within the suprabasalt sediments, could be potentially useful marker horizons, if they possess an identifiable assemblage of characteristics that are correlative over time and space. Some success in dating paleosols has occurred using a variety of dating methods (McSpadden and Tinsley, 1985; Pavich et al., 1985).

Planned activities to help identify, correlate, and date stratigraphic horizons are presented in Sections 8.3.1.2.3.3.1, 8.3.1.2.3.3.4, and 8.3.1.2.4.3.1. These include the following:

- Detailed lithologic and geophysical logs of all suprabasalt sediment boreholes in the Pasco Basin.
- Detailed geologic mapping of sediments in selected areas (White Bluffs, Yakima folds, Snively Basin, Cold Creek syncline).
- Shallow trenching in sediments overlying suspected faults.
- Characterization and age dating of all surface and subsurface tephra and paleosol horizons.
- A comprehensive, three-dimensional basin analysis of the suprabasalt sediments in the Pasco Basin, based on a combination of geophysical survey data, borehole, and outcrop studies.

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1.3 STRUCTURAL GEOLOGY AND TECTONICS OF THE CANDIDATE AREA AND SITE

This section describes the principal structural elements of the geologic setting. It includes a description of the regional tectonic setting that covers the Pacific Northwest, a more detailed description of the structural geology of the Columbia Plateau, and finally a focus on the immediate vicinity of the reference repository location. Topics discussed include the physical characteristics of structures, their origin, the rates at which they developed, and the possibilities for future development.

1.3.1 TECTONIC FRAMEWORK

The Columbia Plateau is a part of the North American continental plate. The Columbia Plateau lies east of the Pacific and Juan de Fuca oceanic plates and is separated from them by the Cascade Range, Puget-Willamette Lowland, and Coast Range geologic provinces. It is further bounded on the north by the Okanogan Highlands, on the east by the Northern Rocky Mountains and Idaho Batholith, and on the south by the High Lava Plains and Snake River Plain. An index map to these geologic subdivisions is presented in Figure 1.3-1.

1.3.1.1 Pre-Cenozoic plate tectonic setting

The Paleozoic and Mesozoic plate tectonic development of the Pacific Northwest is difficult to interpret, since outcrop exposures of pre-Cenozoic rocks are limited. In many cases, the exposed pre-Cenozoic rocks show evidence of complex structural deformation and (or) metamorphism, which further complicates interpretation of their history. Therefore, the size and configuration of pre-Cenozoic lithospheric plates and accreted terranes, along with their sense of relative motion, remain equivocal. The following is a brief introduction to the main elements of the pre-Cenozoic tectonic development of the Pacific Northwest. More detailed discussions of the pre-Cenozoic plate tectonic evolution of the Pacific Northwest can be found in Dickinson (1977, pp. 137-155), Davis et al. (1978, pp. 1-32), Hamilton (1978, pp. 33-70), Brooks and Vallier (1978, pp. 133-161), and Jones et al. (1982, pp. 70-84).

Interpretations of the Paleozoic and Mesozoic plate tectonic history of the Pacific Northwest have evolved over the years from concepts of in situ sedimentation and orogenesis in geosynclines, to concepts involving mobile lithospheric plates and accreted terranes. Since the late 1960's, theories relating mountain building to subduction zones have become common. These theories include the concept that crustal fragments of varying origin, which are carried by the migrating oceanic plates, become accreted to the continental masses. Collision of these allochthonous terranes with the North American plate during pre-Cenozoic time (Fig. 1.3-2) and subsequent translation and rotation of these terranes are thought to have produced the

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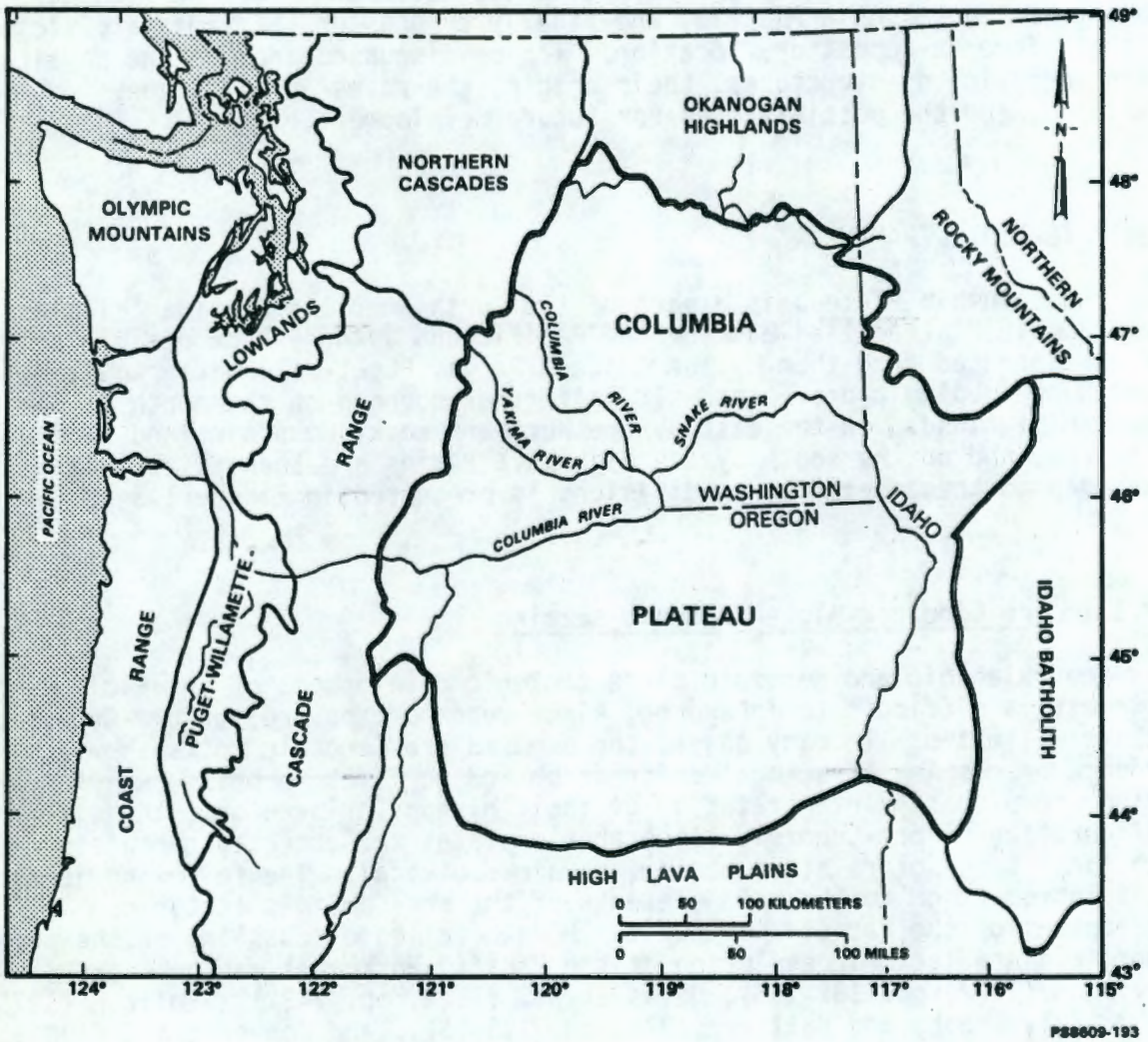

Figure 1.3-1. Index map of geologic provinces (modified from Myers/Price et al., 1979, p. II-4).

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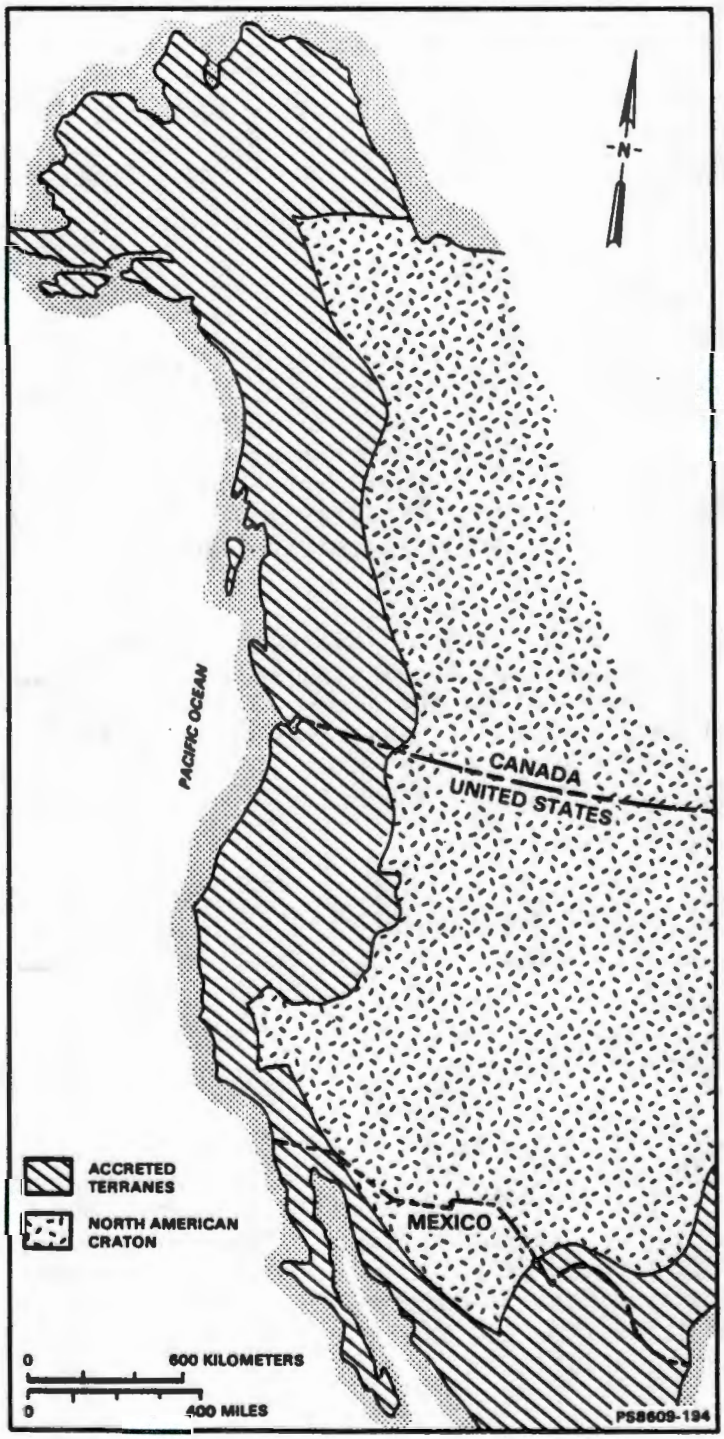

Figure 1.3-2. Map showing suggested distribution of allochthonous terrains in western North America (modified from Ben-Avraham et al., 1981).

current collage of rock types along western North America (Davis, 1977, pp. 2RC.1-2.C.20; Davis et al., 1978, pp. 1-32; Coney et al., 1980, pp. 329-333; Ben-Avraham et al., 1981, pp. 47-54; Jones et al., 1982, pp. 70-84). Collision and accretion of these terranes with western North America may have been a principal force causing some pre-Cenozoic orogenies (Ben-Avraham et al., 1981, pp. 52-54; Jones et al., 1982, pp. 82-84).

1.3.1.2 Cenozoic plate tectonic setting

The Cenozoic plate tectonic history of the Pacific Northwest is complex, but better understood and constrained by geologic data than is the pre-Cenozoic plate tectonic history. One interpretation for the plate configurations and motions inferred for western North America from late Cretaceous to present is shown in Figure 1.3-3 (Dickinson, 1979, p. 2). It should be noted, however, that this interpretation of data is not unique. More recent summaries can be found in Duncan (1982), Engebretson et al. (1984, 1985), and Wells et al. (1984).

While the current plate tectonic framework of the Pacific Northwest is reasonably well understood, the details regarding the borders and behavior of the interacting plates are still not clear. Questions concerning whether subduction is actively continuing, the rates at which it is occurring, and the configuration of the plate boundaries have been debated over the past decade (Heaton and Hartzell, 1987; Tabor and Smith, 1985; Tabor, 1986; Drake, 1982).

1.3.2 TECTONIC HISTORY OF THE CANDIDATE AREA

1.3.2.1 Volcanic history

The Pacific Northwest has experienced a long history of igneous activity. This activity has produced a diverse assemblage of intrusive and extrusive volcanic rocks. The geologic record of igneous processes and events during the past 60 m.y. or so (i.e., Cenozoic Era) is reasonably well preserved, and provides ample basis for predicting the likelihood and nature of future igneous activity that could affect the Pasco Basin. A summary of Cenozoic igneous activity of the Pacific Northwest is presented in Table 1.3-1. Figures 1.3-4 and 1.3-5 show the chronology and geographic distribution of the events described in the table.

1.3.2.1.1 Volcanism of the Columbia River Basalt Group

The eruption of continental flood basalts to form the Columbia Plateau marked what is perhaps the most significant episode of volcanism in the region. Although rare, flood basalt provinces occur on every continent and

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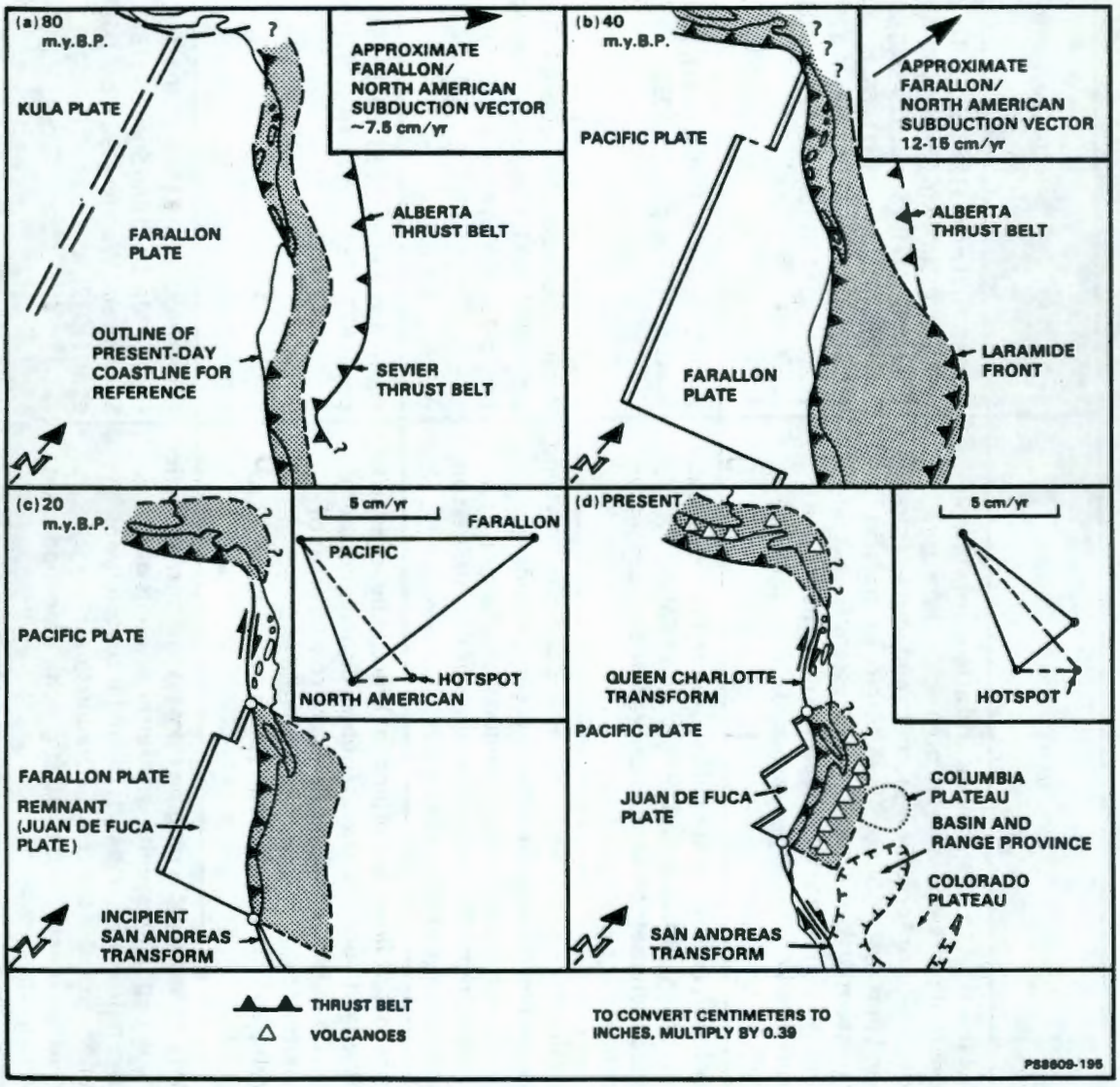

Figure 1.3-3. Sketch maps of plate configurations during the Cenozoic (after Dickinson, 1979, p. 2).

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Table 1.3-1. Summary of Cenozoic igneous activity in the Pacific Northwest (sheet 1 of 4)

Designation on Figures 1.3-4 and 1.3-5	Description	Selected references
A	Marine tholeiitic to alkalic basalt and attendant volcanic breccias that represent accreted oceanic crust and (or) islands (Roseburg Formation-southern and south-central Oregon Coast Range; Siletz River Volanics-central and northwestern Oregon Coast Range; Crescent formation-Coast of Washington State). Reported radiometric and biostratigraphic data suggest an approximate age of 66 to 48 m.y.B.P.	Armentrout et al. (1983, p. 15, 17, 22, 32, 50, 55, 59, 63, 70, 74); Baldwin (1984, pp. 1-40); Brown et al. (1960); Cady (1975; pp. 575-582); Duncan (1982; pp. 10827-10837); Rau (1966, pp. 1-66);Snavely et al. (1968, pp. 458-481; 1977, pp. 9-12); Snavely et al. (1980, pp. 143-146); Wolfe and McKee (1972, pp. 1-70).
B	Alkalic basalt and attendant pillow lavas and breccias of the Yachats basalts of the central Oregon Coast Range. Reported radiometric and biostratigraphic data suggest an approximate age of 43 to 38 m.y.B.P.	Armentrout et al. (1983, p. 31); Snavely and MacLeod (1974, pp. 395-403).
C	Chiefly subaerial alkalic basalt to basaltic andesite flows and submarine breccias associated with oceanic islands (Tillamook volcanics-northern Oregon Coast Range). Reported radiometric and biostratigraphic data suggest an approximate age of 47 to 41 m.y.B.P.	Armentrout et al. (1983, pp. 45, 50); Duncan (1982, pp. 10827-10837); Niem and Van Atta (1973, pp. 75-132); Warren et al. (1945).
D	Subaerial basalt flows and attendant breccias believed to be associated with oceanic islands (Goble volcanics-northern Oregon Coast Range and southwestern coastal areas of Washington State). Reported radiometric and biostratigraphic data suggest an approximate age of 47 to 39 m.y.B.P.	Armentrout et al. (1983, pp. 50, 54); Duncan (1982, pp. 10827-10837); Warren et al. (1945, pp. 1-39).
E	Primarily intrusive rocks ranging from iron-rich granophyric gabbro to nepheline syenite with lesser amounts of extrusive pillow lavas and tuffs of similar compositions (unnamed; found in the central Oregon Coast Range). Reported radiometric and biostratigraphic data suggest an age of 34 to 30 m.y.B.P.	Armentrout et al. (1983, p. 3031); Fiebelkorn et al. (1982); MacLeod and Snavely (1973, pp. 47-74); Snavely and Wagner (1961, pp. D156-D161); Snavely et al. (1972); Vokes et al. (1949).

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Table 1.3-1. Summary of Cenozoic igneous activity in the Pacific Northwest (sheet 2 of 4)

Designation on Figures 1.3-4 and 1.3-5	Description	Selected references
F-J	Calc-alkalic to alkalic volcanic and intrusive rocks that represent the earliest known Cenozoic arc volcanism in the Pacific Northwest. Volcanism began in Montana in the late Paleocene and migrated westward until activity ceased in the late Eocene to early Oligocene. Includes: Challis-Absaroka Volcanics (F) northern Washington, north and central Idaho, and western Montana; Silver Pass Volcanic Member-Swauk Formation (G) Naches Formation (H) and Teanaway Formation (I) central Washington; Clarno Formation-central Oregon. Reported radiometric and biostratigraphic data suggest an approximate age for this arc activity of 58 to 36 m.y.B.P.	Armstrong (1975, p. 50; 1978, pp. 265-282); Dickinson (1979, pp. 7-12); Enlows and Parker (1972, pp. 104-110); Gresens (1982, pp. 218-229); Hammond (1979, pp. 227-234); Nilsen and McKee (1979, pp. 263-269); Pearson and Obradovich (1977, pp. 1-41); Snyder et al. (1976, pp. 91-106); Tabor et al. (1984, pp. 30-43); Taylor (1981, pp. 107-112).
K	The Western Cascade Group of Hammond (1979, pp. 222-223) which encompasses primarily basaltic to dacitic extrusive and intrusive rocks of the ancestral Cascade Range in northern California, Oregon, Washington, and southern British Columbia. Fission-track age determinations (Vance, 1982, p. 241) suggest onset of ancestral Cascade volcanism was approximately 38 m.y.B.P. Upper age of the Western Cascade Group, as defined by Hammond (1979, p. 223), is approximately 5 m.y.B.P.	Armstrong (1978, pp. 265-282); Church (1976, pp. 175-188); Fiske et al. (1963, pp. 3-64); Hammond (1979, pp. 219-237; 1980, pp. 1-31); Hammond et al. (1980, pp. 133-167); Lipman et al. (1972, pp. 217-248); Luedke and Smith (1982); MacDonald (1966, pp. 65-96); McBirney (1978, pp. 437-456); McBirney et al. (1974, pp. 585-589); Peck et al. (1964, pp. 1-56); Priest (1982, pp. 6-15); Snyder et al. (1976, pp. 91-106); Swanson (1966, pp. 1293-1314); Vance (1982, p. 241); Vance and Naesser (1977, p. 520); Williams et al. (1982, pp. 2767-2781); Wise (1970, pp. 1-45).
L	High-alumina basalt, basaltic andesite, and attendant pyroclastic rocks of the High Cascade Group (Hammond, 1979, pp. 223-226). These rocks comprise about 85% of the High Cascade Group in southern Washington, Oregon, and northern California. Reported radiometric and biostratigraphic data suggest that eruptive activity began approximately 5 m.y.B.P. and has continued until present.	Allen (1975, pp. 145-157); Hammond (1979, pp. 223-226; 1980, pp. 16-22); Luedke and Smith (1982); McBirney (1978, pp. 437-456); Peck et al. (1964, pp. 1-56); Taylor (1968, pp. 3-33; 1980, pp. 55-58); Tolan and Beeson (1984, pp. 475-477); Trimble (1963, pp. 36-43); Wise (1970, pp. 29-41).

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Table 1.3-1. Summary of Cenozoic igneous activity in the Pacific Northwest (sheet 3 of 4)

Designation on Figures 1.3-4 and 1.3-5	Description	Selected references
M	Andesites, dacites, and attendant pyroclasitc rocks of the High Cascade Group of Hammond (1979, pp. 223-226). These rocks comprise approximately 15% of the High Cascade Group in southern British Columbia, Washington, Oregon, and northern California. These rocks are equivalent in age to the high-alumina basalts. Young composite volcanic cones that form the peaks of the Cascade Range (e.g., Mount Hood, Mount St. Helens, Mount Rainier) are less than 700,000 yr old. Also included in the High Cascade Group are the Simcoe Volcanics of southern Washington and Newberry Volcano of east-central Oregon (Hammond, 1979, p. 222; MacLeod and Sammel, 1982, p. 123).	Fiske et al. (1963, pp. 65-90); Hammond (1979, pp. 223-226; 1980, pp. 16-22); Harris (1976, pp. 1-320); Luedke and Smith (1982); MacLeod and Sammel (1982, pp. 123-131); MacLeod et al. (1981, pp. 85-103); McBirney (1978, pp. 437-456); Priest (1982, pp. 5-15); Priest et al. (1981); Taylor (1968, pp. 3-33; 1980, pp. 55-58); White (1980, pp. 1-26); White and McBirney (1978, pp. 51-92); Wise (1969, pp. 969-1006).
N	Alkali basalt and trachyandesite flows of the John Day Formation of central Oregon. These flows were of local origin in contrast to the bulk of the John Day Formation, which was derived from the ancestral Cascade Range (Western Cascade Group). Reported radiometric and biostratigraphic data suggest an approximate age of 26 to 25 m.y.B.P.	Peck (1964, pp. 1-26); Robinson (1969, pp. 349-360); Robinson and Brem (1981, pp. 29-40); Swanson (1969); Robinson et al. (1984, pp. 229-232)
O	Subaerial tholeiitic flood basalt flows of the Columbia River Basalt Group. Reported radiometric data suggest an approximate age of 17.5 to 6 m.y.B.P.	Camp (1981, pp. 669-688); McKee et al. (1977); McKee et al. (1981, pp. 31-33); Myers/Price (1979, pp. II.16-II.61); Reidel (1983, pp. 519-542); Swanson et al. (1975, pp. 877-905); Swanson et al. (1979a, pp. 1-59).
P	Basalt, andesite, and rhyolite flows of the Strawberry volcanics of central Oregon. Reported radiometric and biostratigraphic data suggest an approximate age of 20 to 9 m.y.B.P.	Robyn (1977, pp. 1-197; 1978); Robyn et al. (1977, pp. 488-489); Thayer and Brown (1966, pp. 75-78); Wheeler (1976, pp. 1-94; 1982, pp. 3-7).

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Table 1.3-1. Summary of Cenozoic igneous activity in the Pacific Northwest (sheet 4 of 4)

Designation on Figures 1.3-4 and 1.3-5	Description	Selected references
Q	Subaerial basalts, andesites, and rhyolites of the Steens and Owyhee Basalts of southwestern Idaho, southeastern Oregon, northeastern California, and northwestern Nevada. Reported radiometric and biostratigraphic data suggest an approximate age of 20 to 10 m.y.B.P.	Asher (1968); Baksi et al. (1967, pp. 6299-6308); Baldwin (1981, pp. 123-135); Corcoran et al. (1962); Luedke and Smith (1982); McIntyre (1972, pp. 1-115); Pansze (1975, pp. 1-80).
R	Basalt and rhyolite flows and their attendant pyroclastic rocks of the Basin and Range region of central and southern Oregon (High Lava Plains), northwestern California, and northern Nevada. Reported radiometric and biostratigraphic data suggest that volcanism began approximately 15 m.y.B.P. and has continued into the Holocene.	Baldwin (1981, pp. 113-135); Christiensen and McKee (1978, pp. 283-311); Cole and Armentrout (1979, pp. 297-323); Luedke and Smith (1982); McKee et al. (1983, pp. 292-304); Stewart et al. (1977, pp. 67-77); Stewart (1978, pp. 1-25); Walker and Nolf (1981, pp. 105-111).
S	Mainly basalt flows with lesser amounts of associated silicic volcanic rocks of the Snake River Plain of southern Idaho (Idavada volcanics, Idaho Group, and Snake River Group). Age of eruptive activity decreases from west to east, and is thought to be related to a migrating hot spot. Reported radiometric and biostratigraphic data suggest onset of volcanism was approximately 10 m.y.B.P. and has continued to present.	Armstrong (1975); Armstrong et al. (1975, pp. 225-251); Cole and Armentrout (1979, pp. 297-323); King (1977, pp. 46-56); Snyder et al. (1976, pp. 91-105); Strowd (1980, pp. 22-32, 43-59).

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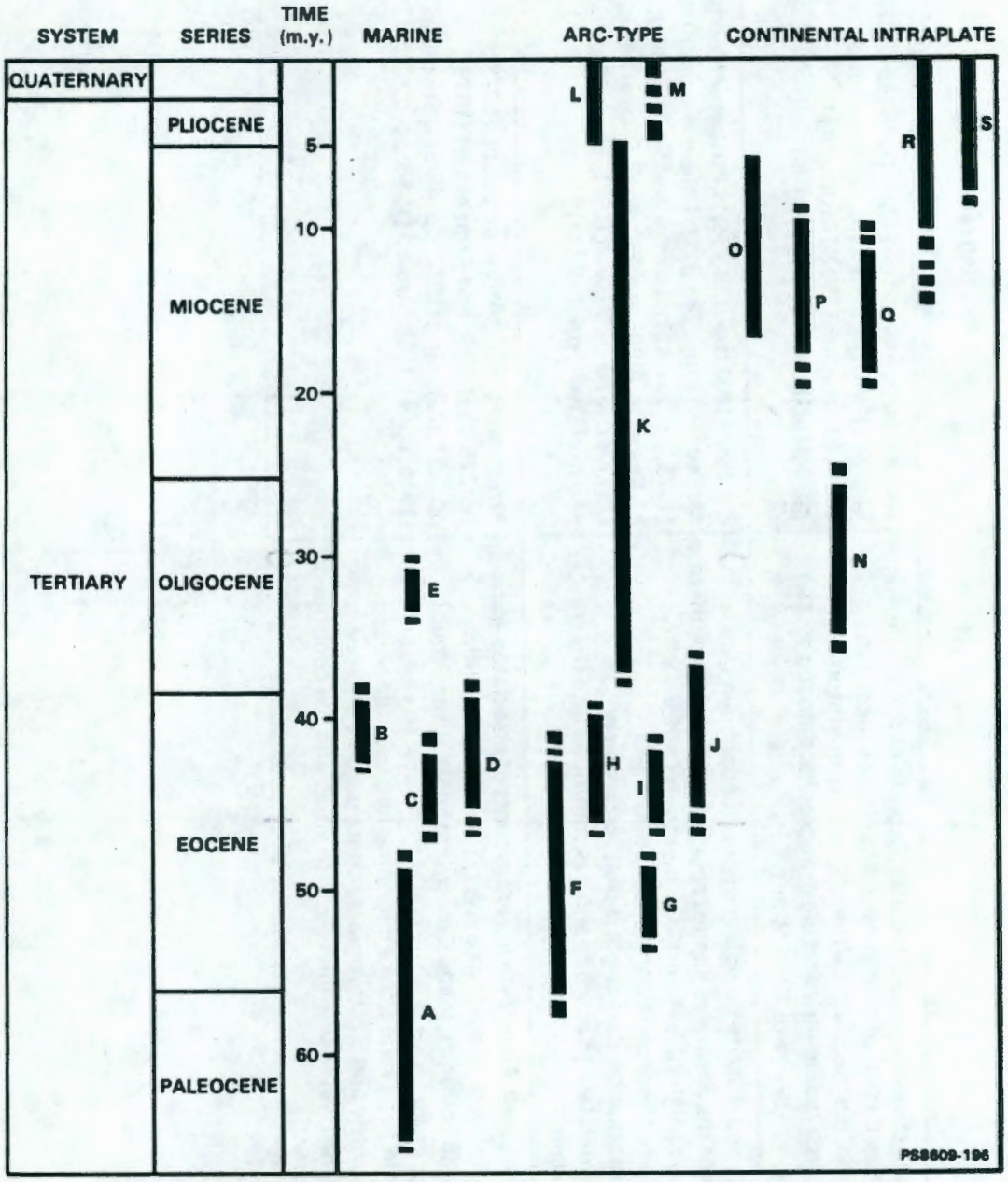

Figure 1.3-4. Chronology of igneous activity. Letters refer to Table 1.3-1.

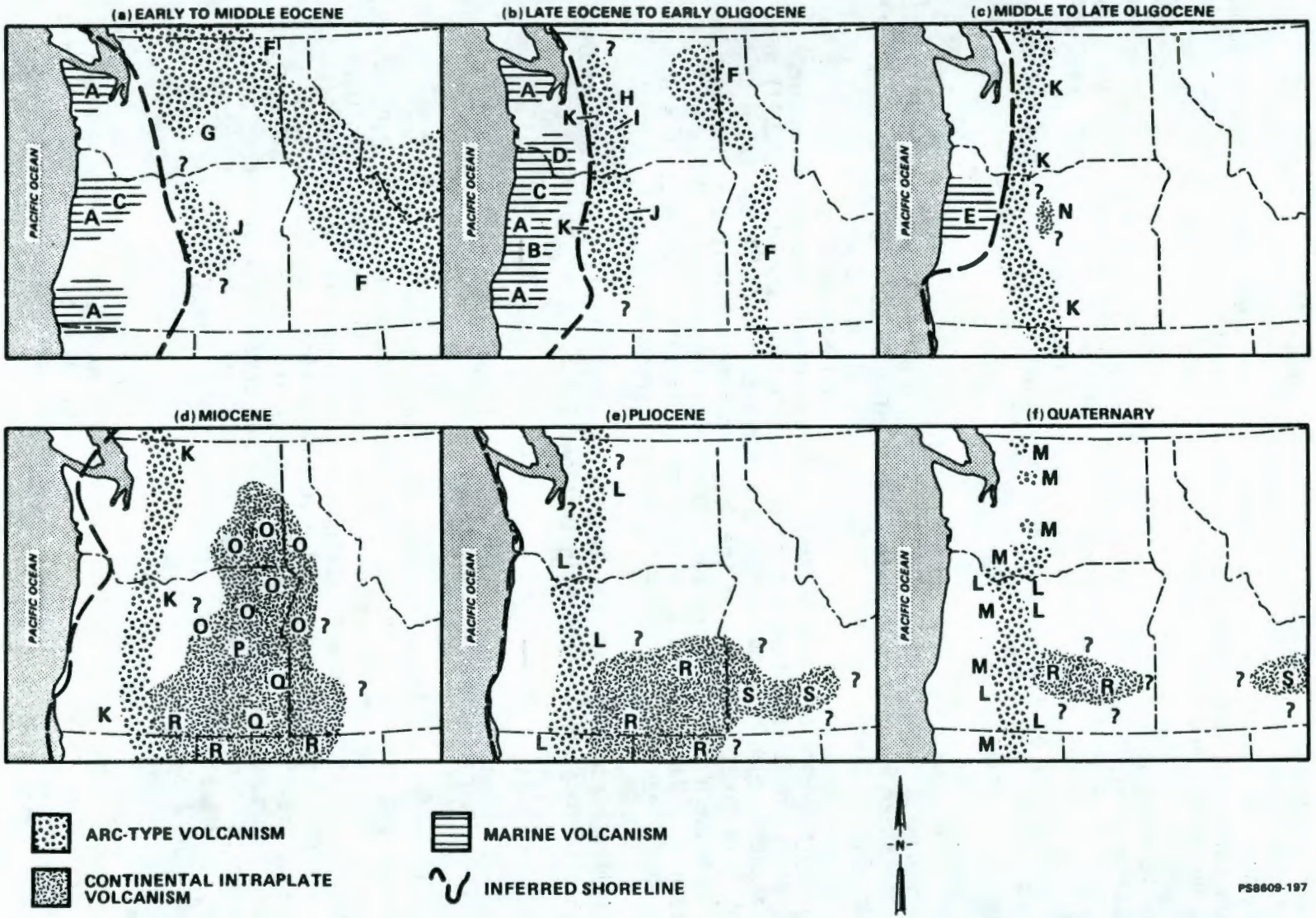

Figure 1.3-5. Sketch maps showing locations of igneous activity. Letters refer to Table 1.3-1.

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are important geologic features (Basaltic Volcanism Study Project, 1981). The areal distribution of Columbia River basalt is shown in Figure 1.3-6. The debate continues about the tectonic processes that gave rise to this episode, and many questions concerning the petrogenetic evolution of the Columbia River basalt are unresolved (Hooper, 1982, pp. 1467-1468; 1984, pp. 495-499).

It is known that the Columbia River basalt lavas were erupted during the period from ~17 to 6 m.y.B.P. (McKee et al., 1977, pp. 463-464; 1981, p. 31). During this 11-m.y. period, ~170,000 km^3 (41,000 mi^3) of basalt were extruded (Tolan et al., 1987). However, these lavas did not erupt at a uniform rate, with more than 98% by volume being erupted during the first 2.5 m.y.--from 17 to 14.5 m.y.B.P. The period from ~14.5 to 6 m.y.B.P. was marked by considerable waning volcanism.

The only known dikes and vents for Columbia River basalt in the vicinity of the Pasco Basin are along the eastern margin of the basin, from Ice Harbor Dam on the Snake River northward to the vicinity of Basin City, Washington (see Fig. 1.2-2; Swanson et al., 1980). These dikes and vents are part of a system that extends for more than 90 km (55 mi) (Swanson et al., 1975, p. 894). A sequence of flows of the Ice Harbor Member (Saddle Mountains Basalt) was erupted from this system ~8.5 m.y.B.P. (McKee et al., 1977) and represents the youngest known Columbia River basalt unit in the Pasco Basin. Although only dikes and vents of the Ice Harbor Member have been observed along the eastern margin of the Pasco Basin, the existence of dikes of Grande Ronde Basalt or Wanapum Basalt is still possible within the Pasco Basin proper, where they could be concealed beneath younger units.

Detailed discussions of the stratigraphy and lithology of the Columbia River Basalt Group are presented in Sections 1.2.1 and 4.1.1.

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1.3.2.1.2 Volcanism of the Cascade Range

The extrusive and intrusive rocks that make up the Cascade Range represent a long history of arc-type volcanism that began ~38 m.y.B.P. (Vance, 1982, p. 241) and has continued until the present. The volcanoes in the Cascade Range consist of a wide variety of lavas and pyroclastic rocks that generally range from basalt to dacite in composition (see Table 1.3-1). These rocks are divided into two groups (Hammond, 1979): an older Western Cascade Group that encompasses rocks emplaced from the onset of Cascadian volcanic activity up to ~5 m.y.B.P., and a younger High Cascade Group that encompasses rocks emplaced since ~5 m.y.B.P. (see Table 1.3-1, items K, L, and M; also Fig. 1.3-4 and 1.3-6).

The only deposits in the Pasco Basin derived from Cascade volcanism are relatively thin layers of air-fall tephra and reworked tuffaceous sediments occasionally interbedded with flows of Columbia River basalt. Air-fall tuffs also are associated with suprabasalt sedimentary deposits. These thin tuff units are described in Section 1.2.2.2.

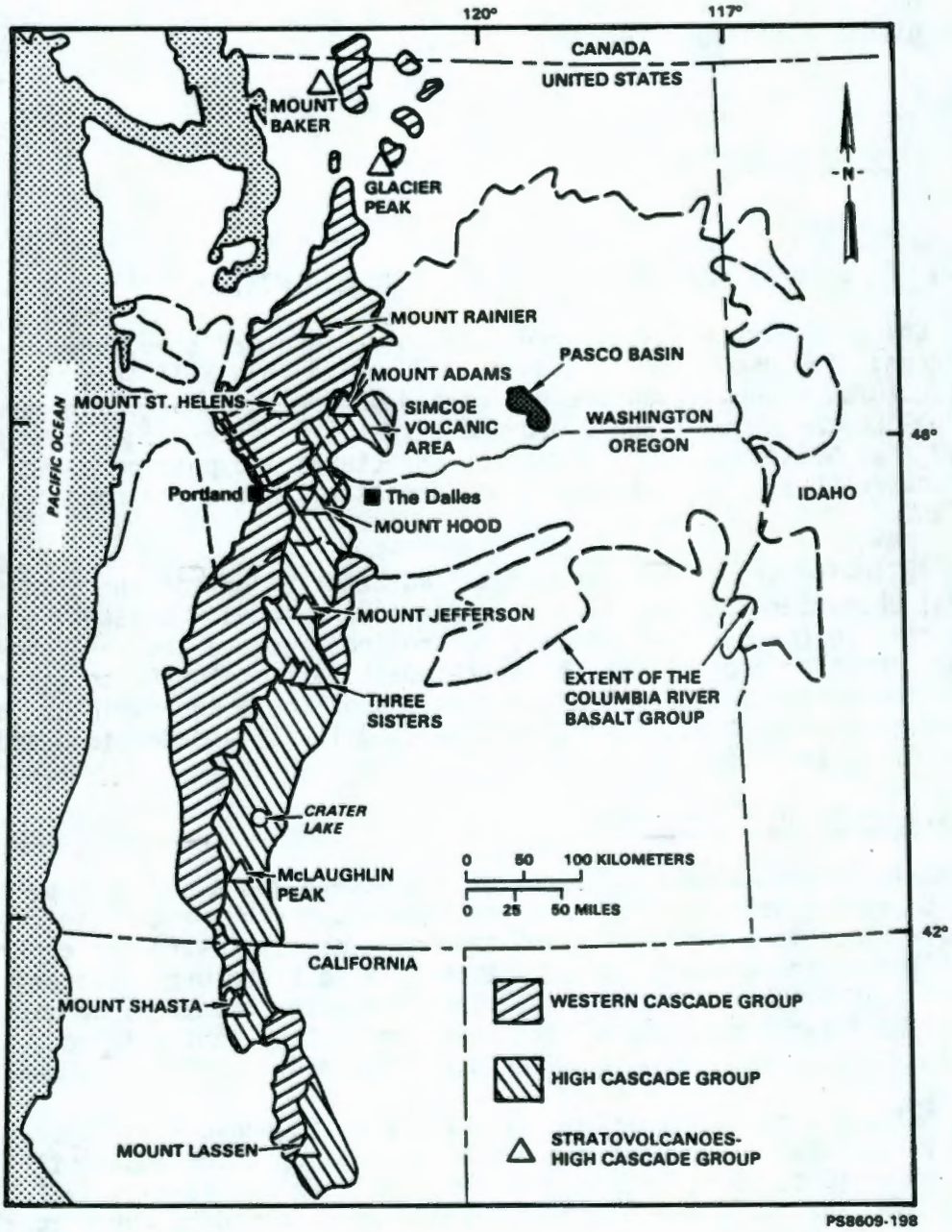

Figure 1.3-6. Areal extent of Columbia River Basalt Group in relation to the Cascade Range.

1.3.2.1.3 Potential for future volcanism

A discussion of potential volcanic hazards from renewed flood basalt activity on the Columbia Plateau and volcanism associated with the Cascade Range is given in Section 1.5.3.

1.3.2.2 Structural history

1.3.2.2.1 Structural subdivisions of the Columbia Plateau

The Columbia Plateau is divided into three informal structural subprovinces: Palouse, Blue Mountains, and Yakima Fold Belt (Fig. 1.3-7). These structural subprovinces are delineated on the basis of their structural fabric, unlike the physiographic provinces that are defined on the basis of landforms (see Section 1.1). Therefore, structural and physiographic subprovinces with similar names will not necessarily have the same geographic boundaries.

The following sections present detailed descriptions of the origins and structural characteristics of each of these subprovinces. Greatest emphasis is given here to the Yakima Fold Belt subprovince because the reference repository location and all but the easternmost part of the Pasco Basin lie within its boundaries. Additional discussions of these subprovinces can be found in Myers/Price et al. (1979, pp. 11-72 to 11-73) and Caggiano and Duncan (1983, pp. 2-11 to 2-16).

1.3.2.2.1.1 Palouse subprovince

The Palouse subprovince consists of a northern and a southern part, referred to as the Palouse Slope and the Clearwater Embayment, respectively. The Palouse Slope is a regional slope that dips gently toward the central Columbia Plateau and exhibits only relatively mild structural deformation in comparison to the other subprovinces. The Clearwater Embayment consists of structural basins and uplifted blocks that are tilted, gently folded, and broken by numerous faults having a variety of trends.

The Palouse Slope is underlain by a wedge of Columbia River basalt that thins gradually toward the east and north and laps onto the adjacent highlands (Swanson and Wright, 1976; Camp and Hooper, 1981; Reidel et al., 1982, 1983). The paleoslope and its present-day expression were formed by the gradual rise of highlands to the east and north, and the subsidence of the Columbia Basin to the west.

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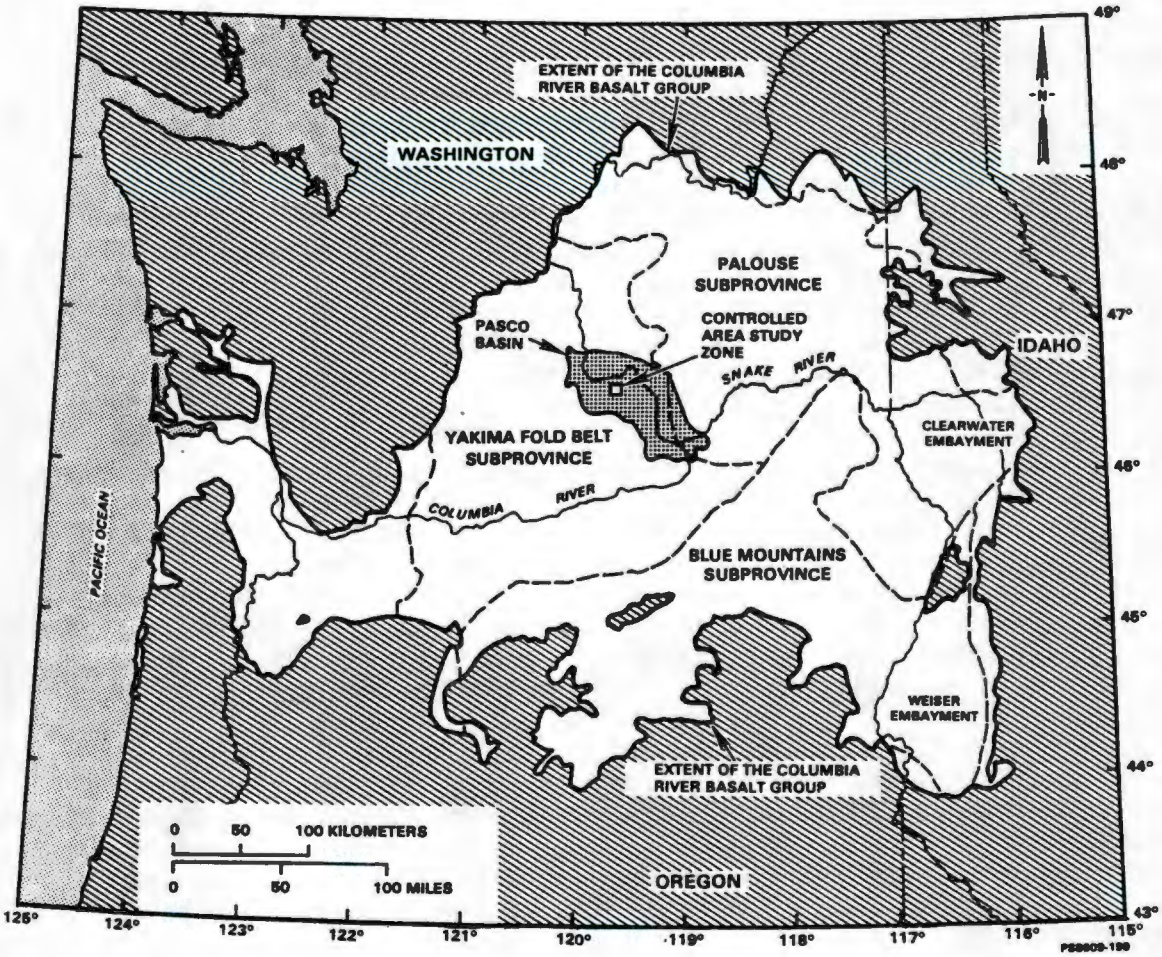

Figure 1.3-7. Index map to structural subprovinces of the Columbia Plateau, which is defined by the distribution of Columbia River basalt flows east of the Cascade Range.

North- to northwest-trending folds of low amplitude and long wavelength are superimposed on the Palouse Slope (Swanson et al., 1980). In the northeastern part of the Palouse Slope, northwest-trending zones of fractures spaced ~10 km (6 mi) apart and extending for 40 km (25 mi) or more are found near Cheney, Washington (Griggs, 1973). These fractures, informally called the Cheney fracture zone, are shown in Figure 1.3-8. This fracture system overlies shallow basement structures, which are presumably influential in the development of these zones of closely spaced fractures. The topographic expression of these fractures has been accentuated by erosion during the Pleistocene cataclysmic floods. No evidence has been found of any late Quaternary movement along any of these fractures (Rigby and Othberg, 1979).

The west-dipping paleoslope is interpreted to have had a gradient of only 2 to 5 m/km (11 to 27 ft/mi) during late Grande Ronde time (~15.5 m.y.B.P.) (Long et al., 1980; Landon et al., 1982), ~2 m/km (11 ft/mi) during Wanapum (15.6 to 14.5 m.y.B.P.) and perhaps early Saddle Mountains time (14.5 to 6.0 m.y.B.P.) (Reidel et al., 1983), and a nearly constant gradient of ~1.5 to 2 m/km (8.2 to 11 ft/mi) since Pomona time (~12 m.y.B.P.; Swanson and Wright, 1976). The relative uniformity of the gradient of this west-dipping paleoslope since the early Miocene--and especially since 12 m.y.B.P.--when projected westward provides a regional plane from which to estimate relative uplift and subsidence within the Pasco Basin (Caggiano and Duncan, 1983).

The Clearwater Embayment is characterized by a pre-basalt terrain that was rugged and mountainous. This terrain had a well-developed system of valleys and ridges that formed as a result of faulted and folded basement rocks (Camp and Hooper, 1981; Swanson et al., 1979a, 1980). Three major topographic basins occur within this embayment: Troy, Lewiston, and Stites Basins (see Fig. 1.3-8). The Troy and Lewiston Basins are topographic expressions of broad fault-bounded synclines (Camp and Hooper, 1981). The southeastern limb of the Troy Basin grades into a monocline that merges northeastward along the strike into the Limekiln Fault. The Limekiln Fault is a normal fault that forms the southeast limb of the Lewiston Basin. The Lewiston Basin is a structural graben, bounded on the north by a faulted asymmetric anticline, the southern edge of which is a reverse fault that forms the north limb of the basin (Camp and Hooper, 1981; Hooper et al., 1985). The Stites Basin is interpreted to represent north-south trending pre-basalt structures that are similar to those observed in the Riggins, Idaho, area to the south (Hamilton, 1962). Reactivation of basement structures during basalt volcanism resulted in vertical block faulting and formation of the basin (Camp and Hooper, 1981).

The pattern and thickness of basalt flows in the basins suggest that all were developing during eruption of Grande Ronde Basalt. The Troy Basin started developing during late Grande Ronde time and continued to develop through Wanapum and Saddle Mountains time (Ross, 1978). The Lewiston Basin was developing by at least middle to late Grande Ronde time (Reidel, 1983) and had developed significant relief by the end of Wanapum time (Reidel, 1983; Camp and Hooper, 1981). The Stites Basin shows evidence for the earliest development in Grande Ronde time and accumulated a great thickness of Grande Ronde flows (Camp and Hooper, 1981). All three basins continued to develop after cessation of basaltic volcanism.

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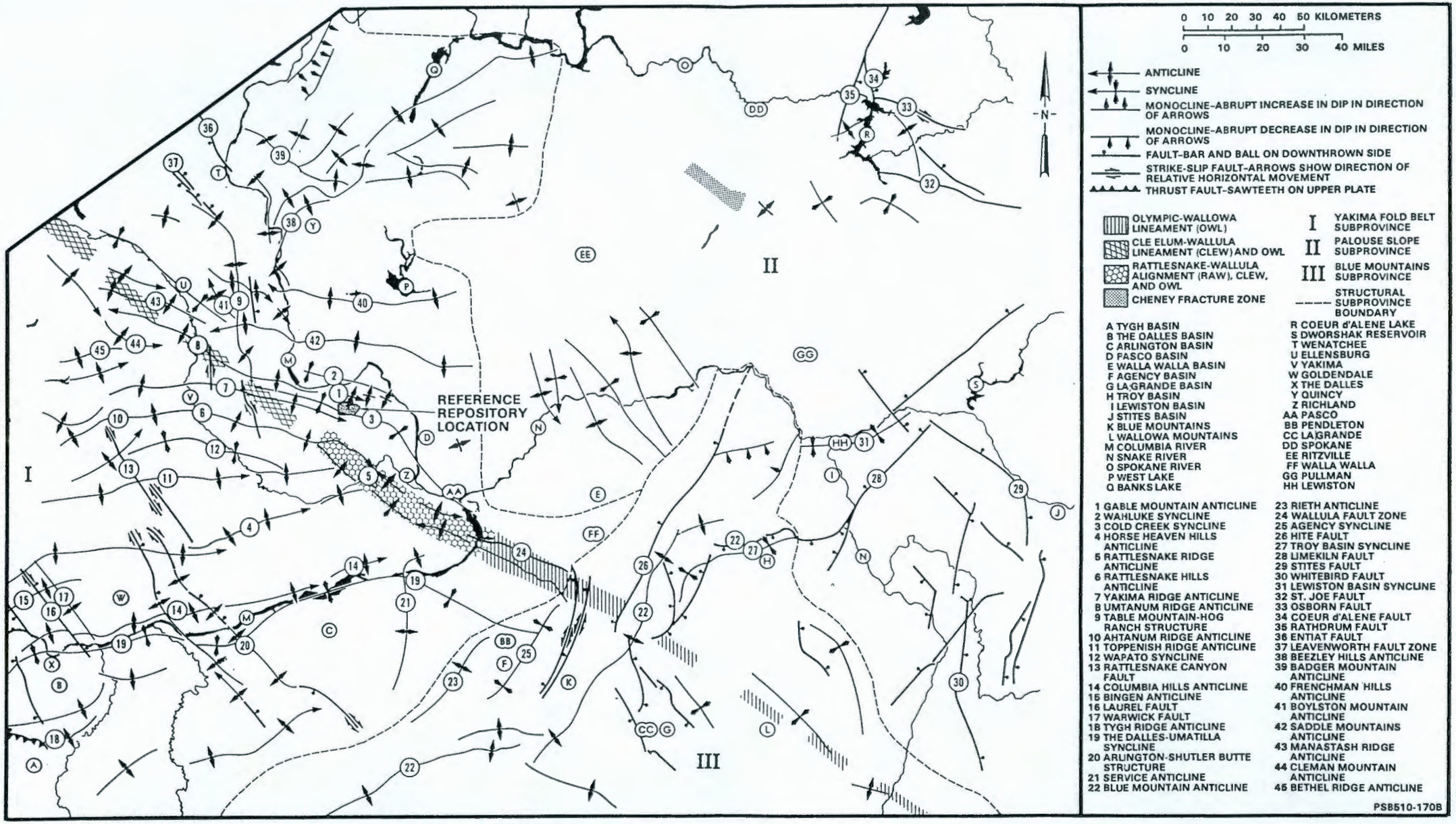

Figure 1.3-8. Structure map of the Columbia Plateau (modified from Tolan, 1986).

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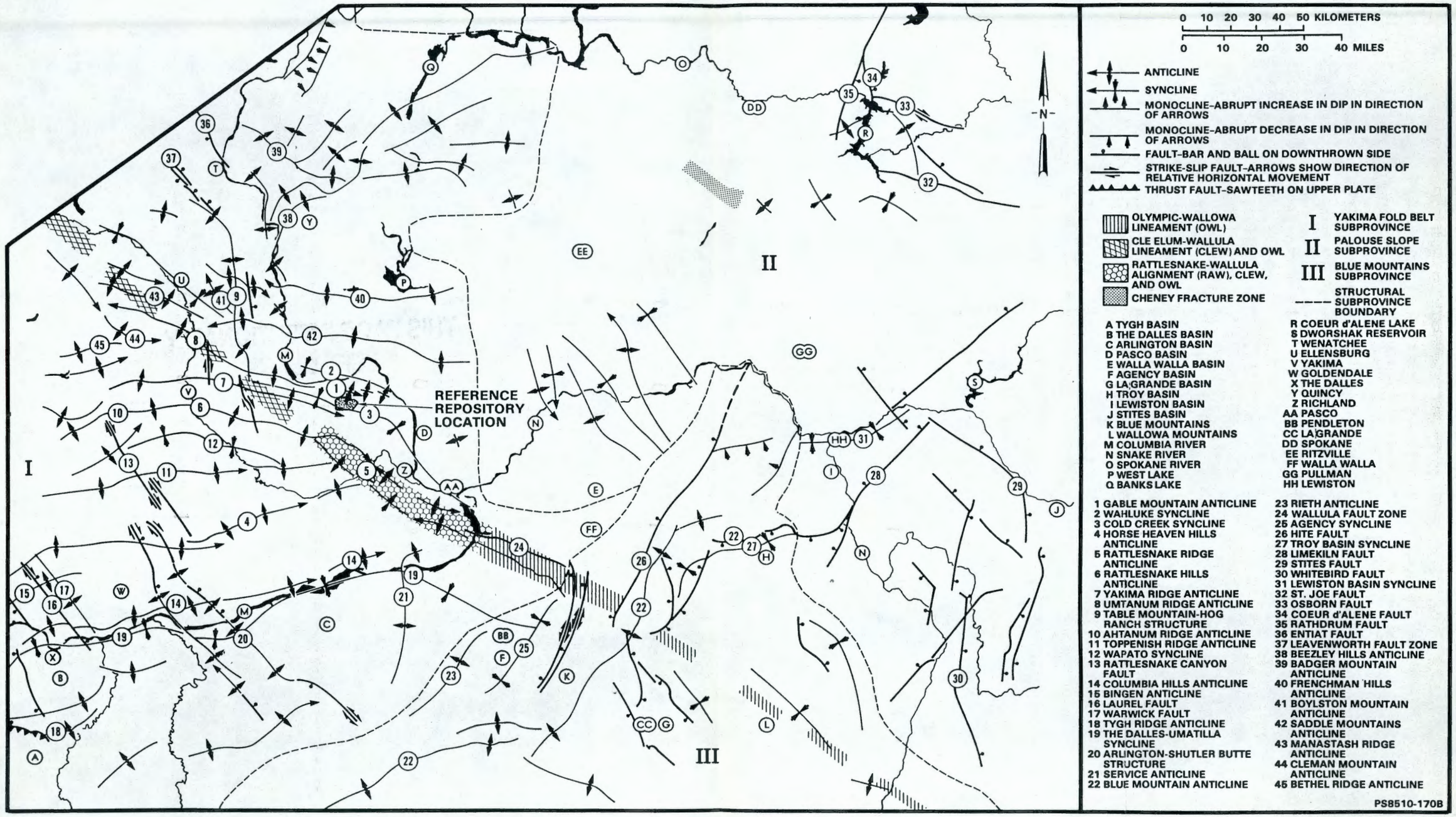

Figure 1.3-8. Structure map of the Columbia Plateau (modified from Tolan, 1986).

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The formation of these basins has been interpreted to be the result of horizontal, north-northwest, south-southeast compression (Ross, 1978; Camp and Hooper, 1981), east-west extension (Taubeneck, 1970), and a combination of the two (Reidel, 1983, 1984). The Lewiston and Troy Basins were interpreted to be the result primarily of the compression and, although the Stites Basin was not thought to be the direct result of that compression, extension along the north-south faults, over preexisting zones of weakness, that bound the basin are not incompatible with such a stress regime (Ross, 1978; Camp and Hooper, 1981).

Most folds and faults associated with these basins are the result of deformation that occurred contemporaneously with Columbia River basalt volcanism (Camp, 1981) over preexisting zones of weakness reflected in the prebasalt valley and ridge system. The anticline and reverse fault associated with the Lewiston Basin involve four basalt formations: Imnaha, Grande Ronde, Wanapum, and Saddle Mountains Basalts. Certain evidence listed below suggests that volcanism was contemporaneous with differential vertical movement of basement block, and that the resulting basins and faults may have formed in a north-south stress region dominated by east-west extension. The evidence for this includes the following:

- Recognition that the three basins formed as a result of a tilted block of the Nez Perce Plateau, which was uplifted along the Limekiln Fault (Camp, 1981), and uplift of the Palouse Slope along the east-west Lewiston Basin folds and faults; alternatively, the Lewiston Basin was downdropped relative to the Nez Perce Plateau and Palouse Slope and folded under north-south compression (Reidel, 1983).

- The Limekiln Fault is a normal fault that was active during Columbia River Basalt Group volcanism (Camp and Hooper, 1981; Reidel, 1978b, 1983).

- Movement along the Limekiln Fault may have occurred in response to regional uplift of the Blue Mountains during volcanism (Camp, 1976) or subsidence of the Lewiston Basin during volcanism (Reidel, 1978b, 1983).

- Parallel trends of dikes, faults, and a pre-basalt high along the present course of the Columbia River (Reidel, 1983).

- Dike swarms, which were feeders for the Columbia River basalt, contain an estimated 20,000 to 30,000 dikes whose average width is ~7 m (20 ft) and whose overall north-northwest trend is within the limits of the trend of post-Oligocene dike swarms in the adjoining extensional Basin and Range tectonic province (Taubeneck, 1970).

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1.3.2.2.1.2 Blue Mountains subprovince

The Blue Mountains subprovince (see Fig. 1.3-7) is a structurally diverse region dominated by the complexly faulted Blue Mountains anticlinorium in its northern portion and a series of structural basins in its central and southern portions. The structural basins are generally of two types: (1) fault-bounded basins (e.g., the La Grande, Baker, and Unity Basins) (see Fig. 1.3-8), and (2) fold-bounded basins (e.g., the John Day Basin). This section will primarily focus on structural features found in the northern and central portions of this subprovince because they lie closer to the controlled area study zone.

In the northern and central portions of the Blue Mountains proper, three main structural elements (Fig. 1.3-9) have been identified (Shannon and Wilson, 1979; Kienle, 1980): (1) the Blue Mountains anticlinorium, (2) the Hite Fault System, and (3) the La Grande Fault System.

Three additional major structural elements, the Service anticline, Wallula Fault Zone, and the southern portion of Raisz's (1945) Olympic-Wallowa lineament (see Fig. 1.3-8), cross the subprovince boundaries between the Blue Mountains and Yakima Fold Belt. The Service anticline will be discussed in this section; discussions of the Wallula Fault Zone can be found in Sections 1.3.2.2.1.3 and 1.3.2.2.2.5. The discussion of the southern portion of the Olympic-Wallowa lineament is found in the section on the La Grande Fault System. For a more complete discussion of the Olympic-Wallowa lineament, see Section 1.3.2.2.1.3.

Blue Mountains anticlinorium

The Blue Mountains anticlinorium is a broad, arcuate upwarp that extends more than 250 km (155 mi) from the foothills of the Cascade Range in northern Oregon to just west of the Lewiston Basin (see Fig. 1.3-8). In the past, numerous workers have characterized this structure as a gentle, symmetrical, anticlinal feature or a gentle anticlinorium with sporadic normal faults (Walker, 1973, 1979; Newcomb, 1965, 1970; Hogensen, 1964; WPPSS, 1977; Shannon and Wilson, 1973). However, more recent studies by Shannon and Wilson (1979), Kienle (1980), Kendall et al. (1981), Ross (1978, 1980), and Swanson et al. (1980) have found that the Blue Mountains anticlinorium contains a higher degree of structural complexity and is more intensely faulted than previously portrayed.

The Blue Mountains anticlinorium displays three different structural geometries (informally called "segments" in this report) along its length (see Fig. 1.3-9). The first structural segment of the Blue Mountains anticlinorium extends from the southwestern end of the Blue Mountains to Wilbur Mountain. This segment generally displays a symmetrical geometry (see Fig. 1.3-9, segment I) with both limbs dipping gently at 2° to 5° (Shannon and Wilson, 1979; Swanson et al., 1981).

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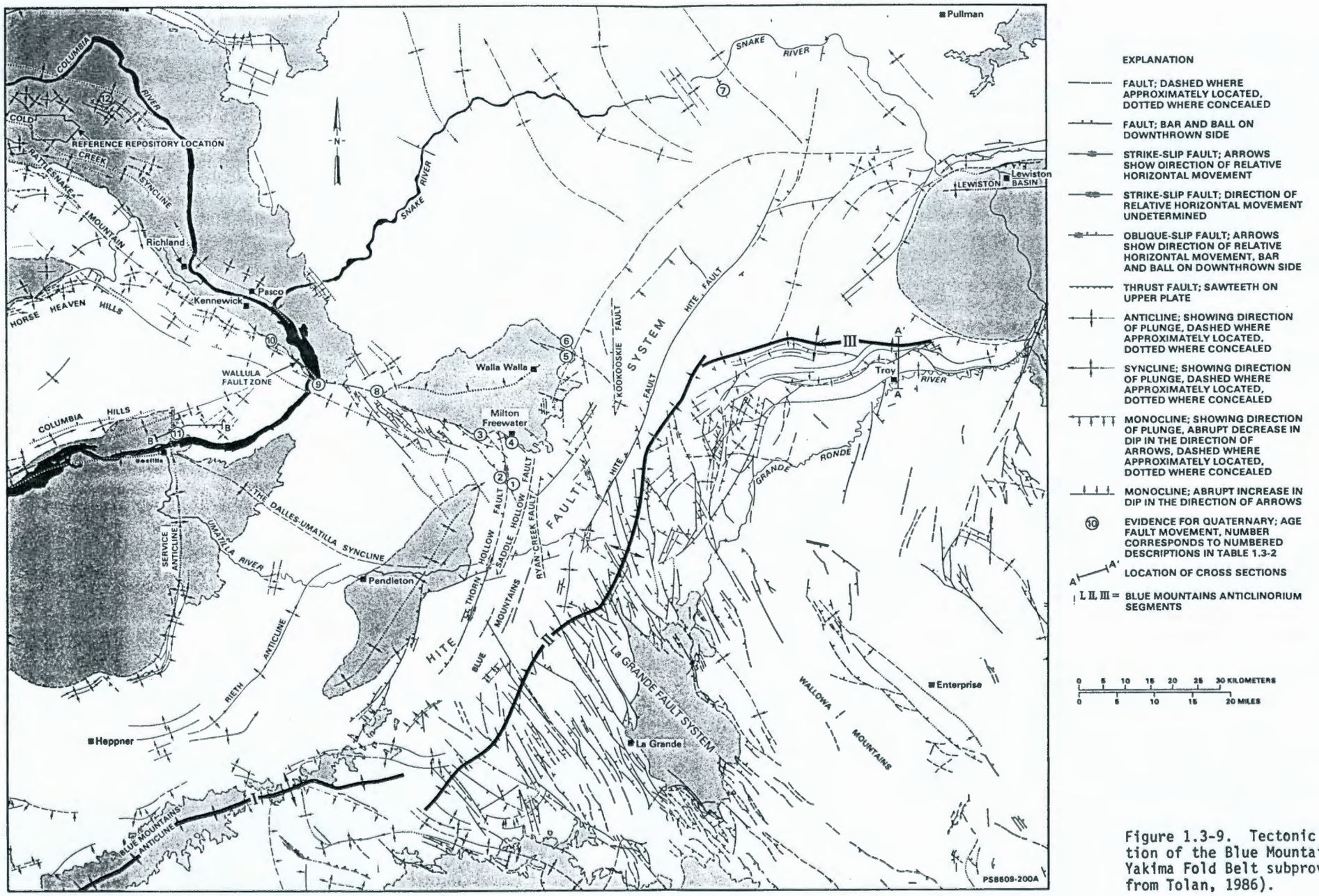

Figure 1.3-9. Tectonic map of a portion of the Blue Mountains, Palouse, and Yakima Fold Belt subprovinces (modified from Tolan, 1986).

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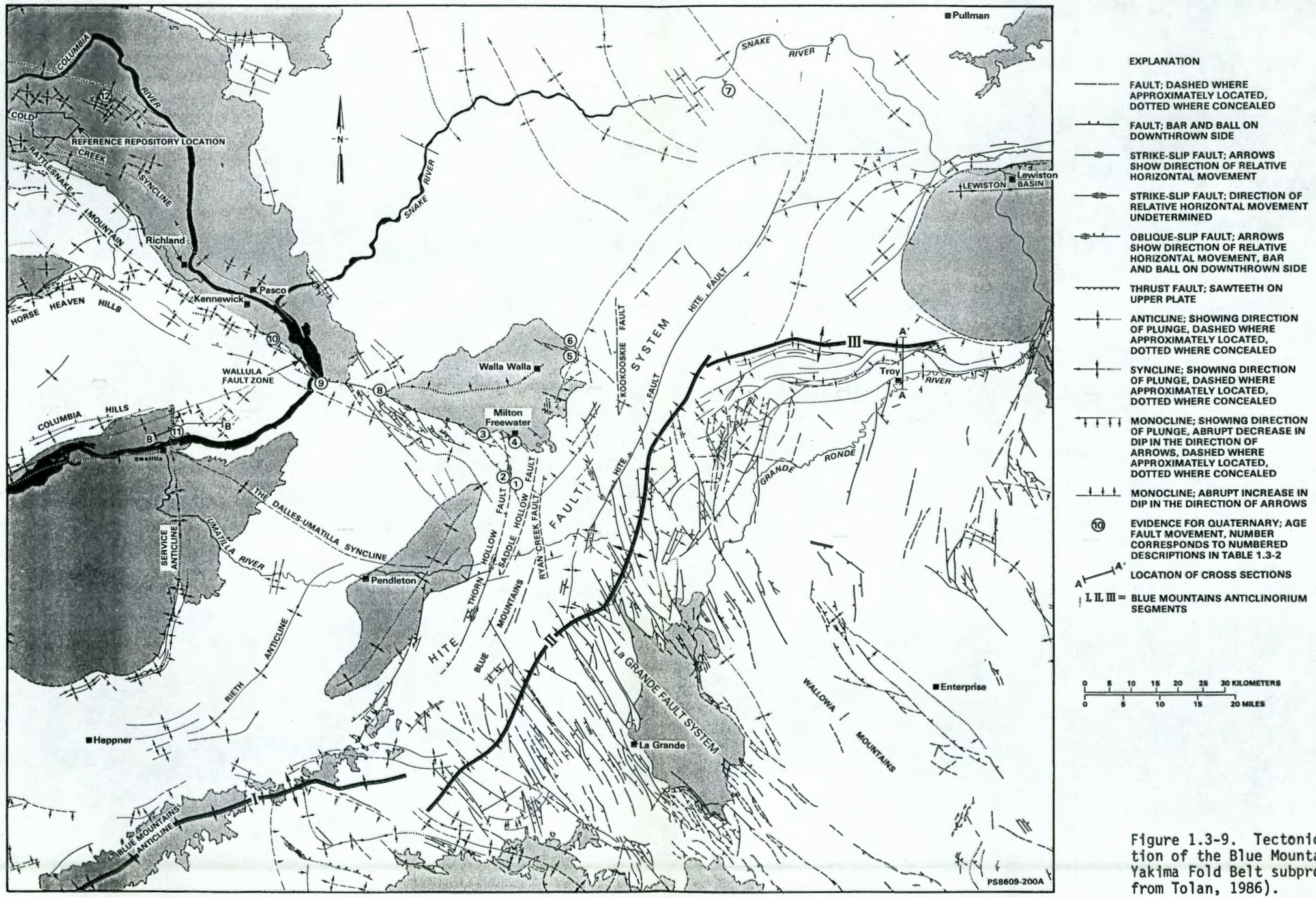

Figure 1.3-9. Tectonic map of a portion of the Blue Mountains, Palouse, and Yakima Fold Belt subprovinces (modified from Tolan, 1986).

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Segment II begins near Wilbur Mountain and continues to near the vicinity of Griffin Peak (see Fig. 1.3-9). In this segment the trend of the Blue Mountains anticlinorium becomes more northerly, and it takes on a broad, box-fold geometry (Shannon and Wilson, 1979; Kienle, 1980; Kendall et al., 1981). The crestal area of this fold is very broad and generally ranges from 6 to 10 km (3.7 to 6.2 mi) in width (Shannon and Wilson, 1979, p. 15). The limbs of the fold in segment II dip gently (3° to 5°) away from the crestal area. The northwestern hinge of the fold in segment II is marked by the Hite Fault System (see Fig. 1.3-9), while the southeastern hinge is not well defined (Shannon and Wilson, 1979, p. 15). Shannon and Wilson (1979, pp. 15-16) estimated the structural relief of the Blue Mountains anticlinorium in segment II to be ~1,200 m (4,000 ft). They derived this figure by taking the difference in elevation of the top of the Frenchman Springs Member between the axis of the Agency syncline and the anticlinal crest of the Blue Mountains east of Tollgate, Oregon (see Fig. 1.3-9).

Segment III of the Blue Mountains anticlinorium begins near Griffin Peak and continues eastward to the vicinity of the southwestern margin of the Lewiston Basin (see Fig. 1.3-8), where it appears to die out (Ross, 1978; Swanson et al., 1980). In this segment of the Blue Mountains anticlinorium, the geometry changes from a broad box-fold to a complexly faulted, asymmetric anticline (Ross, 1978, p. 113-116; Fig. 1.3-10). The maximum structural relief of the Blue Mountains anticlinorium in segment III is on the order of 1,190 m (3,900 ft) based on mapping by Ross (1978). This value was calculated by taking the difference in elevation of the top of the Troy flow (Grande Ronde Basalt) between the axis of the Grouse Flat syncline and the Saddle Butte anticline (see Fig. 1.3-9 and 1.3-10).

At the juncture between segments II and III, a series of low-amplitude folds continue northeasterly along the projected trend of segment II and roughly parallel to the trend of the Hite Fault System (Swanson et al., 1980; see Fig. 1.3-8). It is not clear if these folds are related to the Blue Mountains anticlinorium (Shannon and Wilson, 1979; Swanson et al., 1980).

Field evidence indicates that uplift was initiated along the entire trend of the Blue Mountains anticlinorium prior to the eruption of Columbia River Basalt Group flows. Work by Robinson (1966), Fisher (1967), and Robinson and Brem (1981) has shown that uplift of the Blue Mountains anticlinorium (see Fig. 1.3-9 segment I) controlled, in part, the distribution of John Day Formation pyroclastic/volcaniclastic rocks beginning in middle Oligocene time. The Blue Mountains anticlinorium (see Fig. 1.3-9 segments I, II, and III) continued to grow during the time the Columbia River basalts were being extruded, as evidenced by the absence or thinning of flows over this feature, and the influence of the anticlinorium on the distribution of Columbia River basalt flows (Ross, 1978, pp. 134-136, 153-154; Camp and Hooper, 1981, pp. 659-668; Swanson et al., 1980).

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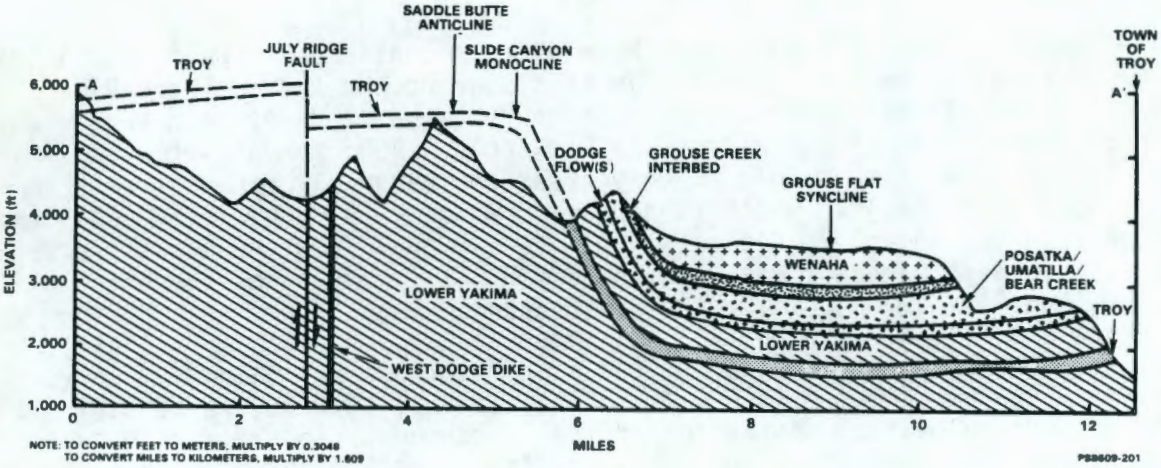

Figure 1.3-10. Cross section through the Blue Mountains near Troy, Oregon.

Hite Fault System

The Hite Fault System consists of a series of northeast-trending, en echelon faults that can be traced for more than 130 km (90 mi) (Shannon and Wilson, 1979; Swanson et al., 1980; Beeson et al., 1985) from the northern flank of the Blue Mountains anticlinorium to the Snake River (see Fig. 1.3-9). Neither the northeastern nor southwestern termination of the Hite Fault System have been precisely located or defined (Shannon and Wilson, 1979, p. 20; Kienle, 1980, pp. 16-22).

Based on reconnaissance geologic mapping, at least seven major faults, with individual lengths from 6 to 60 km (3.7 to 37 mi), have been identified within this fault system (Shannon and Wilson, 1979; Kienle, 1980; Swanson et al., 1980). However, because of the nature of reconnaissance mapping, no complete, detailed geologic map of this fault system exists. Shannon and Wilson (1979, p. 30) recognized the limitations of their reconnaissance studies and stated that literally dozens of smaller faults within the Hite Fault System were not investigated or shown on their maps. Shannon and Wilson (1979, p. 30) concluded that if detailed mapping were conducted along the Hite Fault System, such mapping would probably double or triple the density of faults known to exist.

Shannon and Wilson (1979, pp. 29-30) also included in the Hite Fault System several north-south-trending faults that lie east of the Walla Walla Basin (e.g., Kooskooskie fault; see Fig. 1.3-9). They assigned these faults to the Hite Fault System because they believed them to be genetically related to it. Evidence they cited to substantiate this interpretation was (1) proximity of these faults to the Hite Fault System, (2) compatible throw and sense of movement with the Hite Fault System, and (3) kinematic considerations. However, additional field studies would be needed to substantiate this interpretation.

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The longest and most complex fault in the Hite Fault System is the Tom Hite fault (commonly called the Hite fault), which also marks the southeastern margin of this fault system (Newcomb, 1970; Shannon and Wilson, 1973, 1979, pp. 19-20). The Hite fault can be traced for more than 60 km (37 mi) (Newcomb, 1970; Shannon and Wilson, 1979) and probably has a total length of over 90 km (56 mi) (Kienle, 1980; Slemmons and O'Malley, 1980; Beeson et al., 1985). Mapping of the Hite fault has shown it to consist usually of a zone of en echelon fault strands. As a result, the width of the Hite fault is variable, ranging from as little as 20 m (66 ft) to greater than 1.5 km (0.9 mi) (Shannon and Wilson, 1979, p. 19).

Shannon and Wilson (1979, pp. 19-31) and Kienle (1980, pp. 16-21) have concluded that there have been two major, distinct episodes of movement on most of the major faults in the Hite Fault System. Shannon and Wilson (1979, pp. 19-31) reached this conclusion based on their observations of "multiple generations of fault gouge," interpretation of striae data, and kinematic analysis of shears associated with the Hite fault. From this information, Shannon and Wilson postulated that the first episode began in late Grande Ronde time and consisted of dip-slip (west side down) movement. The second episode consisted of dextral strike-slip movement, which began in early Wanapum time. The amount of dextral offset associated with this second episode could not be determined (Shannon and Wilson, 1979, pp. 19-21).

Shannon and Wilson (1979, pp. 50-51) and Kienle (1980) acknowledged that dextral strike-slip motion along the Hite Fault System is not compatible with the inferred north-south maximum compressive stress regime acting on this region during the Neogene (Smith, 1977, 1978; Kienle and Newcomb, 1974; WPPSS, 1977, 1981; Caggiano and Duncan, 1983). To resolve this apparent conflict, Shannon and Wilson (1979, pp. 50-52) proposed the following two hypotheses:

- The Hite Fault System is older than the folding and was formed under a different stress regime.

- The Hite Fault System and the Wallula/La Grande Fault Systems (described below) are the same age and were formed under a relatively uniform compressive stress with the maximum stress direction oriented at a relatively low angle to the systems.

Kienle (1980) and Shannon and Wilson (1979) preferred the first hypothesis, although field evidence they presented was contradictory and did not clearly favor one or the other. Some of these contradictory data (Shannon and Wilson, 1979, pp. 19-58) included (1) conflicting age relationships, which suggest that Pliocene- to Pleistocene-age movement had occurred on some faults in the Hite Fault System; (2) field relationships that suggest the Hite Fault System formed contemporaneously with the Wallula/La Grande Fault Systems; and (3) possible sinistral strike-slip movement on some of the major faults in the Hite Fault System.

Based on a subsequent field study of a small portion of the Hite Fault System near Tollgate, Oregon, Kendall et al. (1981, p. 64) concluded that the second major episode of movement was sinistral strike-slip rather than dextral

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strike-slip as proposed by Shannon and Wilson (1979) and Kienle (1980). This reinterpretation by Kendall et al. (1981) would remove the kinematic problems associated with producing dextral strike-slip movement on the Hite Fault System while under a north-south maximum compressive stress regime. However, Kendall et al. (1981) have yet to publish the details of their field studies that support their interpretations.

Observed thinning and (or) absence of Grande Ronde and Wanapum Basalt flows across the faults in the Hite Fault System (Shannon and Wilson, 1979; Kienle, 1980; Swanson et al., 1980; Beeson et al., 1985) clearly indicates that this fault system was active by middle Miocene time. There is much conflicting evidence pertaining to the question of Quaternary-age movement associated with this fault system (Shannon and Wilson, 1979; Kienle, 1980; Slemmons and O'Malley, 1980). Shannon and Wilson (1979, pp. 22-31) presented evidence suggesting that several of the major faults they studied within the Hite Fault System (e.g., Peterson Ridge and Thorn Hollow faults; Table 1.3-2) have juxtaposed Columbia River basalt flows against Palouse formation, a middle Pleistocene(?) eolian deposit. Also, Shannon and Wilson (1979, p. 28) describe other circumstantial evidence (e.g., Earthquake Springs; Newcomb, 1965, p. 146) for young movement along the Ryan Creek fault in the Hite Fault System.

Earthquake Springs (see Fig. 1.3-9) occurs on the north-south-trending Ryan Creek fault (Hite Fault System) several kilometers north of where the northwest-trending Dry Creek fault (Wallula Fault System (see Section 1.3.2.2.2.5) intersects this trend. Newcomb (1965, p. 146) states that, prior to the July 16, 1936 Milton-Freewater earthquake (Richter magnitude of 6.1; WCC, 1980c), this spring flowed 273 L/min (60 gal/min). At the time of the earthquake, the flow of the spring increased to ~13,638 L/min (3,000 gal/min) and by August, 14, 1936, had decreased to 4,546 L/min (1,000 gal/min). By 1960, the spring flow was down to 4.5 L/min (1 gal/min). The increased flowage of Earthquake Springs is directly correlatable to the 1936 event, but the mechanism that produced the increased flow rate is not known. The epicenter of the 1936 Milton-Freewater earthquake has been relocated (WCC, 1980c) and is now thought to be within the Hite Fault System, but several tens of kilometers northeast of Earthquake Springs (Section 1.4.1.1.3.2). Because of the uncertainty associated with placing this earthquake on a specific structure, the U.S. Nuclear Regulatory Commission (NRC) (NRC, 1982) suggested that the Milton Freewater earthquake could have occurred along the Hite Fault System, the Rattlesnake Wallula Alignment, or some as-yet unmapped fault (see Section 1.4).

Shannon and Wilson (1979, pp. 53-54), however, question whether the evidence for Quaternary-age movement in faults of the Hite Fault System might not be simply the result of local reactivation of faults resulting from movement on the Wallula/La Grande Fault Systems. This would be a plausible hypothesis, if they are correct in their interpretation that the Hite Fault System is older and was formed under a different stress regime than either the Wallula/La Grande Fault Systems. However, data presented in Kendall et al. (1981) raise a question about this interpretation.

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Table 1.3-2. Description of reported Quaternary-age faulting in the Central Columbia Plateau area

Number in Fig. 1.3-9	Fault name	Primary structural feature	Age of last movement	Sense of movement	Amount of movement	Location	Source of information
1	Thorn Hollow	Hite Fault System	Early Holocene?	Strike-slip	Not determined	SW ¼ NE ¼ Sec. 2 T. 4 N., R. 35 E.	Shannon and Wilson (1979, p. 28)
2	Little Dry Creek	Wallula Fault System	Pleistocene?	Normal	0.5 m (1.6 ft)	NE ¼ Sec. 11 T. 4 N., R. 35 E.	Shannon and Wilson (1979, p. 33-34)
3	Barrett	Wallula Fault System	Late Pleistocene to Holocene?	Dextral oblique-slip	Variable 2 to 50 cm (1 to 20 in) (0.19 to 19.68 in.)	SW ¼ SE ¼ Sec. 25 T. 6 N., R. 34 E.	Shannon and Wilson (1979, p. 35)
4	Milton-Freewater	Wallula Fault System	Holocene (1936)	Dextral strike-slip	Unknown-ground disturbances	SE ¼ Sec. 18 T. 5 N, R. 35 E.	Shannon and Wilson (1979, p. 36)
5	Promontory Point	Wallula Fault System	Pleistocene?	Normal	Not determined	Sec. 10 T. 6 N., R. 37 E.	Shannon and Wilson (1979, p. 40) Kienle (1980, p. 40-41)
6	Buroker	Wallula Fault System	Pleistocene to early Holocene?	Thrust fault with component of sinistral strike-slip	Greater than 1 m (3 ft)	Sec. 31 T. 7 N., R. 37 E.	Shannon and Wilson (1979, p. 16-17) Kienle (1980, p. 41-44)
7	Central Ferry		Pleistocene?	Sinistral oblique-slip	1 to 1.5 m (3 to 5 ft)	Center Sec 22 T 12 N., R 40 E.	Kienle (1980, p. 25)
8	Wallula (near Warm Springs Canyon)	Wallula Fault System	Pleistocene?	Strike-slip or oblique-slip	Not determined	Sec. 12 T. 6 N., R. 32 E.	Farooqui (1979, p. 8-9)
9	Wallula (near Vansycle Canyon)	Wallula Fault System	Early Holocene	Not determined	Not determined	Sec. 3 T. 6 N., R. 32 E.	WPPSS (1977, p. 2RK. 8-9) Farooqui (1979, p. 9-10)
10	Finley Quarry	Cle Elum-Wallula lineament-Domain II	Pleistocene ?	Reverse	Not determined	Sec. 3 T. 7 N., R. 30 E.	Farooqui (1980, p. 4-8)
11	Unnamed	Service anticline	Late Pleistocene?	Strike-slip	Not determined	SE ¼ SW ¼ Sec. 28 T. 6 N., R. 28 E.	Kienle (1980, p. 48-49)
12	Central Gable Mountain	Gable Mountain Anticline (Yakima fold)	Late Pleistocene?	Reverse	5 cm (2 in.)	Sec 19 T. 13 N., R. 27 E.	Golder (1981, p. 34-45)
13	Unnamed fault	Toppenish Ridge (Yakima fold)	Holocene	Both normal and reverse	Up to 4 m (13 ft)	Between latitude: 46° 15'--46°19' longitude: 120°22'--122°40'	Campbell and Bentley (1981, p. 519-524)
14	Union Gap	Ahtanum Ridge (Yakima fold)	Pleistocene?	Reverse	Approximately 7 m (23 ft)	T. 12 N., R. 19 E.	WPPSS (1981, p. 2.5K-53)

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Slemmons and O'Malley (1980, pp. 48-49) did a limited imagery analysis of the Hite Fault System and concluded that there was no morphological evidence of young or recent faulting. However, they did note that at least two recent earthquakes (i.e., 1936 Milton-Freewater and 1979 College Place) appear to be associated with faults of the Hite Fault System (Slemmons and O'Malley, 1980, p. 49). Based on this moderate earthquake activity, they classified the Hite Fault System as "probably active." Slemmons and O'Malley (1980, p. 53) go on to point out, however, that existing geologic field data are insufficient to report properly determine if the Hite Fault System is active. The NRC (1982, p. 6-22) concluded that there is no clear evidence to associate these events with the Hite Fault.

La Grande Fault System

The La Grande Fault System is defined by a broad zone of north-northwest-trending faults (Fig. 1.3-9), which can be traced from the Hite Fault System to the area southeast of La Grande, Oregon (Walker, 1973, 1979; Shannon and Wilson, 1979, p. 41; Gehrels et al., 1980; Gehrels, 1981; Barrash et al., 1980). The southeastern extent of the La Grande Fault System is not well constrained (Walker, 1973, 1979; Swanson et al., 1981). There is a question also as to whether the La Grande Fault System is terminated by the Hite Fault System or whether it continues northwestward to the Wallula Fault System (Shannon and Wilson, 1979, pp. 54-55; Kendall et al., 1981; Gehrels et al., 1979; Gehrels, 1981).

The north-northwest-trending faults of the La Grande Fault System commonly display normal dip-slip and dextral strike-slip components (Shannon and Wilson, 1979; Gehrels et al., 1980; Gehrels, 1981; Barrash et al., 1980). It is unknown whether these components represent simply oblique-slip movement or different deformational episodes as interpreted for the Hite Fault System (Shannon and Wilson, 1979; Gehrels, 1981).

The most distinctive feature of the La Grande Fault System is the La Grande graben (see Fig. 1.3-9), which has been interpreted as a "pull-apart basin" formed by dextral strike-slip movement on the La Grande Fault System (Gehrels et al., 1979; Gehrels, 1981). Cumulative vertical stratigraphic offset on some of the faults that bound the La Grande graben (e.g., Ruckel Ridge fault) has been reported to exceed 1,500 m (4,900 ft) (Shannon and Wilson, 1979, pp. 44-45; Gehrels, 1981).

Evidence presented by Shannon and Wilson (1979), Kendall et al. (1981), and Barrash et al. (1980) suggests that faulting associated with the La Grande Fault System began in early Wanapum time (~15.6 m.y.B.P.). However, field evidence presented by Gehrels (1981) suggests faulting did not begin in the central and southern portions of the La Grande Fault System until after ~7 to 6 m.y.B.P. Direct evidence of recent movement of faults within this system is sparse. Gehrels et al. (1979) and Gehrels (1981) reported finding colluvial terrace gravels, of indeterminate age, in fault contact with Holocene (?) alluvium in the city of La Grande, Oregon. The Slemmons and O'Malley (1980, p. 49) geomorphologic analysis of the La Grande graben led them to conclude that many features in the graben could be the result of recent faulting. However, this interpretation was based on only indirect evidence.

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Relationship of the Wallula Fault Zone and Olympic-Wallowa lineament to the La Grande Fault System

One major question that remains to be resolved is whether the La Grande and Wallula Fault Systems/Olympic-Wallowa lineament are linked in any way. If these fault systems are linked, then there is structural continuity between the Cle Elum-Wallula disturbed zone (Section 1.3.2.2.1.3) and the southern portion of Raisz's (1945) Olympic-Wallowa lineament. If such a link were proven, it would strengthen the case that the Olympic-Wallowa lineament may be a fundamental structural boundary (Skehan, 1965; Wise, 1963; Smith, 1977, 1978; Shannon and Wilson, 1977; Laubscher, 1977, 1981).

Shannon and Wilson (1979, pp. 31-56) presented some field evidence suggesting that the Wallula and La Grande Fault Systems are linked and directly related to one another. However, the evidence presented by Shannon and Wilson (1979) was not conclusive and would need to be substantiated by detailed field mapping in critical areas. Alternatively, Slemmons and O'Malley (1980), Swanson and Wright (1981), and Davis (1981) suggested that the Wallula Fault Zone (Section 1.3.2.2.1.3) ends in the area southeast of Milton-Freewater, Oregon, and that there is no connection with the La Grande Fault System. The Slemmons and O'Malley (1980) interpretation was based on remote-sensing analysis and would have to be validated by detailed field mapping. Swanson and Wright (1981) and Davis (1981) stated that the Wallula Fault Zone terminates southeast of Milton-Freewater, Oregon. Both interpretations were based on unpublished, detailed mapping at an unspecified scale. Swanson et al. (1981) later published a reconnaissance map, scale 1:250,000, of this area. However, the detailed maps that purportedly demonstrate the separation of the two fault systems have not been published, and, therefore, this issue has not been conclusively settled.

Service anticline

This structural feature has been examined at a reconnaissance level during several geologic investigations of this region (Kienle et al., 1973; Kienle, 1980; Swanson et al., 1979a, 1981). However, only one of these studies describes this feature in any detail (Kienle, 1980). In spite of Kienle's study, the Service anticline is one of the least described and documented major structural features in the Blue Mountains subprovince.

Based on available information, the Service anticline can be characterized as a series of generally north-south-trending, doubly plunging, anticlinal segments (see Fig. 1.3-9) whose collective length exceeds 80 km (50 mi) (Swanson et al., 1979a, 1981; Kienle, 1980, pp. 44-45). Both ends of this structural trend diverge from the overall north-south trend. The southern end of the Service anticline abruptly changes to a southwesterly trend (roughly parallel in trend to the Blue Mountains anticlinorium) before terminating, while the northern end changes to a northeasterly trend where it intersects the Columbia Hills (see Fig. 1.3-9).

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The axes of the anticlinal segments in the Service anticline are aligned roughly parallel to the overall trend of the structure (Kienle et al., 1973; Kienle, 1980; Swanson et al., 1981). The amount of vertical structural relief developed on some of these anticlinal segments is estimated to be 152 m (500 ft) (Kienle, 1980, p. 45). Several of the anticlinal segments have faults along, or parallel to, the axis of the segments (Kienle, 1980, pp. 45-52; Swanson et al., 1981). There are a few exposures of the fault zones, and where exposed they appear to be either high-angle reverse faults or vertical strike-slip faults (Kienle, 1980, pp. 45-52) (e.g., Fig. 1.3-11). However, because of limited exposures and the reconnaissance nature of the geologic investigations, it is not known whether there is a through-going "master" fault that traverses the length of this feature.

Kienle (1980, p. 50) suggests that the Service anticline is part of a sinistral wrench fault system. He based this interpretation on (1) his reconnaissance geologic mapping of the feature, (2) the geometry of the Service anticline, and (3) the axial traces of the anticlinal segments. However, Kienle (1980, pp. 50-51) points out that this interpretation would require an east-west orientation of the maximum compressive stress, which would contradict the accepted model of north-south orientation of the maximum compressive stress for this region.

There is no conclusive evidence to establish when the Service anticline began to develop. Kienle (1980) suggests that the Service anticline began to grow by at least Plio-Pleistocene time based on its relationship to the Columbia Hills. Only circumstantial evidence at one location has been found suggesting Quaternary-aged movement on this structural trend. This evidence consists of split/cracked boulders in Pleistocence-age glaciofluvial deposits (Kienle, 1980, pp. 48-49) that are on the projected trend of a fault shown on Figure 1.3-11. However, Slemmons and O'Malley (1980, p. 19) provisionally classified the Service anticline as an active structure based solely on three historic earthquakes whose epicenters are located near this structural trend. More detailed work will be required to settle this question.

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1.3.2.2.1.3 Yakima Fold Belt subprovince

The Yakima Fold Belt contains four major structural elements: Yakima folds, Cle Elum-Wallula disturbed zone, Hog Ranch-Naneum Ridge anticline, and northwest-trending wrench faults. The following general description is organized around these structural elements. For a more detailed description of specific portions of these structures that are in close proximity to the reference repository location, see Section 1.3.2.2.2.

Yakima folds

The principal characteristic of the Yakima Fold Belt is a series of continuous, narrow, asymmetric anticlines that have wavelengths between ~5 to 30 km (3 to 19 mi) and amplitudes commonly less than 1 km (0.6 mi). These anticlinal ridges are separated by broad synclines or basins that, in many cases, contain thick accumulations of Neogene- to Quaternary-age sediments. It is generally agreed that the Yakima folds developed under approximately

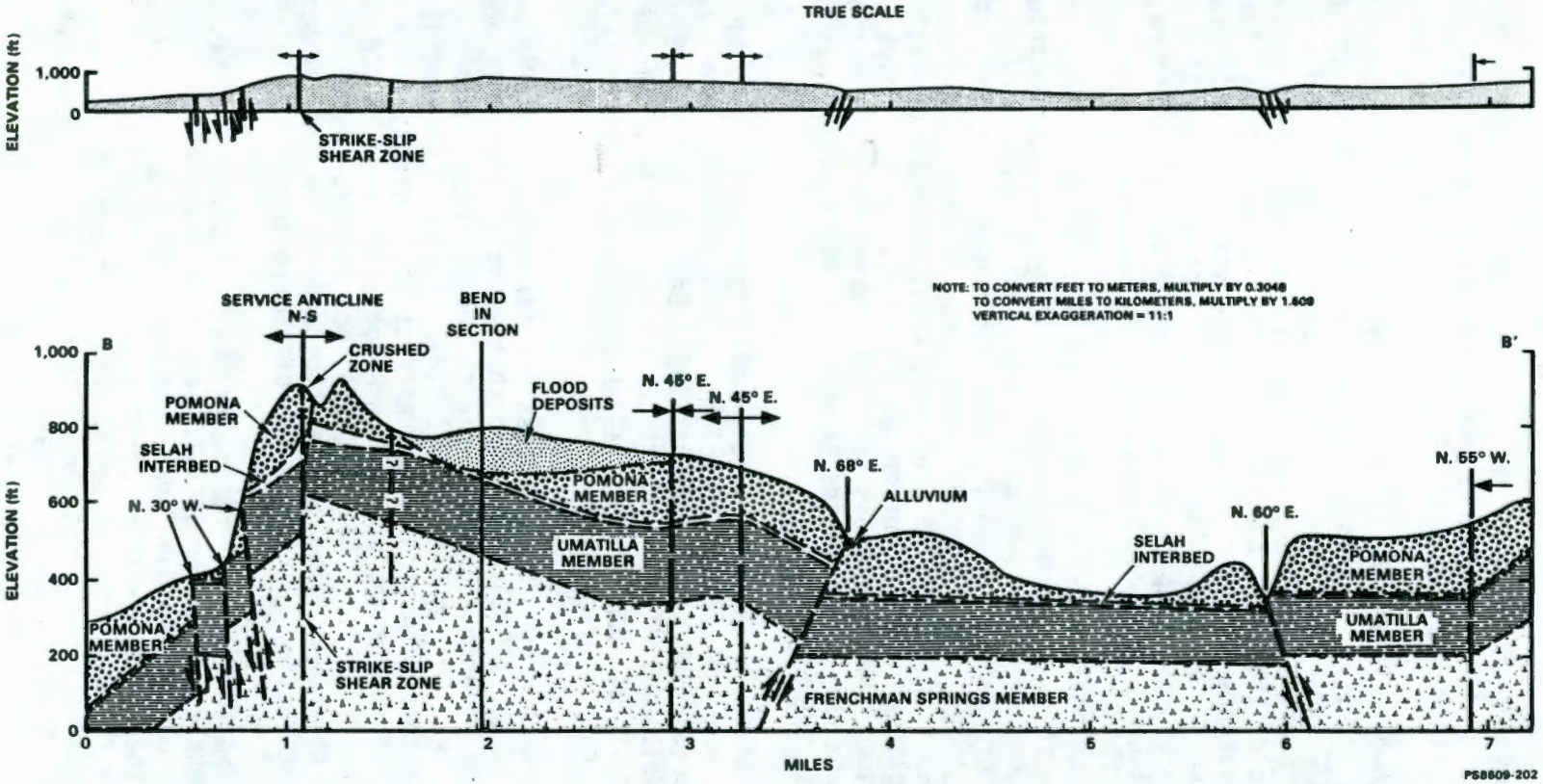

Figure 1.3-11. Cross section through the Service anticline.

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north-south compression. However, the axial trends of Yakima folds throughout the subprovince are not constant and appear to vary systematically, producing a crude, radial pattern (see Fig. 1.3-8).

In the southwestern portion of the subprovinces, several anticlinal folds have been traced into, and possibly through, the Cascade Range (Tolan et al., 1984; Beeson and Tolan, 1984; Beeson et al., 1985; Tolan, 1986). Along the west-central and northwestern margin of the subprovince, it is uncertain whether Yakima fold structures continue into the Cascade Range. Tabor et al. (1984) provide evidence that the Manastash Ridge structure continues into the Cascade Range from the Columbia Plateau. The eastern portion of the subprovince is marked by a rapid decrease in amplitude of the folds, which appear to die out on the Palouse Slope (see Fig. 1.3-9).

The cross-sectional geometry of the anticlines varies from nearly symmetrical, open folds to asymmetric folds with one steep or overturned limb. Changes in the geometry of the anticlines along strike give many of them a segmented character (Swanson et al., 1979a, 1981; Bentley et al., 1980; Reidel, 1984; Hagood, 1985). Segment boundaries are usually delineated by a cross-trending fault or fold. The cross-sectional geometry of the synclines between the anticlines is dependent on the wavelength of the folds. Shorter wavelengths produce asymmetric cross-sectional geometries, while longer wavelengths produce very broad basins in which it may be difficult to define an axial trace for the syncline.

Thrust or high-angle reverse faults, whose fault planes strike parallel to subparallel to the axis of the anticline, are often found along both limbs of the anticlines (Swanson et al., 1979a, 1981; Bentley et al., 1980; Reidel, 1984; Hagood, 1985). The amount of vertical stratigraphic offset associated with these faults varies but commonly exceeds hundreds of meters for faults along the steeply dipping limb of the fold.

The total amount of shortening across the Yakima Fold Belt is not known. However, Bentley et al. (1980) calculated that ~2 km (1.1 mi) of shortening has occurred on the Wishram and Ortley faults, which occur in the Columbia Hills near The Dalles, Oregon (see Fig. 1.3-8). They did not specify whether their calculations took into account the effects of folding. Price (1982, p. 62) estimated 25% shortening on Umtanum Ridge, with a total minimum width reduction of 850 m (2,790 ft). Reidel (1984, pp. 972-973) calculated the shortening resulting from folding and faulting across the Saddle Mountains, at Sentinel Gap, to be ~35% or ~3 km (1.9 mi) of shortening.

The timing of deformation along the Yakima fold structures has been a subject of much debate. Prior to 1980, numerous interpretations suggested that the onset of folding may have been seen as early as Grande Ronde time, ~16 m.y.B.P., in the extreme western portion of the subprovince (Beeson and Moran, 1979b). In the west-central and central portions of the subprovince, the onset was suggested as late Wanapum or even Saddle Mountains time, ~15 to 6 m.y.B.P. (Mackin, 1961; Schmincke, 1967; Bingham et al., 1970; Bentley, 1977; Thoms et al., 1977; Swanson and Wright, 1978).

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Since 1980, nearly all studies present compelling evidence to indicate that deformation was under way along the fold trends by at least Grande Ronde time (Bentley, 1980b; Bentley et al., 1980; Bentley and Farooqui, 1979; Reidel et al., 1980; Reidel, 1984; Hagood, 1985; Fecht et al., 1985; Beeson et al., 1985). Reidel (1984), Hagood (1985), and Bjornstad (1985) have provided evidence that the anticlinal ridges in and around the Pasco Basin continued to grow in post-Columbia River basalt time based on deformation and (or) thinning observed in late Miocene to Pliocene sediments.

There is very little direct field evidence to indicate Quaternary deformation along these anticlinal ridges (see Table 1.3-2). Only three cases of suspected Quaternary faulting associated with Yakima fold anticlines have been documented: (1) the central Gable Mountain fault in the Pasco Basin, (2) the Toppenish Ridge fault in the Yakima Valley, and (3) the Union Gap fault in Ahtanum Ridge (see Table 1.3-2).

Evidence that suggests Quaternary movement on the central Gable Mountain fault (see Section 1.3.2.2.2.3) has been found (PSPL, 1982, p. 20-5). This evidence includes faulting of glaciofluvial deposits, which were dated at ~13,000 yr B.P., and offsets of as much as 6.5 cm (2.6 in.). Fractures in these deposits are continuous with a reverse fault in the underlying Columbia River basalt along which progessively older units are increasingly offset. However, an alternative, nontectonic interpretation attributes the youngest observed offset to rapid hydrostatic loading and unloading that occurred during cataclysmic flooding (PSPL, 1982, p. 20-5).

Campbell and Bentley (1980, 1981) describe a zone of nearly 100 surface ruptures on Toppenish Ridge that they interpret to represent late Quaternary tectonic deformation (see Fig. 1.3-8). These surface ruptures occur along a 32-km (20-mi) portion of the ridge, between its crest and the base of its northern limb. The total width of the zone varies from 0.5 to 2.2 km (0.3 to 1.4 mi). Individual scarps are approximately parallel to the ridge trend, and they range from 0.1 to 3 km (0.06 to 1.9 mi) in length. Dip-slip separations on individual ruptures do not exceed 4 m (13 ft) (Campbell and Bentley, 1981, p. 521). The age of these features was established by dating organic matter in sediments deposited in small sag ponds that were created by the surface ruptures. Carbon-14 dates for this organic material are 505 ± 160 yr and 620 ± 135 yr (Campbell and Bentley, 1981, p. 521).

These surface ruptures cut deposits that are physically similar to those that contain tephra that is ~13,000 yr old, but the ruptures cutting these deposits are inferred to be much younger than this 13,000-yr date (Campbell and Bentley, 1981, p. 522). An alternative explanation for these ruptures is landsliding or ridge-top spreading (Davis, 1981). A tectonic origin for the surface ruptures is generally favored, but there is insufficient data to dismiss the hypothesis of a nontectonic origin as suggested by Davis (1981).

A third fault inferred to be of Quaternary age was exposed during highway construction near Union Gap, Washington, on Ahtanum Ridge (see Fig. 1.3-8). At this location, a high-angle reverse fault offsets Yakima River terrace gravels by at least 7 m (23 ft) and results in the juxtaposition of the Ginkgo

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flow (Frenchman Springs Member, Wanapum Basalt) against the gravels (Campbell, in WPPSS, 1981, p. 2.5k-53). There is no reliable date for these terrace gravels, but Campbell believes that they are Pleistocene (WPPSS, 1981, p. 2.5k-53). The fault zone is capped by undeformed slack-water cataclysmic flood sediments dated elsewhere at 13,000 yr B.P., indicating that the last movement of the fault occurred prior to that time.

Based on studies since 1980, it appears that many, if not all, Yakima fold structures have continued to grow since the end of Columbia River basalt volcanism ~6 m.y.B.P. The paucity of direct field evidence for late Pliocene to Quaternary deformation on the western portion of many of the Yakima folds may be the result of an unpreserved stratigraphic record or the lack of deposition for this period of time. The Ringold Formation is present on the eastern portion of most of these folds in the Pasco Basin, however, thus allowing the location of post-Miocene through Pliocene deformation to be determined (see Section 8.3.1.2.4.3.1.1). Analysis of the recorded seismic history of portions of the Yakima Fold Belt subprovince (e.g., Malone et al., 1975; Rohay and Davis, 1983) indicates that these data are compatible with the continued development of the Yakima Fold Belt. Geodetic data are also compatible, but the data are of questionable geologic significance because present measurements are within error limits of the instruments.

Prior to 1980, estimates for the rate of uplift of Yakima folds were largely based on the assumption that topographic relief on these structures developed after the basalts were emplaced (e.g., Brown, 1970; Kienle et al., 1978; Glass, 1977: Shannon and Wilson, 1978). However, more recent studies have demonstrated that many Yakima fold structures were growing by at least late Grande Ronde Basalt time (Beeson and Moran, 1979b; Bentley and Farooqui, 1979; Bentley et al., 1980).

New estimates for the long-term average rate of uplift (i.e., combined uplift and subsidence) have been calculated for Umtanum Ridge, Saddle Mountains, and Horse Heaven Hills in the eastern portion of the Yakima Fold Belt. These studies indicate that the long-term average rate of uplift was between 600 and 250 m/m.y. (2,000 and 800 ft/m.y.) during Grande Ronde Basalt time and slowed by the end of the Miocene to <40 m/m.y. (130 ft/m.y.) (Reidel et al., 1983; Reidel, 1984; Hagood, 1985). A more detailed discussion of this topic is given in Section 1.3.2.4.1. More detailed work is necessary to verify and constrain these estimates (see Section 8.3.1.2.4.3.1.1, Deformation). Reidel (1984) points out that there is a correlation between the rate of growth of these folds and the eruption rates of the Columbia River basalt, suggesting that there might be a connection between volcanism and deformation.

The origin of the Yakima folds is a subject of much debate. Much of this debate has centered on whether or not the folds are a product of thin-skinned tectonics, involving detachment or decollement, or basement tectonics, where the Columbia River basalt is coupled with deformation in sub-basalt layers. The available subsurface data are insufficient to resolve this question. This topic is further discussed in the section on regional tectonic models (Section 1.5.2). Plans to resolve some of these controversies are described in Section 8.3.1.2.4.3.1.

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Cle Elum-Wallula disturbed zone

The Cle Elum-Wallula disturbed zone is the central portion of the larger topographic alignment called the Olympic-Wallowa lineament. The Olympic-Wallowa lineament extends from the northwestern edge of the Olympic Mountains to the northern edge of the Wallowa Mountains in Oregon (Raisz, 1945, pp. 479-485). The Cle Elum-Wallula disturbed zone is a narrow zone ~10 km (6 mi) wide that transects the Yakima Fold Belt and is interpreted to be a fundamental structural element of the Columbia Plateau (Laubscher, 1977, 1981; Kienle et al., 1977; Bentley, 1980c; Davis, 1981). This zone is characterized by an abrupt change in trend of Yakima folds (Kienle et al., 1977, p. 6), an aligned belt of doubly plunging anticlines, and the Wallula Fault Zone (see Fig. 1.3-8 and 1.3-9).

The Cle Elum-Wallula disturbed zone has been informally divided into three structural domains by Davis (1981).

I. A broad zone of deflected or anomalous fold and fault trends, extending south of Cle Elum, Washington, to Rattlesnake Mountain.

II. A narrow belt of topographically aligned domes and doubly plunging anticlines ("The Rattles"), extending from Rattlesnake Mountain to Wallula Gap.

III. The Wallula fault zone, extending from Wallula Gap to the Blue Mountains.

Laubscher (1977, 1981) and Davis (1981) believe that structures within the three domains defined by Davis (1981) contain features that are characteristic of dextral displacement on a wrench fault. There is no direct field evidence, however, to indicate a continuous fault through all three structural domains (Myers/Price et al., 1979; Davis, 1981). Based on analogies with wrench fault zones elsewhere, Davis (1981, p. 2.5N-33) believes that a case can be made for the existence of a transcurrent fault zone at some depth in domain II (Rattlesnake-Wallula alignment) that is continuous with the Wallula Fault Zone of domain III.

Reidel et al. (1984) observed clockwise rotation of the paleomagnetic field direction in Pomona Member flows (Saddle Mountains Basalt) at sites along the Cle Elum-Wallula disturbed zone. These data also support the hypothesis that the Cle Elum-Wallula disturbed zone is a zone of dextral shear strain. However, Reidel et al. (1984, p. 269) note that the rotation is segmented and that the overall pattern is indistinguishable from that observed on the Yakima folds. They suggest several alternative interpretations: (1) the observed rotation is caused by the same mechanism that localized rotation along the Yakima fold anticlines; and (2) the clockwise rotation resulted from dextral shear along the Cle Elum-Wallula disturbed zone and local tectonic rotation associated with the growth of the anticlines. This is further discussed in Section 1.5.2.2.2.2.5.

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The age and timing of deformation along the entire length of the Cle Elum-Wallula disturbed zone is not well constrained. Studies along the Rattlesnake-Wallula alignment (domain II of Davis, 1981) suggest that deformation began at least by late Grande Ronde time and continued through the Miocene (Reidel et al., 1983; Reidel and Fecht, 1981). A recalculation of the net growth rate for Rattlesnake Mountain (combined uplift and subsidence) yields an average rate of 75 m/m.y. (250 ft/m.y.).

Evidence for Quaternary deformation has been reported for fourteen localities either in or directly associated with the Cle Elum-Wallula disturbed zone (see Table 1.3-2):

- Little Dry Creek fault south of Milton-Freewater, Oregon.
- Buroker fault east of Milton-Freewater, Oregon.
- Unnamed fault south of Umapine, Oregon.
- Wallula Fault Zone east of Warm Springs Canyon, Oregon.
- Wallula Fault Zone near Wallula Gap, Washington.
- Wallula Fault Zone near Finley Quarry, Washington.

The last three localities lie along a 20-km (12-mi) segment of the Wallula Fault Zone. No evidence for Quaternary deformation has been reported northwest of the Finley Quarry location. However, the lack of evidence for Quaternary deformation farther northwestward along the Cle Elum-Wallula disturbed zone may be due to the absence of a well-preserved stratigraphic record. Additional, detailed field mapping is planned to reduce the uncertainty in present conclusions regarding Quaternary activity (Section 8.3.1.2.4.3.1).

The origin of the Cle Elum-Wallula disturbed zone is a much debated subject. There are disagreements over whether the Cle Elum-Wallula disturbed zone was formed during the Miocene and whether it was controlled by a preexisting structural features in sub-basalt rocks (Laubscher, 1977, 1981; Shannon and Wilson, 1978; Davis, 1981). Recent work in the central Cascade Range by Tabor et al. (1984, p. 43) suggests that at least the northwesternmost portion of the Cle Elum-Wallula disturbed zone was controlled by preexisting structure.

Hog Ranch-Naneum Ridge anticline

This north- to northwest-trending feature is a broad structural arch that is known to extend from southwest of Wenatchee, Washington, to at least the Yakima Ridge (see Fig. 1.3-8). Tabor et al. (1982) have traced this feature north of the Columbia Plateau into the Wenatchee Mountains, where they have demonstrated that structures involving Eocene rocks and sedimentation patterns are involved with this uplift. The southern extent of this feature is not known. However, Hagood (1985, pp. 45, 85-88) presents isopach data on

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Columbia River basalt flows that suggest this feature continues as a buried structure to the south of Yakima Ridge and possibly into the Horse Heaven Hills area.

The Hog Ranch-Naneum Ridge feature defines a portion of the northwestern boundary of the Pasco Basin (see Fig. 1.3-8). Little is known about the structural geology of this portion of the feature, as it has only been mapped at a reconnaissance level (Bentley, 1977; Swanson et al., 1979a). A discussion of the structural significance of this feature to the geologic setting is presented in Section 1.5.

Northwest-trending wrench faults

Geologic mapping in the Columbia Plateau west of ~120° W longitude has revealed numerous northwest-trending, dextral strike-slip faults (Newcomb, 1969, 1970; Kienle et al., 1973; Bentley et al., 1980; Swanson et al., 1979a, 1981). These structures are classified as wrench faults by several workers (e.g., Bentley et al., 1980; Bentley, 1980c; Anderson, 1985; Anderson and Tolan, 1986) on the basis of several characteristics, including the following:

- Conjugate en echelon faults.
- Genetically related en echelon folds, which typically have amplitudes greater than 100 m (300 ft) on the plateau.
- Reversal of apparent dip slip displacement along strike.

The mean strike direction for these faults is 320° (Anderson and Tolan, 1986). At least four of these fault zones can be traced for more than 100 km (62 mi), and they cross several Yakima fold trends (Swanson et al., 1981; Anderson and Tolan, 1986; Bentley et al., 1980). In addition to the northwest-trending faults, there are less numerous northeast-trending, sinistral wrench faults that have a mean strike direction of 013° (Anderson and Tolan, 1986). The dextral and sinistral wrench faults do not appear to be present east of ~120° W. longitude, with the possible exception of the Cle Elum-Wallula disturbed zone/Rattlesnake-Wallula alignment (Swanson et al., 1979a, 1980, 1981; Myers/Price et al., 1979).

Recent work by Anderson and Tolan (1986, p. 82) has shown that the northwest-trending dextral wrench faults of regional extent developed contemporaneously with the Yakima folds and that deformation along these structures has apparently continued into the Holocene. The reason for the apparent absence of these structures in the central portion of the Columbia Plateau is not known. The role of these wrench faults in the tectonic development of the Columbia Plateau is not clear and is a topic of debate (Kienle et al., 1973; Bentley, 1977, 1980c; Laubscher, 1981; Davis, 1981).

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1.3.2.2.2 Structural features of the Pasco Basin and reference repository location

The Pasco Basin is the principal structural unit within which the candidate site is located. It is defined on the north by the Saddle Mountains, on the south by the Rattlesnake Hills and Rattlesnake-Wallula alignment, on the east as the junction between the Yakima Fold Belt and Palouse subprovinces (which generally coincides with the Ice Harbor dike system and Jackass anticline/monocline), and on the west by the Hog Ranch-Naneum Ridge anticline. An index map to the structural features is presented in Figure 1.3-12, and the individually numbered features on that map are further described in Table 1.3-3. In the following discussion of specific structural features of the Pasco Basin shown on Figure 1.3-12, the features will be referenced only by their number on the map.

The structure of the Pasco Basin can be described in terms of four separate structural elements as follows:

- The Ice Harbor dike swarm and Jackass anticline/monocline, a northwest-trending zone that marks the change from the Palouse Slope to the Yakima Fold Belt.
- The Hog Ranch-Naneum Ridge anticline, a north-trending anticline that extends northward to the North Cascades.
- Anticlinal and synclinal features of the Yakima folds that trend easterly across the basin.
- The Rattlesnake-Wallula alignment, a topographic alignment consisting of Rattlesnake Mountain and a series of doubly plunging anticlines ("The Rattles").

Summaries of the geologic mapping that has been conducted in the Pasco Basin and adjacent regions can be found in WPPSS (1981) and Myers/Price et al. (1979, Plate III). Most of this mapping is of a reconnaissance nature, although several investigations have included highly detailed mapping as well (e.g., Fecht, 1978; Reidel, 1984, 1987; Hagood, 1985). Detailed mapping projects are in progress in several areas around the Pasco Basin, and additional, detailed mapping is planned as part of site characterization (Sections 8.3.1.2.3.3.4 and 8.3.1.2.4.3.1).

The uncertainty in the following descriptions is partially a function of the level of detail used in mapping individual features. Reducing this uncertainty is an important objective of site characterization.

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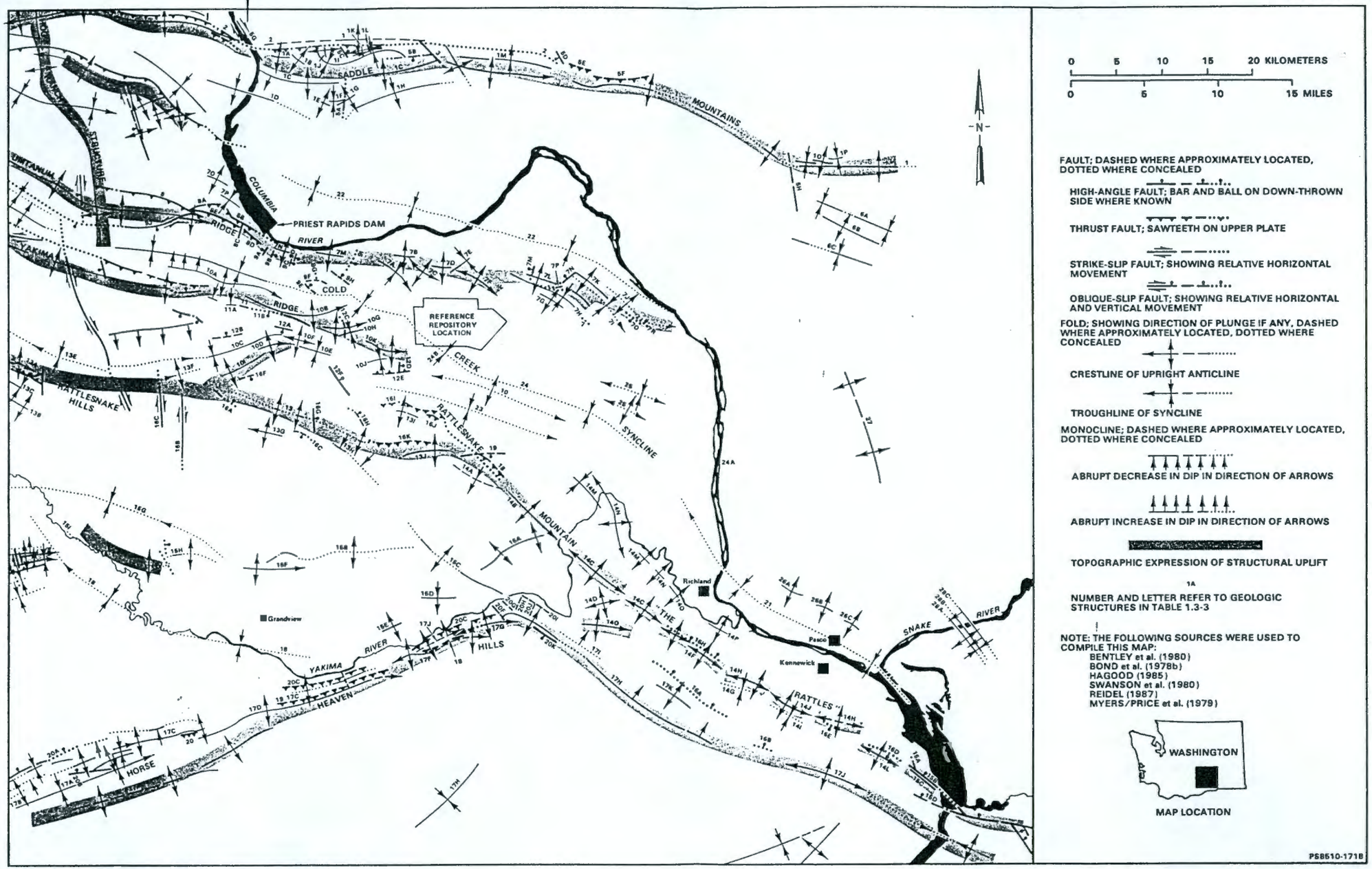

Figure 1.3-12. Structure map of the Pasco Basin and surrounding area (modified from Tolan, 1986). See Table 1.3-3 for description of individually numbered features.

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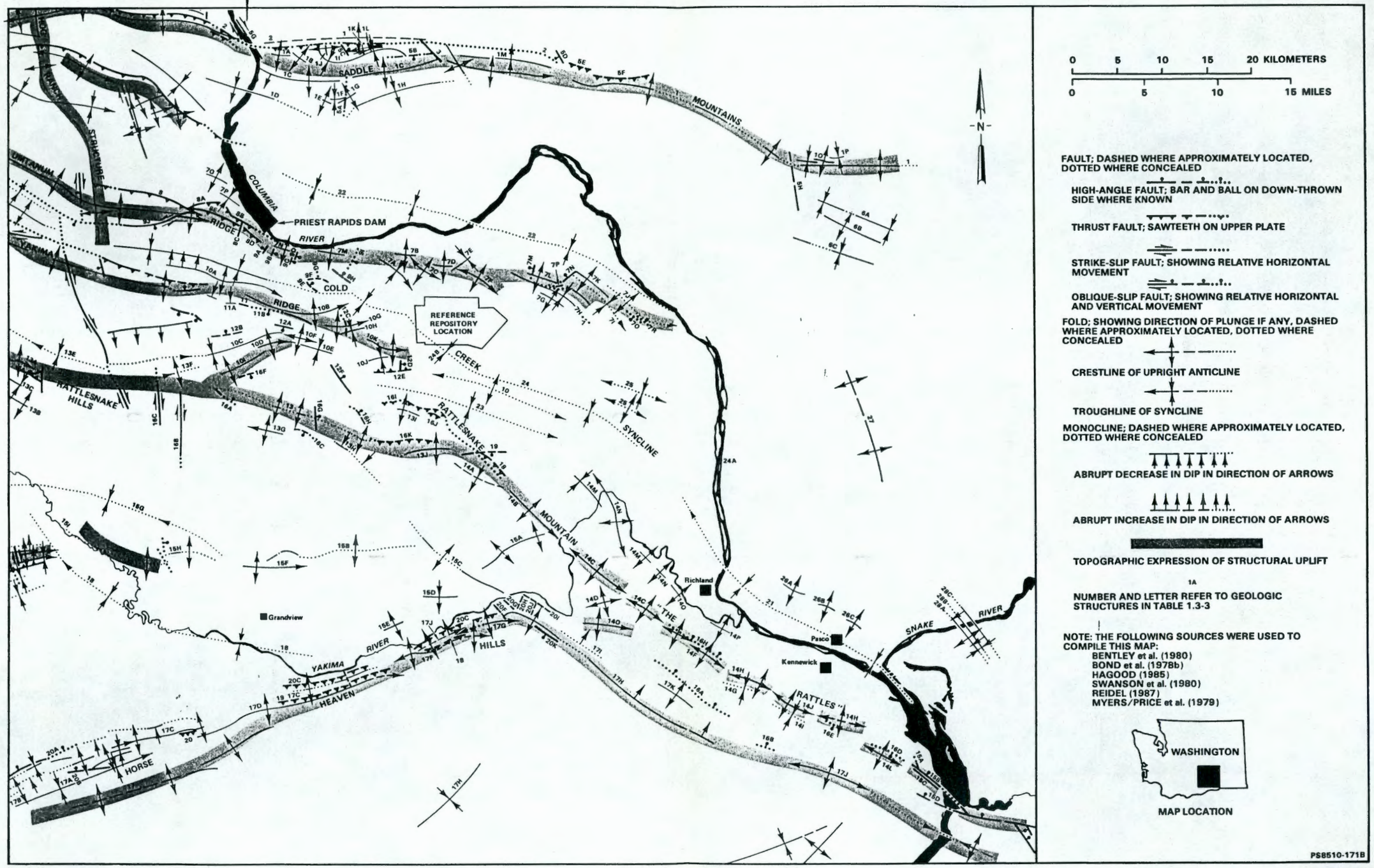

Figure 1.3-12. Structure map of the Pasco Basin and surrounding area (modified from Tolan, 1986). See Table 1.3-3 for description of individually numbered features.

9 2 1 2 5 0 2 0 5 5 9

Table 1.3-3. Characteristics of folds and faults within or near the Pasco Basin (sheet 1 of 10)
(See Fig. 1.3-12 for a location map)

Primary structure	Secondary structure	Map number Fig. 1.3-12	Minimum distance from RRL (km)	Fold characteristics		Fault characteristics				References
				Length (km)	Geometry	Length (km)	Strike/dip	Type of displacement	Age of latest displacement	
Saddle Mountains anticline		1	26	110	Asymmetric, amplitude to 600 m, plunges to E., E.-SE. trend, gentle to open, box fold in part, faulted on N. side, second-order folds trend E.-W. to NW.-SE.					Myers/Price et al. (1979); Price (1982); Reidel (1978a, 1984)
	Related folds or structure	1A-1P	23	3-11						
	Saddle Mountains fault	2	29			>40	E.-W./45° or less west side Sentinel Gap; 45° at Smyrna Bench	Reverse fault at base of the Saddle Mountains. structure. Maximum stratigraphic displacement 600 m; maximum shortening 3 km on west side of Sentinel Gap	<10.5 m.y.	Reidel (1978a, 1984); Grolier and Bingham (1978)
	Smyrna fault	3	26			2	NW./vertical	Tear fault that separates Smyrna Bench and Sentinel Gap segments of Saddle Mountains.	<10.5 m.y.	Reidel (1978a, 1984)
	Hansen Creek fault	4	29			~5	E.-W./S.	Interpreted to be a high-angle reverse fault, displaces Priest Rapids against Frenchman Springs flows	<14 m.y.	Bentley (1977); Myers/Price et al. (1979)
	Unnamed faults related to the Saddle Mountains anticline	5A-5H	23			4-5	E.-W./ unknown and N.-S./ unknown	High-angle normal; high-angle reversed; tear faults. See Grolier and Bingham (1971) for alternative mapping; superseded by Reidel (1984)	<12 m.y.	Myers/Price et al. (1979); Reidel (1984)

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CONSULTATION DRAFT

Table 1.3-3. Characteristics of folds and faults within or near the Pasco Basin (sheet 2 of 10)
(See Fig. 1.3-12 for a location map)

Primary structure	Secondary structure	Map number Fig. 1.3-12	Minimum distance from RRL (km)	Fold characteristics		Fault characteristics				References
				Length (km)	Geometry	Length (km)	Strike/dip	Type of displacement	Age of latest displacement	
Saddle Mountains anticline (continued)	Related folds on south side of structure	6A-6C	34	6	Low amplitude <30 m; >1 km wave length					Reidel (1984)
Umtanum Ridge-Gable Mountain anticline		7	3	130	Asymmetric, E.-W. trend, first-order fold, segmented, plunging at east end, open to tight					Myers/Price et al. (1979); PSPL (1982)
	Folds related to Umtanum Ridge	7A-7P	2	2-5	Asymmetric, amplitude to 750 m, variable plunge, E.-W. to W.-NW.-E.-SE. trend, open to tight, box fold in parts					Goff (1981); Myers/Price et al. (1979); Price (1982)
	Umtanum fault and fault zone	8 8B-8C	18			>12	N. 60° W./30° to 40° S	Reverse, dip-slip, displacement on order of 150 m vertical and 300 m horizontal	>13,000 yr B.P.	Goff and Myers (1978); Price (1982); PSPL (1982)
	North reverse fault	8A and 9J	24			1.5		Reverse, inferred	Post-Wanapum Basalt/pre-Ellensburg growth	PSPL (1982)
	Reverse (?) fault	8B	18			Un-known	Unknown	Reverse, inferred	<14 m.y.	PSPL (1982)
	Twin fault	8C	21			>0.6	NE./unknown	Interpreted to be tear fault within Umtanum anticline	<14 m.y.	Myers/Price et al. (1979); PSPL (1982)
	Buck thrust	8D	19			2.6	N. 50°-N. 80° W./gently NE.	Thrust, zone 9 to 15 m thick, dies out in Umtanum anticline, 250-m displacement	<15.5 m.y.	Price (1982)

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CONSULTATION DRAFT

Table 1.3-3. Characteristics of folds and faults within or near the Pasco Basin (sheet 3 of 10)
(See Fig. 1.3-12 for a location map)

Primary structure	Secondary structure	Map number Fig. 1.3-12	Minimum distance from RRL (km)	Fold characteristics		Fault characteristics				References
				Length (km)	Geometry	Length (km)	Strike/dip	Type of displacement	Age of latest displacement	
Umtanum Ridge-Gable Mountain anticline (cont.)	Upper reverse	8C	21			~2.4	N. 60° E./S.	Thrust, similar to buck thrust	<15.5 m.y.	PSPL (1982)
	Umtanum Ridge cross faults	9A-9D and 9I	8			<1	NW.-SE. and N.-S./ unknown	All normal cross faults of the Umtanum anticline, displacements of a few meters	<12 m.y.	Goff (1981)
	South limb fault	9E-9H	8							
		9J	27			7 km		Tear fault		Swanson et al. (1979a, 1979b)
	Folds related to Gable Butte	7A-7F	2	1-5	Symmetric, amplitude to 150 m, generally plunge to SE., W.-NW., E.-SE. to E.-NE., W.-SW. trend, open, rounded hinges					Fecht (1978); PSPL (1982)
	Folds related to Gable Mountain	7G-7L	5	≤13	Asymmetric to symmetric, amplitude to 300 m, most plunge to SE., W.-NW., E.-SE. to NW.-SE. trend, open to tight, rounded to angular hinges					Fecht (1978); PSPL (1982)
	West fault, Gable Mountain	7M	5			~0.8	N. 34° E./ steeply west	Normal, stratigraphic throw <5 m	<10.5 m.y.	Fecht (1978); PSPL (1982)
	Central fault, Gable Mountain	7N	8			<3.2	N. 55° E./ 30° S.	Reverse, 50-m dip-slip displacement, variable displacement with depth	13,000 yr B.P.	Fecht (1978); PSPL (1982)
	South fault, Gable Mountain	7O	13			≤1.2	E.-W./35° to 40° S.	Reverse, displacement 12 m	<10.5 m.y.	PSPL (1982)
	North-dipping fault, Gable Mountain	7P	6			Unknown	N. 65° W./ 13° N	Reverse, 9.1 to 15.2 m wide in drill holes, stratigraphic throw 98 m	<10.5 m.y.	PSPL (1982)

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CONSULTATION DRAFT

Table 1.3-3. Characteristics of folds and faults within or near the Pasco Basin (sheet 4 of 10)
(See Fig. 1.3-12 for a location map)

Primary structure	Secondary structure	Map number Fig. 1.3-12	Minimum distance from RRL (km)	Fold characteristics		Fault characteristics				References
				Length (km)	Geometry	Length (km)	Strike/dip	Type of displacement	Age of latest displacement	
Umtanum Ridge-Gable Mountain anticline (cont.)	DB-10 (upper) fault	7Q	8			0.8	Due S./25° to 45° W.	Reverse, dip-slip, ~55 m displacement	<10.5 m.y.	Myers/Price et al. (1979); PSPL (1982)
	Southeast anticline fault	7R	14			Un-known	N. 39° W./ 30° SW.	Reverse fault based on borehole data	>730,000 yr B.P.	PSPL (1982)
Yakima Ridge anticline	Cairn Hope Peak anticline and related folds	10A-10B 10G, 10H 10J, 10K	2	≤75	Asymmetric, SE. plunge, W.-NW.-E.-SE. trend, E. end buried by sediments, eastern exposed part is series of an echelon, doubly plunging, asym-metric folds					Bond et al. (1978b); Goff (1981); Myers/Price et al. (1979); Cochran (1982)
	Buried extension of Yakima Ride anticline	10								
	Silver Dollar fault and flexures	11 11A, 11B	11	3	Flexures along Silver Dollar fault trend	~7	W.-NW./ unknown	Interpreted to be high angle-reverse fault (or normal), zone width 50 to 70 m, displaces Frenchman Springs Member against Umatilla and Pomona Members	<14 m.y.	Goff (1981); Myers/Price et al. (1979)
	Other Yakima Ridge faults	12A-12F	3			≤1	Variable	Reverse and tear faults; small faults associated with larger folds	<10.5 m.y.	Myers/Price et al. (1979)
Rattlesnake Hills-Rattlesnake Mountain uplift	Rattlesnake anticline, western segment	13, 13A-13C 13E-13J	11 8	56	Asymmetric, E.-W. trend, tight, rounded hinge, numerous second-order folds on hinge and crest					Bond et al. (1978b); Myers/Price et al. (1979)
	Rattlesnake Hills northeast extension	10C-10F 10I	11	20	Asymmetric complex fold that trends northeast off of Rattlesnake Hills					Myers/Price et al. 1979, Plate III

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CONSULTATION DRAFT

Table 1.3-3. Characteristics of folds and faults within or near the Pasco Basin (sheet 5 of 10)
(See Fig. 1.3-12 for a location map)

Primary structure	Secondary structure	Map number Fig. 1.3-12	Minimum distance from RRL (km)	Fold characteristics		Fault characteristics				References
				Length (km)	Geometry	Length (km)	Strike/dip	Type of displacement	Age of latest displacement	
Rattlesnake Hills-Rattlesnake Mountain uplift (cont.)	Rattlesnake Mtn anticline, and eastern segment; the "Rattles"	14A-14C 14E-14L	14	70	Asymmetric, NW.-trending series of doubly plunging, slightly en echelon, locally faulted folds. #14A is asymmetric, amplitude 350 m NW trend, and faulted on N. side					Bond et al. (1978b); Jones and Landon (1978); Myers/Price et al. (1979)
	Folds north of "The Rattles" Horn anticline Horn syncline	14M-14P 14Q 14R	18	10	Low-amplitude folds along Yakima River that parallel "The Rattles" to the north					Myers/Price et al. (1979)
	Rattlesnake anticline, second-order folds on south limb	15A-15I	24	5 to 16	Variable plunge and trend					Bond et al. (1978b); Myers/Price et al. (1979)
	Faults of western Rattlesnake Hills	16A-16H	18			<2	N.-S. and NW.-SE./ unknown	Minor dip-slip cross faults associated with larger anticlines. Displacements in tens of meters	<10.5 m.y.	Myers/Price et al. (1979)
	Maiden Springs fault	16C	29			~2.5	Unknown	Inferred, high-angle reverse fault with 45 to 60 m displacement	<10.5 m.y.	Bond et al. (1978b)
	Twenty-Nine-Thirty-Six fault	16G	13			4	N.-S./vertical	Scissor fault, W. side up, 90 m displacement	<10.5 m.y.	Bond et al. (1978b)
	Fault of central Rattlesnake Hills	16H	10			1.5	NW./un-known	Vertically juxtaposes Priest Rapids basalts and Pomona basalts	<10.5 m.y.	Bond et al. (1978b)

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CONSULTATION DRAFT

Table 1.3-3. Characteristics of folds and faults within or near the Pasco Basin (sheet 6 of 10)
(See Fig. 1.3-12 for a location map)

Primary structure	Secondary structure	Map number Fig. 1.3-12	Minimum distance from RRL (km)	Fold characteristics		Fault characteristics				References
				Length (km)	Geometry	Length (km)	Strike/dip	Type of displacement	Age of latest displacement	
Rattlesnake Hills-Rattlesnake Mountain uplift (cont.)	Thrust faults of Snively Basin area	16I-16K	7			>1	NW.-SE./ moderate	Not exposed, but Saddle Mountains Basalts section is repeated three times vertically with angular discordance at lower fault	<10.5 m.y.	Myers/Price et al. (1979)
	Rattlesnake Mountain fault	18	11			16	N. 50° W./ steep	Probably reverse, 400 m vertical displacement, zone 100 m wide, includes upper local fault, dies out into Rattlesnake Mountain anticline to SE. Appears to merge with faults of Snively Basin	<10.5 m.y.	Bond et al. (1978b); Myers (1981)
	Upper Rattlesnake Mountain Fault	18A								
	Rattlesnake Springs fault	12D	3			~1.5	N.-NE./ unknown	Inferred fault to account for geometry change of Yakima Ridge strike-slip	<10.5 m.y.	Myers/Price et al. (1979)
	South Yakima Ridge normal fault	12E	3			1.5	E.-W./N.	Inferred reverse fault under S. limb of Yakima Ridge	<10.5 m.y.	Myers/Price et al. (1979)
"The Rattles" brachy anticlines		14C, 14E-14L	24	3-10	Aligned asymmetric doubly plunging anticlines (brachyanticlines); NW.-SE. trend; represent the SE. part of the Rattlesnake-Wallula alignment					Myers/Price et al. (1979); WPPSS (1977, 1981)

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CONSULTATION DRAFT

Table 1.3-3. Characteristics of folds and faults within or near the Pasco Basin (sheet 7 of 10)
(See Fig. 1.3-12 for a location map)

Primary structure	Secondary structure	Map number Fig. 1.3-12	Minimum distance from RRL (km)	Fold characteristics		Fault characteristics				References
				Length (km)	Geometry	Length (km)	Strike/dip	Type of displacement	Age of latest displacement	
"The Rattles" brachy anticline (cont.)	Related folds	14C-14D	32		Second-order asymmetric anticlines between Horse Heaven Hills and the "Rattles"					Myers/Price et al. (1979)
	Wallula Fault Zone	15B	66			50	NW./steep	Maximum vertical offset 330 m, scissor-type displacement, last movement horizontal Fault zone ~330 m wide	>13,000 yr	Gardner (1977); Gardner et al. (1981); Farooqui (1979)
	Wallula Gap fault	15D	67			~5	NW./steep	Splay extension west of Columbia River		
	Other faults	15A-15C 16A-16F	40			vari-able up to 8	Generally NW. to W.-NW./ unknown	Related to brachy anticlines; dip-slip movements up to 50 m; includes faulting at Finley Quarry (#16d)	At least 7,000 yr at Finley Quarry	Jones and Landon (1978); Bond et al. (1978b); Farooqui and Thoms (1980)
Horse Heaven Hills uplift (western segment)		17	32	>80	Asymmetric, ~200 m amplitude, NE.-SW. trend, open, monoclinal northern hinge. Complex with many segments					Bond et al. (1978b); Myers/Price et al. (1979). See Hagood (1985) for most recent interpretation
	Prosser anticline	17D	34	24	Asymmetric, double-hinged, N. 70°-80° E. trend, northeast plunge					Hagood (1985)
	Drake anticline	17C	37	11	Asymmetric, low-relief, double-hinged, parallels Prosser anticline					Hagood (1985)

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CONSULTATION DRAFT

Table 1.3-3. Characteristics of folds and faults within or near the Pasco Basin (sheet 8 of 10)
(See Fig. 1.3-12 for a location map)

Primary structure	Secondary structure	Map number Fig. 1.3-12	Minimum distance from RRL (km)	Fold characteristics		Fault characteristics				References
				Length (km)	Geometry	Length (km)	Strike/dip	Type of displacement	Age of latest displacement	
Horse Heaven Hills uplift (western segment) (cont.)	Gibbon anticline	17F	33	12	Asymmetric, locally double- hinged, N. 70° E. trend, broad, may be en echelon with Prosser anticline					Hagood (1985)
	Chandler anticline	17G	32	7	Asymmetric, double-hinged, N. 70° E. to N. 85° W. trend					Hagood (1985)
	Kiona anticline/ Badger Canyon anticline/ monocline	17H	31	29	Asymmetric, double-hinged, W. to NW. trend					Hagood (1985)
	Phelps anticline/ monocline	17J	58	10	Asymmetric, NE. trend, monocline at northeast end					Hagood (1985)
	Gibbon fault	18	32			5	NE./vertical	Reverse, juxtaposes Selah interbed against Levey interbed, 70-m vertical displacement	<10.5 m.y.	Hagood (1985)
	Prosser fault	19	37			13	NE./unknown	Interpreted fault to account for topographic relief along Horse Heaven Hills	<10.5 m.y.	Hagood (1985)
	Phelps fault	20C	31			10	NE./ moderate	Thrust or reverse, juxtaposes Pomona Member against Elephant Mountain Member	<10.5 m.y.	Hagood (1985)
	Other faults of western Horse Heaven Hills	20A-20K	28			Vari-able	Variable	Small faults on N. slope of Horse Heaven Hills, partly owing to landsliding	<8.5 m.y.	Hagood (1985)

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CONSULTATION DRAFT

Table 1.3-3. Characteristics of folds and faults within or near the Pasco Basin (sheet 9 of 10)
(See Fig. 1.3-12 for a location map)

Primary structure	Secondary structure	Map number Fig. 1.3-12	Minimum distance from RRL (km)	Fold characteristics		Fault characteristics				References
				Length (km)	Geometry	Length (km)	Strike/dip	Type of displacement	Age of latest displacement	
Horse Heaven Hills uplift (eastern segment)	Jumpoff Joe anticline, Johnson Butte, and related folds	17J	32	70 (extends east of Wallula Gap)	Asymmetric, doubly plunging, NW.-SE. trend, gentle to open					Bond et al. (1978b); Jones and Landon (1978); Myers/Price et al. (1979); see Hagood (1985) for most recent interpretation
	Small fold on back slope of Horse Heaven Hills	17L								
	Webber Canyon anticline	17K	40	5	Western extension of Webber Canyon monocline					Hagood (1985)
	Webber anti-cline/monocline	17I	34	5	Subtle, low-relief, NW. trend					Hagood (1985)
	Badger Coulee fault, Webber Canyon fault	16A,16B	40, 55			5, 9	NW./vertical	Faults of the Badger Canyon monocline. Maximum vertical displacement 80 m down to NE.	Unknown	Hagood (1985); Bond et al. (1978b)
Pasco syncline		21	~25	>40	Symmetric, SE. curvilinear trend, not exposed					Myers/Price et al. (1979)
Wahluke syncline		22	~8	~40	Asymmetric, plunges SE. from the NW. and to the NW. from the SE. end of structure, not exposed					Myers/Price et al. (1979)
Benson Ranch syncline		23	~5	~25	Asymmetric, low amplitude, SE. plunge, E.-W. to NW.-SE. trend, not exposed					Myers/Price et al. (1979); Myers and Price (1981)

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CONSULTATION DRAFT

Table 1.3-3. Characteristics of folds and faults within or near the Pasco Basin (sheet 10 of 10)
(See Fig. 1.3-12 for a location map)

Primary structure	Secondary structure	Map number Fig. 1.3-12	Minimum distance from RRL (km)	Fold characteristics		Fault characteristics				References
				Length (km)	Geometry	Length (km)	Strike/dip	Type of displacement	Age of latest displacement	
Cold Creek syncline Wye Barricade depression		24 24A	0	60	Asymmetric, low-amplitude, 3° to 5° SE. plunge, W.-NW.-E.-SE. trend, gentle, two depressions along trough					Myers/Price et al. (1979); Myers and Price (1981)
Related anticlines		25	13	5	W.-NW. trending					Myers (1981)
Folds of the eastern Pasco Basin (Palouse subprovince)		26A, 26C, 27, 28A-28C	42	3 to 6.5	Low-amplitude folds on the Palouse slope, W.-NW.-E.-SE. and N.-NW.-S.-SE. trends, parallel to Pasco syncline					Myers/Price et al. (1979)
Lower Yakima Valley Syncline		29	30	30	Broad, open syncline					

NOTE: RRL = reference repository location.
To convert kilometers to miles, multiply by 0.62.
To convert meters to feet, multipy by 3.281.

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CONSULTATION DRAFT

1.3.2.2.2.1 Ice Harbor dike system and Jackass anticline/monocline

The eastern boundary of the Pasco Basin is interpreted to be where the Palouse paleoslope dips into the Pasco Basin. This is marked by an abrupt increase in thickness of the suprabasalt sediments, Columbia River basalt, and pre-Columbia River basalt sedimentary rock (Myers/Price et al., 1979, Appendix E; Reidel et al., 1980; Prieto et al., 1985, Fig. 12). Geophysical data used to define the base of basalt and underlying rock (Prieto et al., 1985, Fig. 12) are inadequate to locate accurately the eastern margin of the Pasco Basin in the subsurface.

Two features mark the eastern boundary: the Jackass monocline/anticline and the Ice Harbor dike system. The Jackass monocline/anticline, mapped as an anticline by Swanson et al. (1980, No. 27), is a diffuse structure approximately 16 km (10 mi) wide that generally coincides with the increase in dip. The Ice Harbor dike swarm, also approximately 16 km (10 mi) wide, based on aeromagnetic maps of Swanson et al. (1979c), spans the area of flexure with intermittent exposures.

The Palouse paleoslope has been relatively stable since at least 12 m.y.B.P. and probably throughout the Miocene, but the Pasco Basin has been an area of subsidence and sediment accumulation since the early Tertiary (Mitchell and Bergstrom, 1983; Reidel and Fecht, 1981, pp. 3-1 to 3-44). The role, if any, the Pasco Basin plays in the localization of the Ice Harbor dikes that were intruded 8.5 m.y.B.P. is uncertain. The exact nature of the sub-basalt surface along the eastern Pasco Basin boundary also is uncertain. The surface basalt flows are gently folded and change from a 1° to 2° dip on the Palouse Slope to a 4° to 5° dip into the Pasco Basin (Reidel et al., 1983). One interpretation of the abrupt increase in basalt and pre-basalt sediment may be that the Ice Harbor dike system may correspond to a buried fault (Reidel, 1984, p. 963) and that the eastern boundary may be the margin of a sub-basalt graben. Although the orientation of the eastern boundary of the Pasco Basin parallels folds farther east, the relationship between the extensional dikes and the compressional folds is unclear. Additional detailed mapping and geophysical studies will be necessary to resolve these uncertainties (see Section 8.3.1.2.3.3.4).

1.3.2.2.2.2 Hog Ranch-Naneum Ridge anticline

The western boundary of the Pasco Basin is the broad, north-south-trending Hog Ranch-Naneum Ridge anticline (Mackin, 1961; see Fig. 1.3-8 and 1.3-12) that can be traced north to the plateau margin, where it abruptly changes to a northwest trend in the North Cascades (Tabor et al., 1982). This is clearly a basement-controlled feature that plunges to the south (Campbell, 1985); no evidence can be found for the structure south of the Horse Heaven Hills (Hagood, 1985). The anticline may plunge deeply into the subsurface or it may have been unable to deform the overlying basalt units because of their thickness--greater than 3.5 km (2.2 mi) (Orange and Berkman, 1985).

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Along the Frenchman Hills, pre-basalt sedimentary units thin over the Hog Ranch-Naneum Ridge structure (Campbell, 1985), as do the Columbia River basalts. A gravity gradient parallels the feature, but the exact relationship between the Hog Ranch-Naneum Ridge anticline and the gravity anomaly is unclear. The increase in thickness of the basalt into the Pasco Basin suggests that the Hog Ranch-Naneum Ridge anticline may be fault controlled at depth (Campbell, 1985) and that the western flank of the basin may be fault controlled below the basalt. However, available geophysical data are not adequate to support this interpretation (Section 1.5.2.4).

1.3.2.2.2.3 Anticlinal features

Uplift and erosion of anticlinal ridges in the Pasco Basin provide exposures of structures that can be mapped and studied directly, whereas structures in synclines are buried and can only be studied indirectly via boreholes and geophysical data. Anticlines and synclines are related spatially, temporally, and genetically; therefore, the knowledge obtained by direct study of exposures in anticlines helps provide an understanding of the structural geology of the related synclines.

Because the following structures have been mapped at various levels of detail, the level of certainty in the following discussions is also variable. Anticlinal ridges in the Pasco Basin include the Saddle Mountains, Umtanum Ridge-Gable Mountain, Yakima Ridge, Rattlesnake Hills, and the Horse Heaven Hills. A discussion of the timing of deformation for these structures can be found in Section 1.5.2.4.2.3.

Saddle Mountains

The Saddle Mountains is a broad anticlinal uplift that trends generally east-west for 110 km (68 mi) and forms the northern boundary of the Pasco Basin. This area has been mapped in detail by Reidel (1987) and described by Reidel (1984). Previous studies are summarized in those reports. Two dominant structural features associated with the Saddle Mountains are the Saddle Mountains anticline (see Table 1.3-3 and Fig. 1.3-12, No. 1) and the Saddle Mountains fault (No. 2), although the complex geometry of the anticline has resulted in other secondary anticlines, synclines, and monoclines that parallel the main trend of the structure (Reidel, 1987, Plates I-III; 1984, Fig. 3a and 3b).

The Saddle Mountains can be divided into six segments on the basis of differences in geometry of the fold (Fig. 1.3-13 and 1.3-14; Reidel, 1984, 1987, Fig. 3a and 3b). The McDonald Springs and Smyrna Bench segments are the most complex structurally. The Saddle Mountains fault is either a reverse or thrust fault that has an unknown dip angle. Although it generally parallels the Saddle Mountains anticline, it does not appear to have the same length and may not extend east of Smyrna Bench. At least 3.0 km (1.9 mi) of crustal shortening due to horizontal compression has been measured on the Saddle Mountains fault on the west side

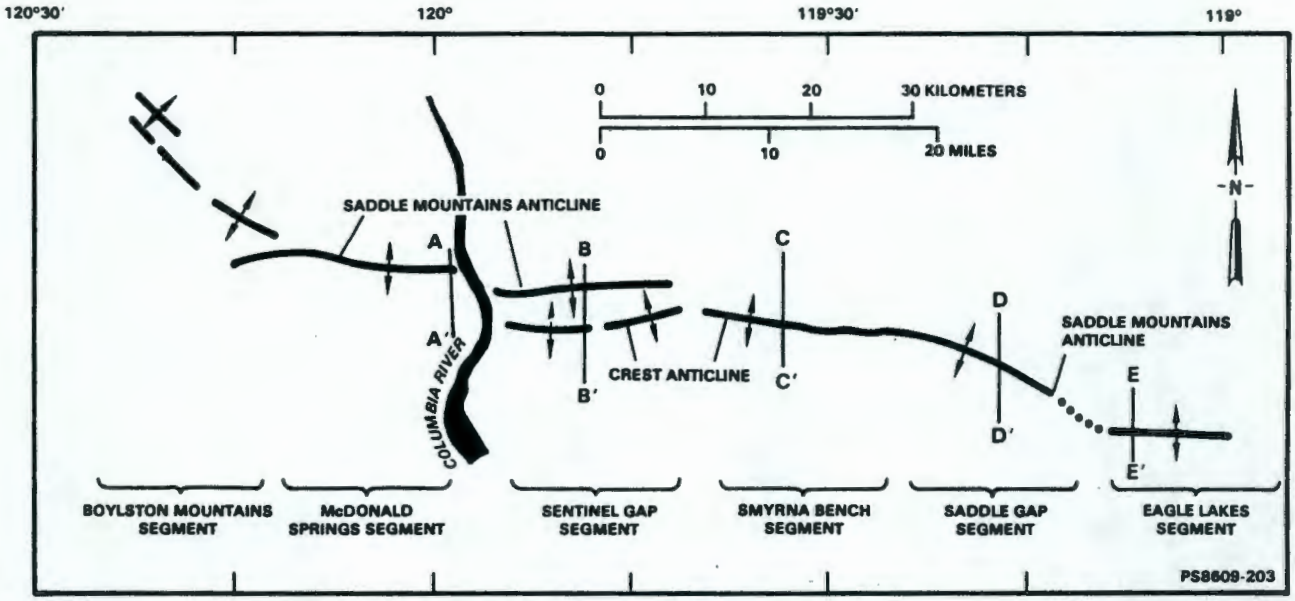

Figure 1.3-13. Structural segments of the Saddle Mountains.

of Sentinel Gap (Reidel, 1984, p. 972), but this decreases to no detectable shortening at the east end in the Eagle Lakes area. Other secondary structures associated with the Saddle Mountains uplift are described by Reidel (1984, 1987) and summarized in Figure 1.3-12 and Table 1.3-3.

Umtanum Ridge-Gable Mountain

Umtanum Ridge-Gable Mountain is a nearly continuous structural and topographic high that extends from the east end of Gable Mountain just northeast of the reference repository location westward and west-northwestward to near Ellensburg, Washington, a distance of ~110 km (68 mi). The structure consists of two major segments in the Pasco Basin: the Umtanum Ridge anticline (No. 8A through No. 8C and No. 9A through No. 9J) and the Gable Butte-Gable Mountain fold (No. 7A through No. 7P). The geometry of the fold is, however, more complex than just two segments (Fecht, 1978; Goff, 1981; PSPL, 1982; Barsotti, 1986, p. 87).

The eastern part of the Umtanum Ridge segment (east of the Hog Ranch-Naneum Ridge axis) consists of an asymmetrical, eastward-plunging anticline whose crest branches into several subsidiary en echelon folds along the major fold trend with several cross faults (see Fig. 1.3-12; Goff and Myers, 1978; Goff, 1981, pp. 41-46; Price, 1981, pp. 18-25, Plate IV; Barsotti, 1986, pp. 90-96). West of Priest Rapids Dam, this fold is interpreted by Bentley (1980a) to include three imbricate thrust slices in which the basalt is folded, overturned, and thrust over the relatively undeformed Mabton interbed.

The Umtanum fault (No. 8A through No. 8C) is a buried, reverse or thrust fault along the base of Umtanum Ridge near Priest Rapids Dam (Mackin, 1955, pp. III-4-5 through III-4-8; Price, 1982, pp. 52-58) (Fig. 1.3-15). The fault juxtaposes the vertical Frenchman Springs Member in the Umtanum Ridge

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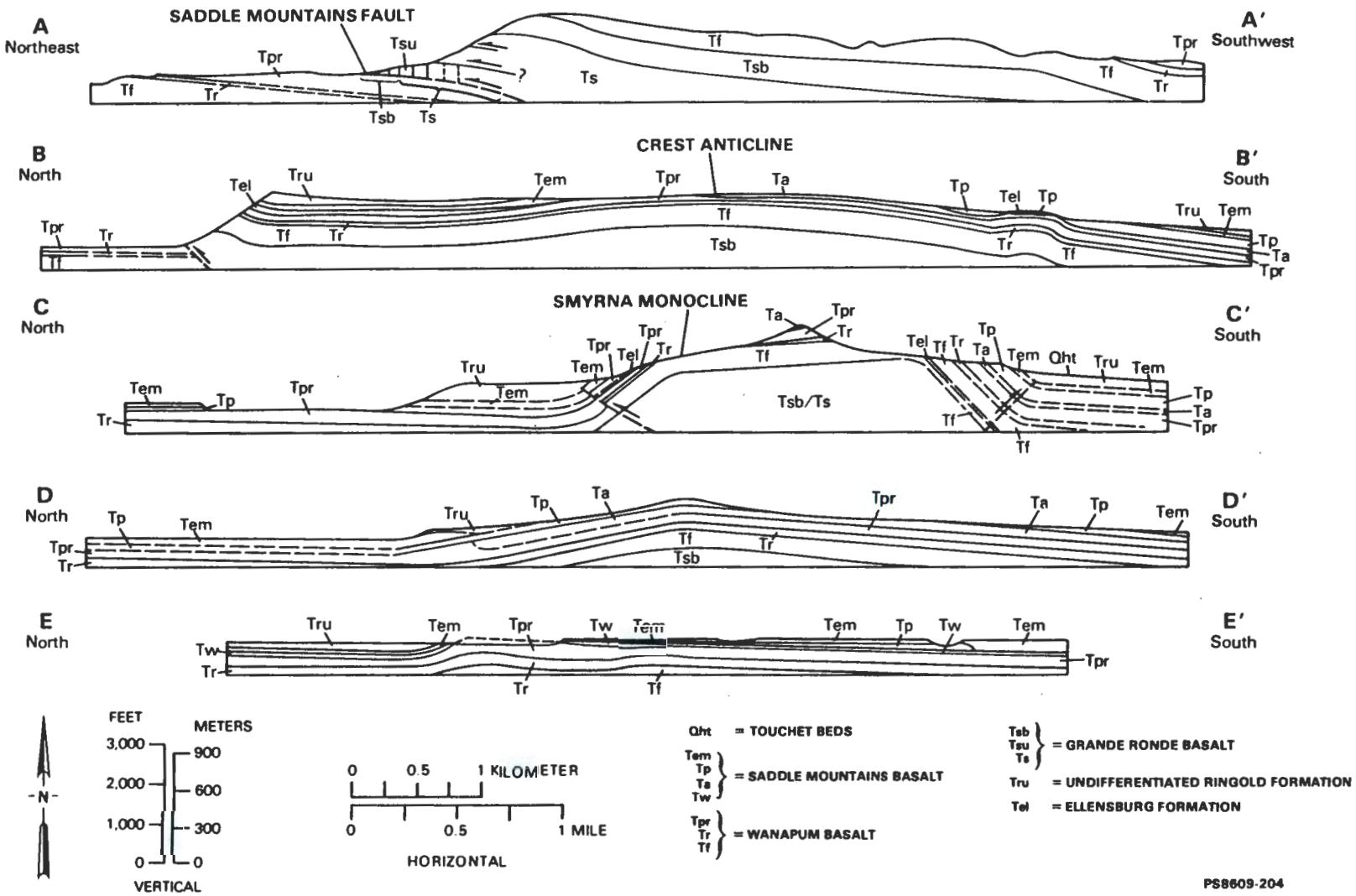

Figure 1.3-14. Cross sections through the Saddle Mountains.

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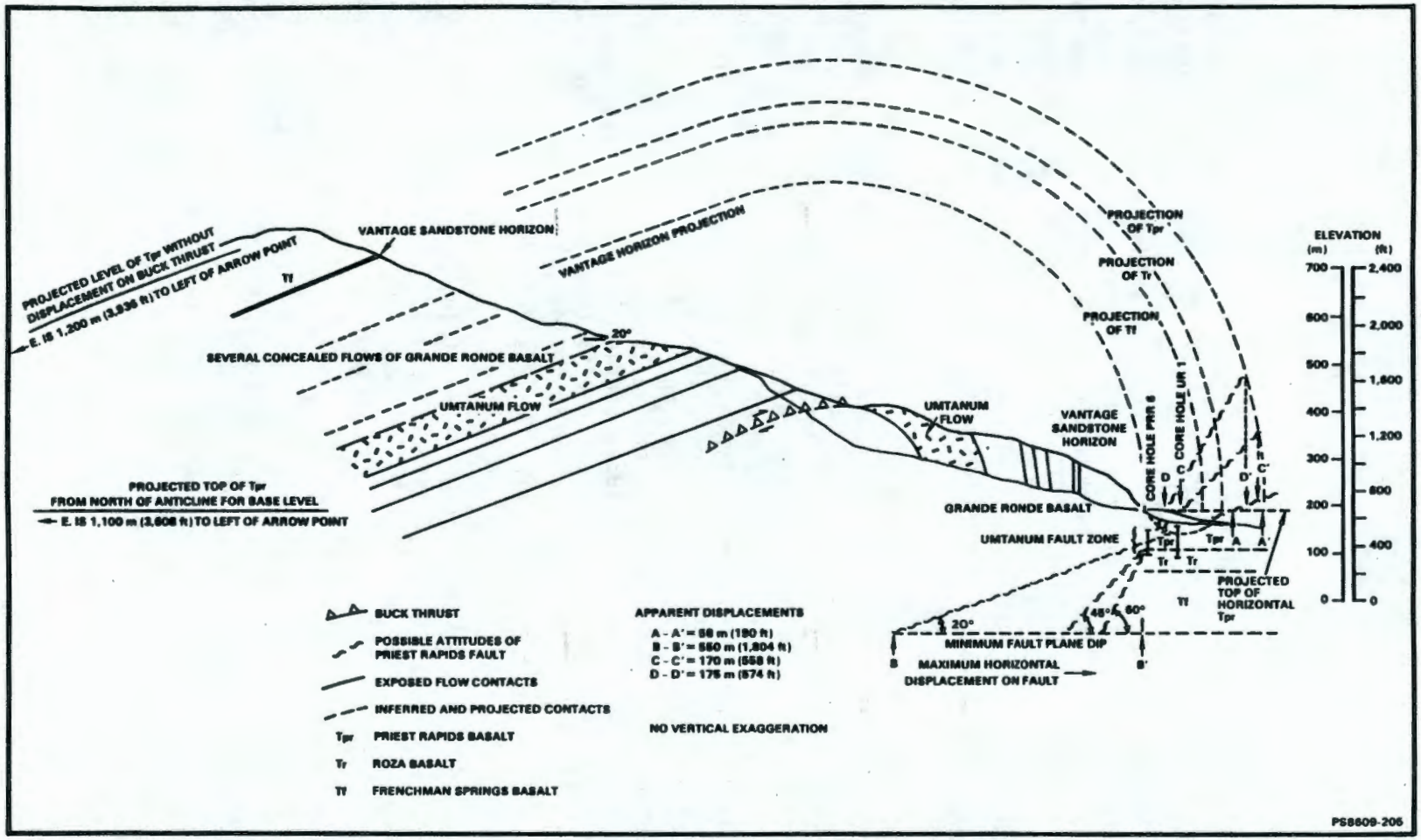

Figure 1.3-15. Cross sections through the Umtanum Ridge near Priest Rapids Dam (from Price, 1982, Fig. 25).

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anticline and the horizontal Priest Rapids Member in the Wahluke syncline. Results from drilling suggest that this fault dips southward under the ridge at 30° to 40° (PSPL, 1982, pp. 2N12-2N14), although it could be as high as 60° (Price, 1982, p. 58). The zone of fault breccia is approximately 36 m (120 ft) thick (Price, 1982, p. 55).

Continuity of the Umtanum fault eastward toward Gable Mountain cannot be established by exposures. However, structural relief and complexity appear to decrease toward the east, where the uplift is interpreted by Goff (1981, p. 69) as a simple, asymmetrical, eastward-plunging anticline whose north limb is steep. Although the fault is covered east of Priest Rapids Dam, fault displacement probably decreases as structural relief across the Umtanum fold decreases. The current interpretation is that the Umtanum fault dies out ~11 km (7 mi) east of Priest Rapids Dam (Myers and Price, 1981, pp. 8-13 to 8-15); however, topographic and structural relief extend to the east end of Gable Mountain, suggesting that faulting could occur along the entire north side of the structure.

Surface mapping and borehole and geophysical data indicate that Umtanum Ridge, Gable Butte, and Gable Mountain are one continuous structure (PSPL, 1982, p. 2K-18). Gable Mountain and Gable Butte are two, topographically isolated, anticlinal ridges of basalt and interbedded sediments that provide the only extensive bedrock outcrops in the central part of the Pasco Basin. Gable Mountain and Gable Butte are composed of a series of northwest-trending, doubly plunging, en echelon anticlines, synclines, and associated faults. The folds are interpreted as second-order folds within the closure of an asymmetrical, first-order fold (Fecht, 1978, pp. 37-48). The faults on Gable Mountain have been investigated using extensive trenching and drilling of three previously mapped faults (PSPL, 1982, Section 20). These faults are referred to as the south, central, and west faults (No. 7M through No. 7O) (Bingham et al., 1970, pp. 48-62; Fecht, 1978, pp. 43-47). During trenching investigations (PSPL, 1982, Section 20), a fourth, buried fault was discovered (No. 7R).

Borehole DB-10, which is south of Gable Mountain, penetrated a structure thought to be a tight, secondary fold associated with Gable Mountain (Myers/Price et al., 1979, pp. III-121 to III-123). Core from DB-10 revealed two fault zones containing slickensides and tectonic breccia (No. 7Q). One occurred at ~120 m (400 ft) in depth and the other at approximately 175 m (575 ft) in depth (Myers/Price et al., 1979, pp. III-142 to III-146). Repetition of stratigraphic section across the two faults indicates that they are reverse faults with approximately 55 m (180 ft) of combined displacement. Two additional boreholes were drilled adjacent to DB-10, and it was determined that the upper fault strikes north-south, dips west 25° to 45° and is approximately 0.8 km (0.5 mi) long (PSPL, 1982, pp. 20-47). Because of the close geometric and spatial relationship exhibited by Gable Mountain faults and folds, it was concluded that all Gable Mountain faults are related to folding in a north-south to northeast-southwest compressional stress regime (PSPL, 1982, p. 20-6).

The reexamination of trenches excavated during the late 1960s across the of central Gable Mountain fault (No. 7N through No. 7P) resulted in detection of features that suggest Quaternary movement (PSPL, 1982, p. 20-5; see Table 1.3-2) (see Section 1.3.2.2.1.3). These features include slickensides on clastic dikes in the hanging wall, clastic dikes intruded along the fault plane, and fractures in glaciofluvial deposits that overlie the bedrock fault. The trenches exposed offsets in glaciofluvial sediments of as much as 6.5 cm (2.6 in.) along narrow fractures that are continuous with a reverse fault in the basalt. These offset sediments are correlated with other glaciofluvial sediments that contain Mount St. Helens "set S" ash, which has a date of approximately 13,000 yr B.P.

Data from boreholes show that the central Gable Mountain fault has much greater displacement at depth in the basalt. The top of the Esquatzel flow is offset approximately 50 m (165 ft). The displacement in the glaciofluvial deposits is interpreted to be caused either by the latest tectonic movement on an older fault of greater displacement at depth or by rapid hydrostatic loading and unloading during cataclysmic flooding (PSPL, 1982, p. 20-5). If the displacement is due to tectonic movement, it represents the closest known fault to the reference repository location that is of Quaternary age. Because of the data and the uncertainty in this interpretation, further work will be done to address the possibility of Quaternary-age faulting within the Pasco Basin (Section 8.3.1.2.4.3.1).

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Yakima Ridge

The Yakima Ridge uplift (No. 10, No. 10A, No. 10B, No. 10G, and No. 10K) extends from west of Yakima, Washington, to the center of the Pasco Basin, where it forms the southern boundary of the Cold Creek syncline. The dominant fold within the Yakima Ridge uplift, east of the Hog Ranch anticline, is the Cairn Hope Peak anticline (No. 10A). The shorter and steeper north limb of this anticline dips 30° to 40° to the north, and its southern limb dips 10° to 15° to the south. The anticline trends N. 70° W. to N. 75° W. and plunges gently southeastward. The southern limb contains two monoclines. The northern Cairn Hope Peak monocline (No. 11A) trends N. 60° W. and is interpreted by Bond et al. (1978b, pp. 67-87) to merge eastward into the Silver Dollar fault (No. 11B) of Goff (1981). The southern monoclines trend northeast and merge with the Cairn Hope Peak monocline. The easternmost surface expression of the Yakima Ridge uplift, as mapped by Bond, in Myers/Price et al. (1979, Plate III), is represented by an anticline (No. 10K), which plunges eastward into the Pasco Basin.

A north-dipping reverse fault (No. 12E), which has an associated cross fault (No. 12D) with a strike-slip component, occurs south of the main ridge along the southeastern end of the exposed part of Yakima Ridge. The cross fault was previously mapped by Bond (in Myers/Price et al., 1979, Plate III) as N. 20° to 25° E. vertical fault, but has been remapped as a north-trending tear fault by the BWIP geologists. The cross fault is of limited extent and cannot be traced north of the southern limb of Yakima Ridge. The reverse fault (No. 12E) parallels the main trend of Yakima Ridge. This fault was

proposed to account for a linear escarpment and apparent structural displacement of the extreme eastern and southern ends of Yakima Ridge (WPPSS, 1977, pp. 2RH6-5 and 2RH6-6).

Further investigations of the buried eastern extension of Yakima Ridge are planned to reduce uncertainties regarding structures in the vicinity of the reference repository location (see Section 8.3.1.2.3.3.4). Data from surface geologic mapping are minimal, since only a few exposures of basalt occur in the area (see Myers/Price et al., 1979, Plate III-1). A reconnaissance investigation of the subsurface structure using gravity and ground-magnetic surveys was conducted by Cochran (1982), and he supplemented these data with borehole, aeromagnetic, and seismic data (Myers and Price, 1981). Gravity and magnetic observations were made on an orthogonal grid at intervals varying from 150 to 300 m (500 to 1,000 ft) (Cochran, 1982). The interpretation was largely qualitative, but some quantitative modeling was done using a simple stratigraphic model.

Cochran (1982, pp. 73-86) observed two predominant trends in the potential-field data over the buried part of the structure: a northwest and an east-west trend. Each has multiple smaller, secondary trends that are oblique to the major feature. The east-west trend coincides with the subsurface extension of Yakima Ridge (Holmes and Mitchell, 1981, p. B-45) and is interpreted to be a westerly plunging anticline that has had little erosional modification (Cochran, 1982, p. 74). The northwest trend is smaller in scale and does not appear to be related to the larger features (e.g., as the Rattlesnake-Wallula alignment). It appears more likely to be related to cross folds or cross faults on Yakima Ridge. More work will be necessary to determine the exact nature of these features.

The relationship between Yakima Ridge and its easterly extension has not been clearly defined. Faulting, folding, or both of these mechanisms with subsequent erosional modification can explain the available data.

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Rattlesnake Hills

The Rattlesnake Hills uplift, in conjunction with the Rattlesnake-Wallula alignment, forms the southern boundary of the Pasco Basin. The Rattlesnake Hills extend from near Yakima, Washington, on their west end, easterly to Snively Basin, where they abruptly terminate against the Rattlesnake-Wallula alignment (Swanson et al., 1979a; Myers/Price et al., 1979, Plate III). The Rattlesnake Hills uplift is an asymmetrical anticline (No. 13) that has been faulted (Bond et al., 1978b). It has a steeply dipping north limb and more gently dipping south limb. The 3629 fault (No. 16G) and Maiden Springs fault (No. 16G) occur at a change in fold geometry and probably developed in response to that change. The 3629 fault is interpreted here as a cross fault.

At the eastern end of the Rattlesnake Hills is Snively Basin, a complex area that has only been mapped in a reconnaissance manner (Myers/Price et al., 1979, Plate III-1). The fold geometry of Snively Basin is more complex and least similar to any other Yakima fold. Several thrust faults are present

(No. 16J and No. 16K) that may connect with faults associated with Rattlesnake Mountain. In addition, the structural relief along the Rattlesnake Hills and Rattlesnake Mountain abruptly decreases into Snively Basin.

The Rattlesnake Hills-Snively Basin area has some of the greatest uncertainties as to its exact structural nature. This area will be mapped in detail as part of site characterization activities (Section 8.3.1.2.3.3.4).

Horse Heaven Hills

The Horse Heaven Hills uplift (No. 17) is an anticlinal ridge that consists of northwest- and northeast-trending segments. Geologic mapping along this feature has shown the structure to be segmented by several en echelon, asymmetric folds and associated faults that have developed on these main trends (see Hagood, 1985, for most recent interpretation and summary of previous interpretations).

The northwest trend of the Horse Heaven Hills uplift parallels the trend of the Rattlesnake-Wallula alignment, has several second-order folds superimposed on it, is cut by northwest-trending, high-angle faults, and merges to the southeast with the Wallula Fault Zone (No. 15A, No. 15B, No. 15C, and No. 15D). Figure 1.3-16 is a cross section (Hagood, 1985) at Webber Canyon through this northwest-trending segment.

Numerous second- and third-order folds and monoclines have developed on both segments of the main structural trend near and to the west of the bend in the Horse Heaven Hills uplift (Hagood, 1985). The folds commonly contain thrust and reverse faults in the vicinity of the northern flanks and hinges of anticlines, and these features are parallel to the flanks and hinges (see Fig. 1.3-12). Several short, steep faults that radiate northward from the bend in the uplift (No. 20F through 20J) are interpreted to be cross faults associated with folding of the Badger Canyon anticline/monocline (No. 17H).

1.3.2.2.2.4 Synclinal features

The synclines within the Pasco Basin (see Fig. 1.2-12) are the Pasco (No. 21), Wahluke (No. 22), Benson Ranch (No. 23), and Cold Creek synclines (No. 24). All are buried beneath sediments of the Ringold and Hanford Formations. Only the western end of the Cold Creek syncline is not buried by thick sedimentary deposits. The characteristics of these structures are known only from boreholes and geophysical surveys.

The geophysical methods and techniques that have thus far been used have not been capable of providing high resolution of structures at and below repository depths, and the interpretation of the data does not always provide a unique solution (see Section 1.3.2.2.3). However, the uppermost surface of the thick section of basalt that lies at shallow depths is well suited for investigation by geophysical methods. In addition, while deep boreholes are relatively few, shallow boreholes--to or just into the uppermost basalt--are relatively abundant. For these reasons, the understanding of structures buried in the Pasco Basin relies most heavily on interpreting variations in

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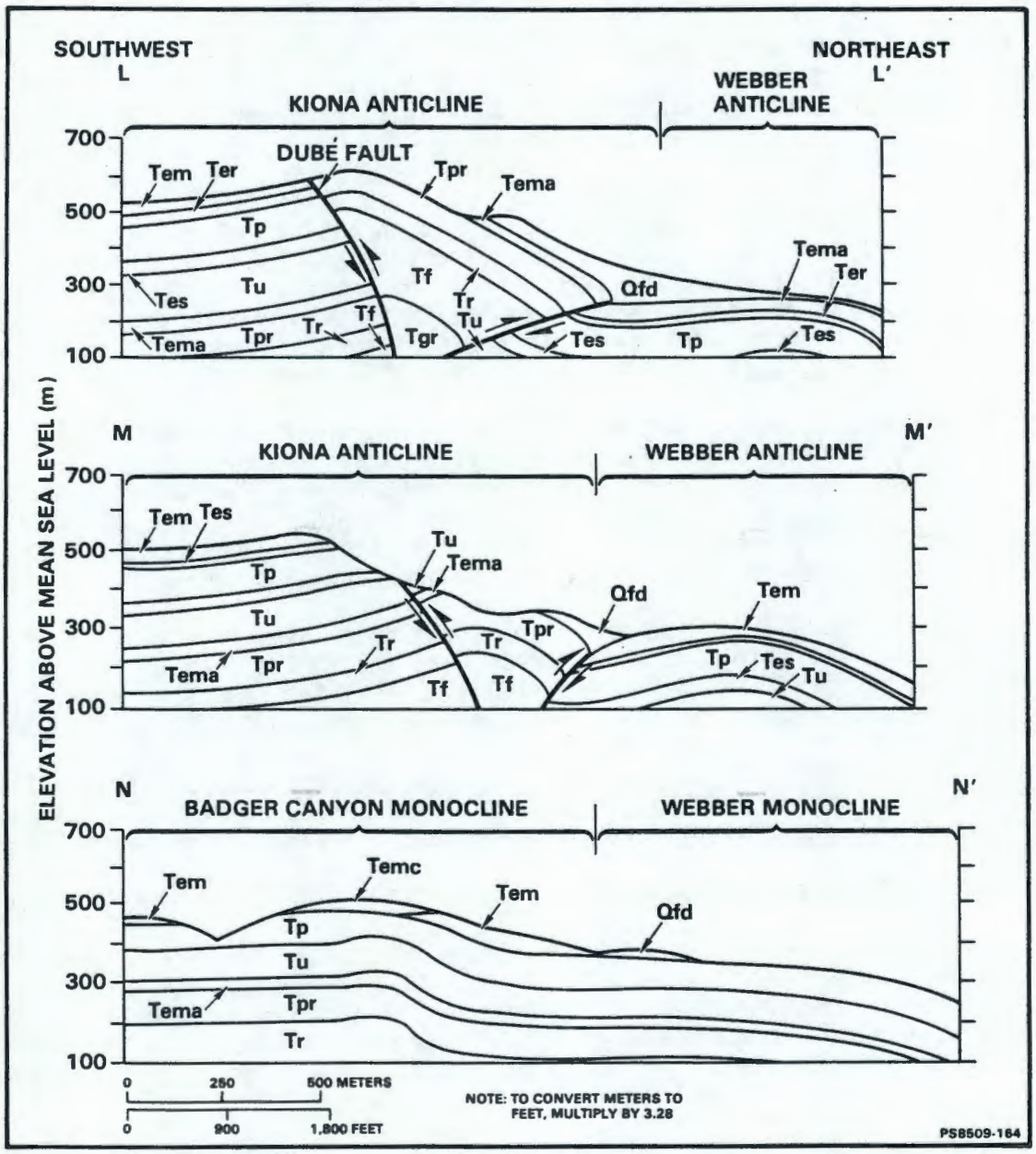

Figure 1.3-16. Cross sections through Horse Heaven Hills-Webber Canyon.

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that uppermost basalt layer and overlying sediments. The uppermost basalt flow, however, presently provides the most easily identifiable horizon for identifying structures in the basin. Sediments overlying the top basalt flow can provide age constraints on structural features that are more easily detected in the top of basalt.

A structure contour map of the contact between the uppermost basalt and the suprabasalt sedimentary deposits within the Pasco Basin is shown in Figure 1.3-17. Fecht et al. (1987) describe the methods used, estimates of possible errors, and assumptions made to produce this map. They concluded that the bedrock surface portrayed on the map represents structural rather than erosional relief. To define the sediment-basalt contact, data were used from geologic and topographic maps, 460 boreholes, and geophysical methods (e.g., gravity, seismic reflection, aeromagnetic, and ground-magnetic survey results). To identify the stratigraphic position of the uppermost basalt in each borehole, chemical analyses were made of cuttings and core. Potential errors introduced in the contact elevation at this point came from uncertainty in the elevation of borehole, deviations in the angle of borehole, and uncertainty in establishing the contact on the basis of cuttings. The maximum expected variability (error) in the contact elevations is estimated to be ±12 m (±38 ft).

The major features of each syncline within the Pasco Basin are described below.

Pasco syncline

The Pasco syncline (No. 21) is located in the southeastern part of the Pasco Basin. It is bounded by "The Rattles" of the Rattlesnake-Wallula alignment on the south and by the Palouse Slope on the north. It is a broad, gentle, low-amplitude (approximately 60-m (200-ft)), long wavelength (approximately 16- to 25-km (10- to 16-mi)), northwest-trending fold. The Pasco syncline loses definition in the Wye Barricade depression (No. 24A), which is a relatively broad (approximately 20-km (12-mi)) and flat structural depression. The Wye Barricade depression is the focus of decreasing structural relief for several folds, which include (1) Wahluke syncline (No. 22), (2) Umtanum Ridge-Gable Mountain uplift (No. 8), (3) Cold Creek syncline (No. 24), (4) Yakima Ridge extension uplift (No. 10), and (5) Benson Ranch syncline (No. 23).

Wahluke syncline

The Wahluke syncline (No. 22) lies between the Saddle Mountains uplift and the Umtanum Ridge-Gable Mountain uplift. It is an asymmetrical syncline with the axis much closer to the Umtanum Ridge-Gable Mountain uplift than to the Saddle Mountains uplift. The top of basalt is approximately 60 m (200 ft) below mean sea level in the lowest part of the Wahluke syncline (see Fig. 1.3-17). It, too, is a low-amplitude (150- to 240-m (500- to 800-ft)), long wavelength fold.

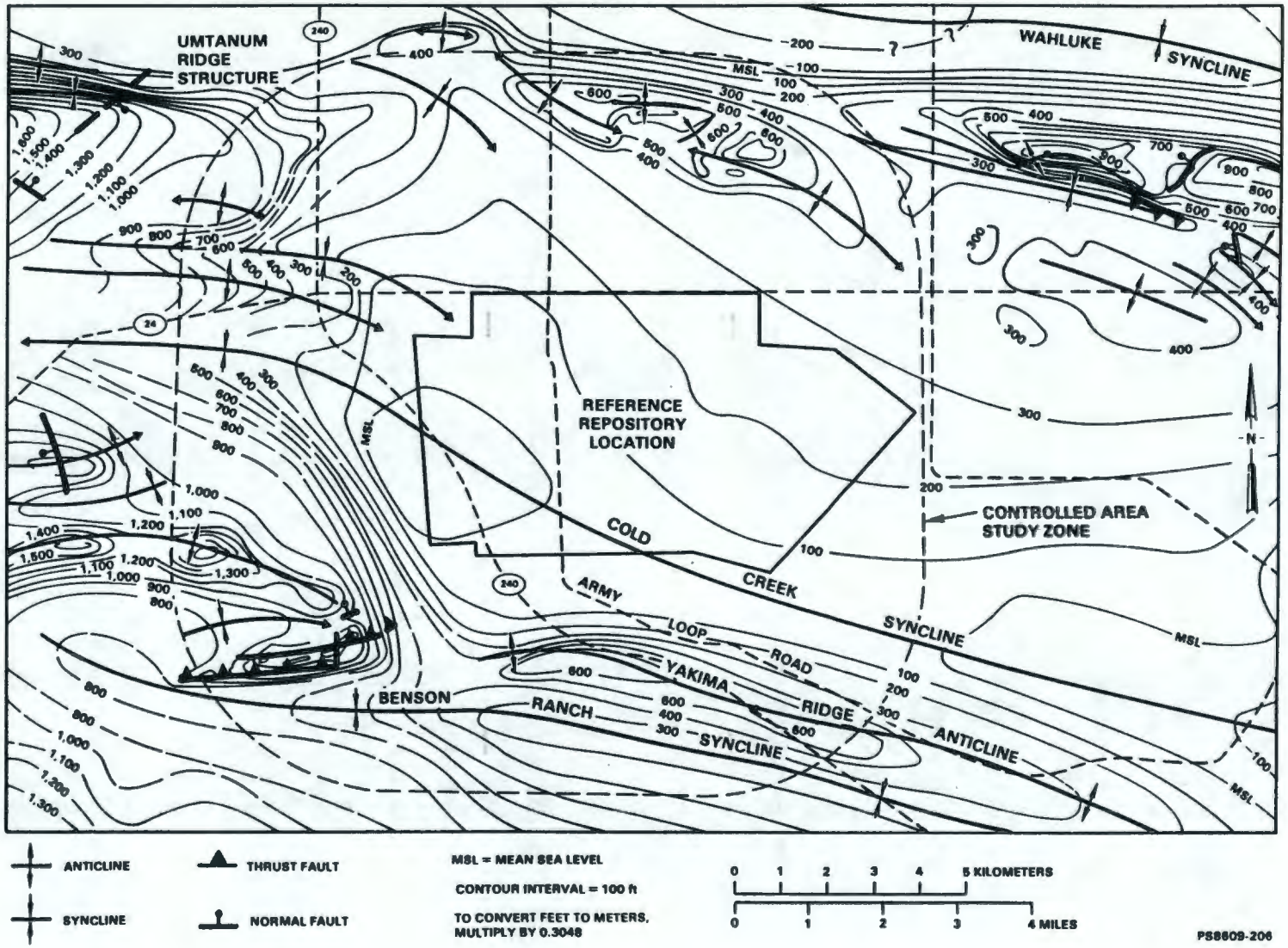

Figure 1.3-17. Top of basalt map (modified from Fecht et al., 1987). This map shows more detail than Figure 1.3-12 (Tolan, 1986) and is the best available interpretation of the area at this time.

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Benson Ranch syncline

The Benson Ranch syncline (Myers/Price et al., 1979, Plate III-4a) is a low-amplitude syncline (approximately 120 m (400 ft)) (No. 23) that is situated between Yakima Ridge and the Rattlesnake Hills-Rattlesnake Mountain uplift. The lack of detailed data in the area places a high uncertainty on the geometry of the fold. From borehole data, this syncline appears to be symmetrical, and plunges gently toward the southeast from Dry Creek Valley to the center of the Pasco Basin. Geophysical data suggest that the Benson Ranch syncline and Yakima Ridge uplift (No. 10A, No. 10B, and No. 10K) continue southeastward (No. 10) into the Pasco Basin, where they apparently lose definition and probably die out toward the Wye Barricade depression (No. 24A).

Cold Creek syncline

The Cold Creek syncline (No. 24) lies between the Umtanum Ridge-Gable Mountain uplift (No. 7A through No. 7R) and the Yakima Ridge uplift (No. 10, No. 10A, No. 10B, and No. 10K). Although there are no surface exposures of this fold, the relatively high density of boreholes in the area indicate a greater confidence in the interpretation of the area. The Cold Creek syncline is an asymmetric and relatively flat-bottomed structure (see Fig. 1.3-17). Its amplitude is higher and wavelength is shorter west of than east of the Hanford Site. Like the Wahluke syncline, the southern limb is the steeper limb. The Wye Barricade depression (No. 24A) marks the southern extent of the Cold Creek syncline. The Cold Creek Valley depression lies along the western portion of the Cold Creek syncline (No. 24B). The top of basalt in the center of the Cold Creek Valley depression is nearly flat, except for small, monoclinal flexures.

The reference repository location is located within the Cold Creek syncline (No. 24). Detailed structure contour maps of the reference repository location and vicinity have been prepared for the top of basalt by Fecht et al. (1987; see Fig. 1.3-17), and for the top of Wanapum Basalt, top of Grande Ronde Basalt, top of Cohassett flow, and top of the very high-magnesium oxide flow by Landon and Bjornstad (1986). These maps are reproduced in Figures 3.1-17 through 3.1-21. They show generally flat-lying basalt with a slight dip to the southwest. The axis of the Cold Creek syncline passes through the southern side of the reference repository location, where the orientation changes from a nearly east-west trend to a northwesterly trend for a short distance, and then resumes a nearly east-west trend in the upper Cold Creek Valley. The exact nature of this deflection is uncertain because of a lack of boreholes and geophysical data for that part of the Cold Creek syncline.

A gravity anomaly suggestive of structural control is present on the northern limb of the Cold Creek syncline, just to the west of the reference repository location (Fig. 1.3-22). This feature is a north-south trending gravity gradient of limited length, and it correlates with features observed in magnetic intensity data, as well as fault-like solutions from Werner

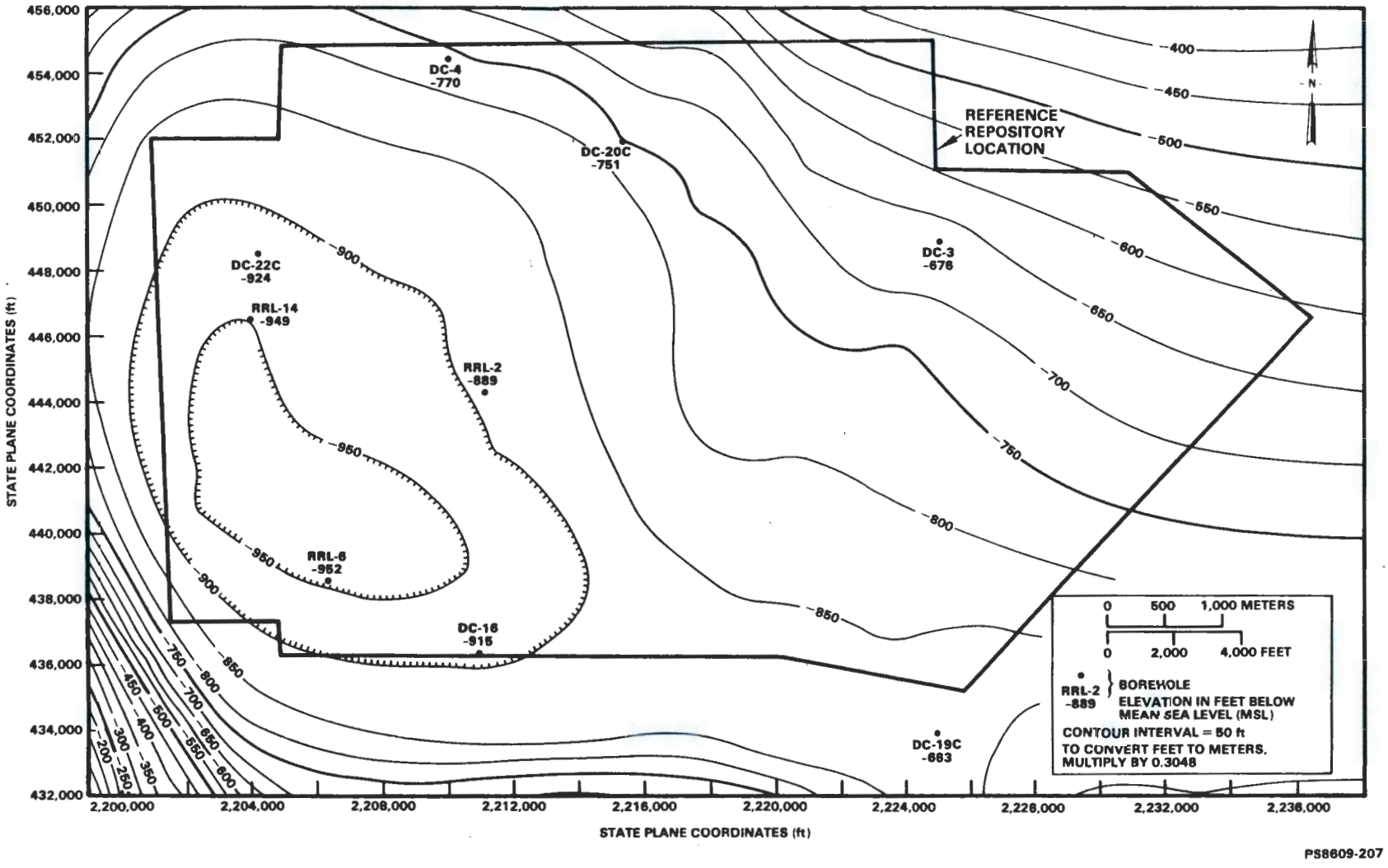

Figure 1.3-18. Top of Wanapum Basalt structure contour map (modified from Landon and Bjornstad, 1986).

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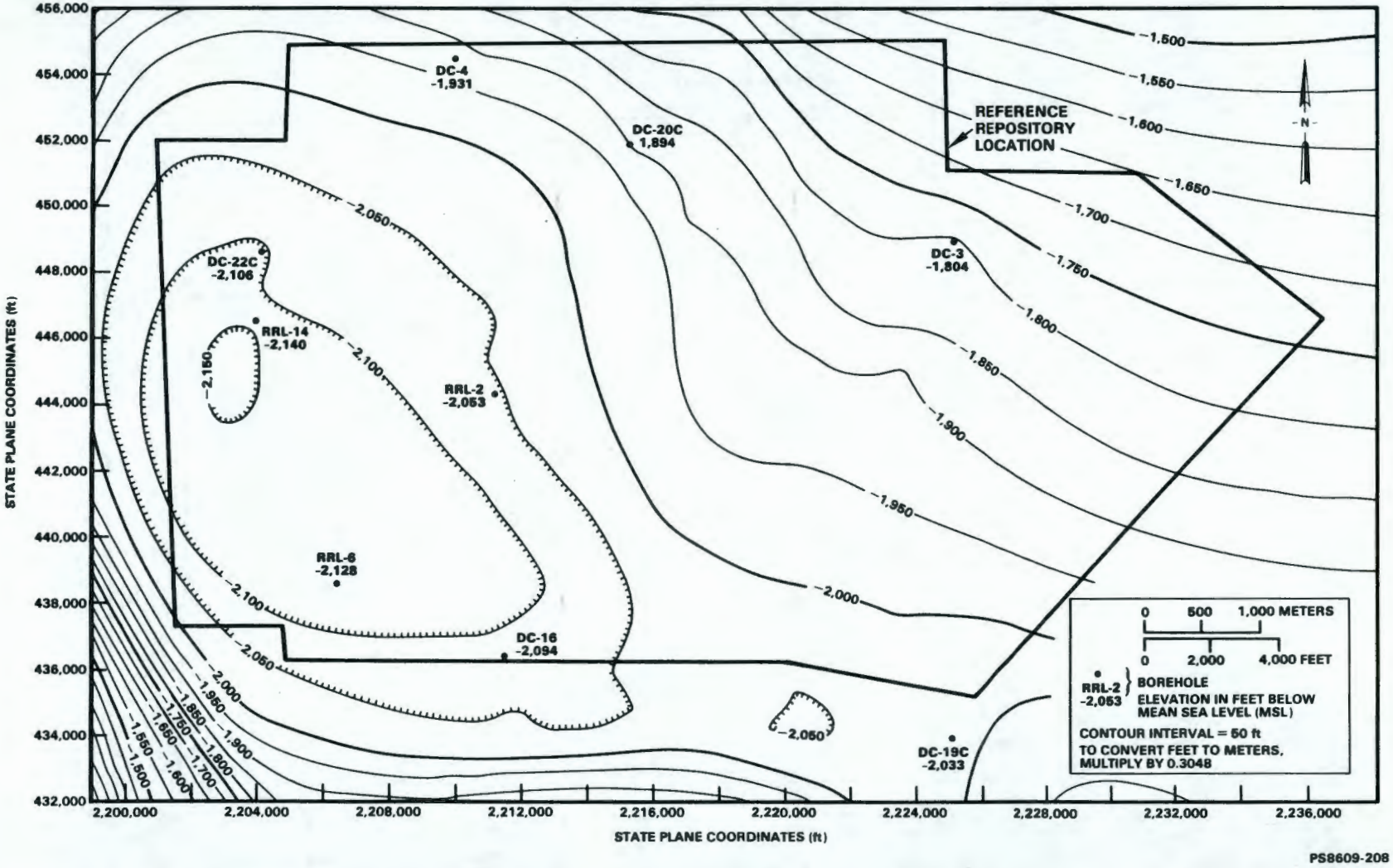

Figure 1.3-19. Top of Grande Ronde Basalt structure contour map (modified from Landon and Bjornstad, 1986).

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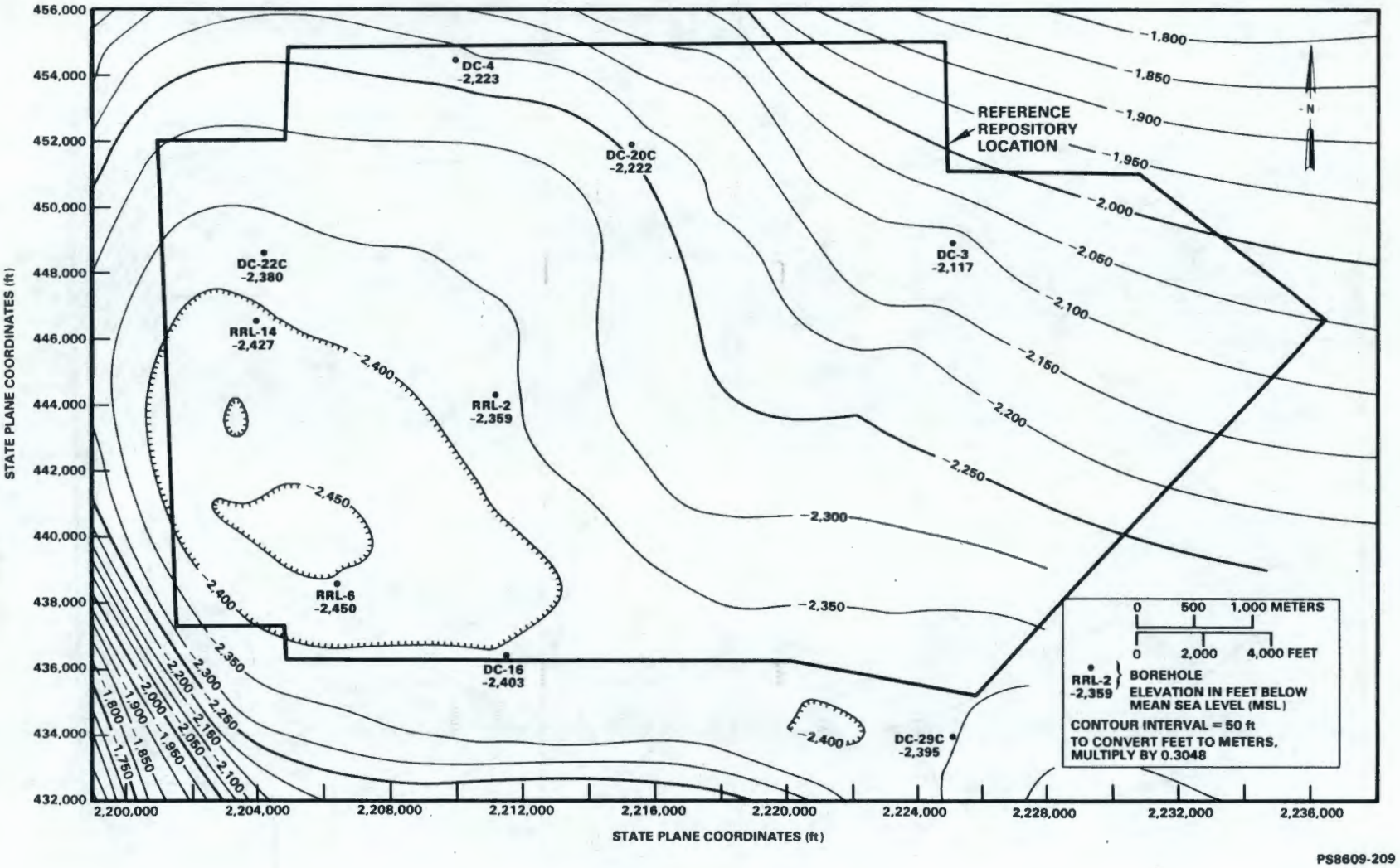

Figure 1.3-20. Top of Cohassett flow structure contour map (modified from Landon and Bjornstad, 1986).

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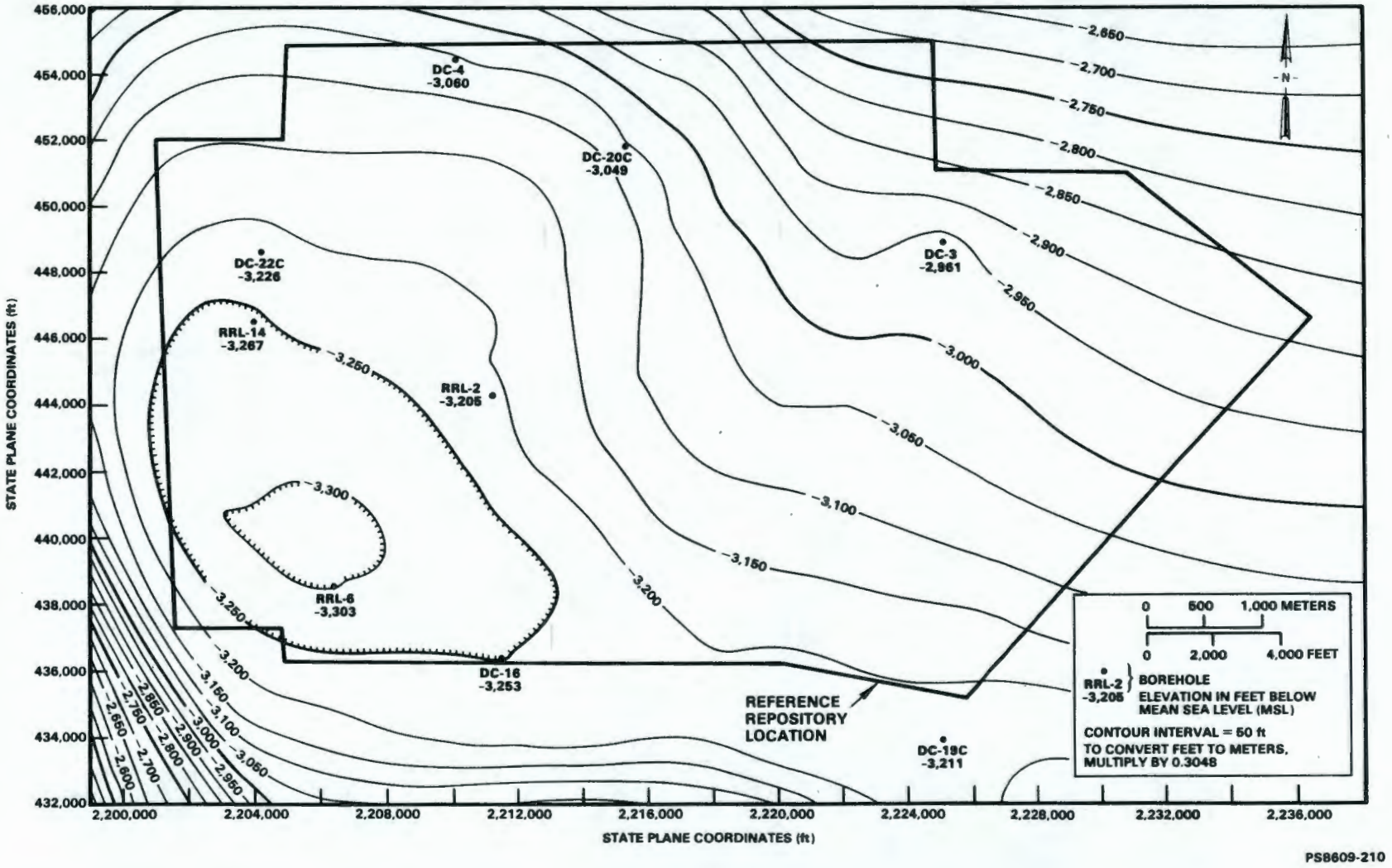

Figure 1.3-21. Top of very high magnesium oxide flow (Grande Ronde flow 19) structure contour map (modified from Landon and Bjornstad, 1986).

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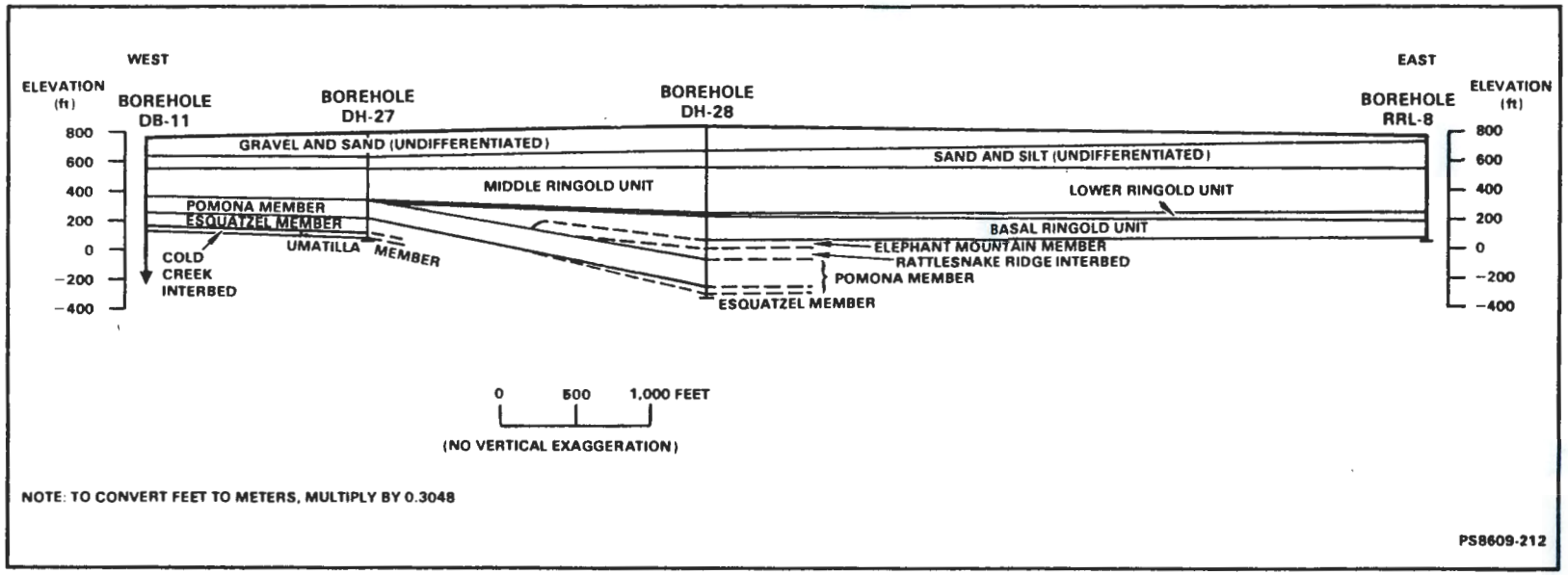

Figure 1.3-22. West-to-east cross section of suprabasalt sedimentary units at the northwest corner of the reference repository location.

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deconvolution of aeromagnetic survey data (see Section 1.3.2.2.3). Further discussion of this geophysical anomaly, referred to as the Yakima Barricade geophysical anomaly, is presented in Section 1.3.2.2.3.7.

Because of the location of this anomaly, which is within an area across which a large hydrologic head difference has been observed (see Section 3.9.1.2.3), the feature has received additional investigation. Two boreholes, drilled across the geophysical gradient, constrain its location and characteristics (boreholes DH-27 and DH-28; see Fig. 1.3-22). A cross section between these boreholes (see Fig. 1.3-22) shows that the top of the Pomona Member (12 m.y.B.P.) increases in elevation from about -20 m (-70 ft) on the east in borehole DH-28 to 100 m (234 ft) on the west in borehole DH-27, suggesting 120 m (394 ft) of relief over a relatively short distance (790 m (~2,600 ft)). The overlying Elephant Mountain Member (10.5 m.y.B.P.) apparently pinches out in an east-west direction across the feature. Relief atop the basalt and lower Ringold units is 44 m (145 ft) and 30 m (100 ft), respectively. The top of the next younger unit, the middle Ringold, appears to be undeformed across the feature.

The present data suggest that this feature is either a steeply dipping fold or a high angle fault that formed during the late Miocene to early Pliocene. However, the top of the middle Ringold unit (age ~5 m.y.B.P.) is undeformed, suggesting that vertical movement along this feature ended by late Pliocene.

Because of the existing evidence that the feature may represent structure of tectonic origin, and its proximity to the reference repository location, additional borehole and geophysical investigations are planned (see Section 8.3.1.2.3.3.4). Further investigation of the hydrologic characteristics in this area are also planned (see Section 8.3.1.3).

1.3.2.2.2.5 The Rattlesnake-Wallula alignment

The Rattlesnake-Wallula alignment (Jones and Deacon, 1966) is composed of two structural elements in the Pasco Basin: the Rattlesnake Mountain uplift and "The Rattles." The southeastern extension of this alignment is the Wallula fault zone. The Rattlesnake-Wallula alignment is the southeastern part of the Cle Elum-Wallula disturbed zone, a zone of deformation that extends from the western edge of the Columbia Plateau to the east of Wallula Gap (see Section 1.3.2.2.1.3). The structural elements of the Rattlesnake-Wallula alignment and the structural relationship between the Rattlesnake-Wallula alignment and Pasco Basin are discussed below.

Rattlesnake Mountain

Rattlesnake Mountain (No. 14A and No. 14B) forms the northwestern part of the Rattlesnake-Wallula alignment in the Pasco Basin. Rattlesnake Mountain is separated from the Rattlesnake Hills, a Yakima Fold, by Snively Basin. The geometry of the structures associated with the Rattlesnake-Wallula alignment are similar to the Saddle Mountains, Umtanum Ridge, and Yakima Ridge, in that they are asymmetrical, anticlinal ridges that have high-angle reverse or

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thrust faults along their steep northern flanks (Fig. 1.3-23). Several faults are associated with Rattlesnake Mountain, including the Rattlesnake Mountain fault (No. 18) and faults in Snively Basin (No. 16I, No. 16J, and No. 16K).

The Rattlesnake Mountain fault (No. 18) lies along the northeast flank of Rattlesnake Mountain within and parallel to the hinge area of the Rattlesnake Mountain anticline. These faults may extend westward into Snively Basin and the Rattlesnake Hills, but detailed mapping has not been completed so this assumed continuation has a high degree of uncertainty.

"The Rattles"

A series of anticlines that extend southeast of Rattlesnake Mountain along the Rattlesnake-Wallula alignment are informally referred to as "The Rattles" (No. 14C, No. 14F, No. 14H, No. 14J, and No. 14L). They include Red Mountain and Badger Mountain (No. 14C) and merge with the eastern segment of the Horse Heaven Hills (No. 17J) near Wallula Gap. At the gap, their trend merges with the Wallula Fault Zone (No. 15B, No. 15C, and No. 15D). Faults subparallel to the northwest trend of these ridges (No. 14G, No. 14I, No. 15A, and No. 15) are found along some of the hills (Myers/Price et al., 1979, pp. III-130 and III-131).

Wallula Fault Zone

The Wallula Fault Zone extends from the eastern limit of "The Rattles," near Wallula Gap, southeastward along the north side of the Horse Heaven Hills to the vicinity of Milton-Freewater, Oregon, where the zone intersects the Blue Mountains (WPPSS, 1981, pp. 2.5-95 to 2.5-96; No. 15B). The zone is up to 330 m (1,080 ft) wide and contains brecciated basalt and clay gouge (Gardner et al., 1981). The fault dips steeply to the south. Drag folds, stratigraphic separation (south side up), and subhorizontal slickensides are the basis for interpreting the fault as a reverse or oblique-slip fault, whose youngest movement was dominantly right lateral (Farooqui, 1979). Several splays have been mapped that are associated with this fault zone, including the Wallula fault, which is a short splay between the Rattlesnake-Wallula alignment and the Horse Heaven Hills trend at Wallula Gap (No. 15D).

The age of faulting on the Wallula fault near Warm Springs, Oregon, has been postulated as Quaternary by Farooqui (1979, pp. 8-11; see Table 1.3-2) who found colluvium of undetermined age in fault contact with tectonic breccia. Tectonic breccia are overlain by late Pleistocene Touchet Beds (approximate age 13,000 yr) and loess. Data from trenching support an interpretation that faulting may be as young as Quaternary, but older than glaciofluvial Touchet Beds (WCC, 1981a, pp. 69-72). Trenches across the Wallula fault also were studied by Gardner et al. (1981, pp. 34-37). They found that faulted basalt of the Ice Harbor Member is overlain by undisturbed glaciofluvial gravels and Touchet Beds. This led them to conclude that the last fault movement took place between Ice Harbor time (8.5 m.y.B.P.) and the latest cataclysmic flooding (13,000 yr B.P.).

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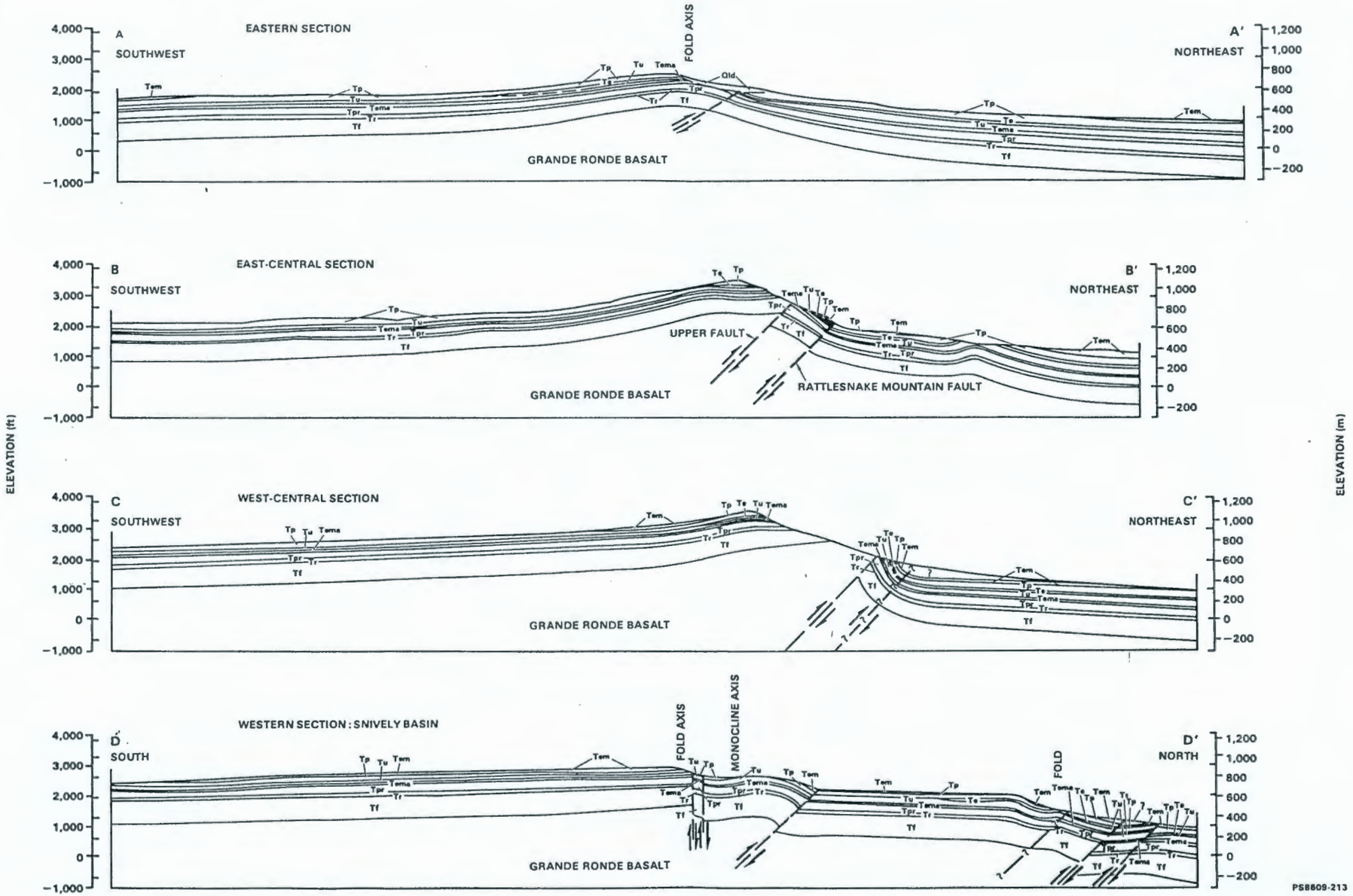

Figure 1.3-23. Cross sections through Rattlesnake Mountain (Fecht et al., 1984, pp. 33-34 and Plate I).

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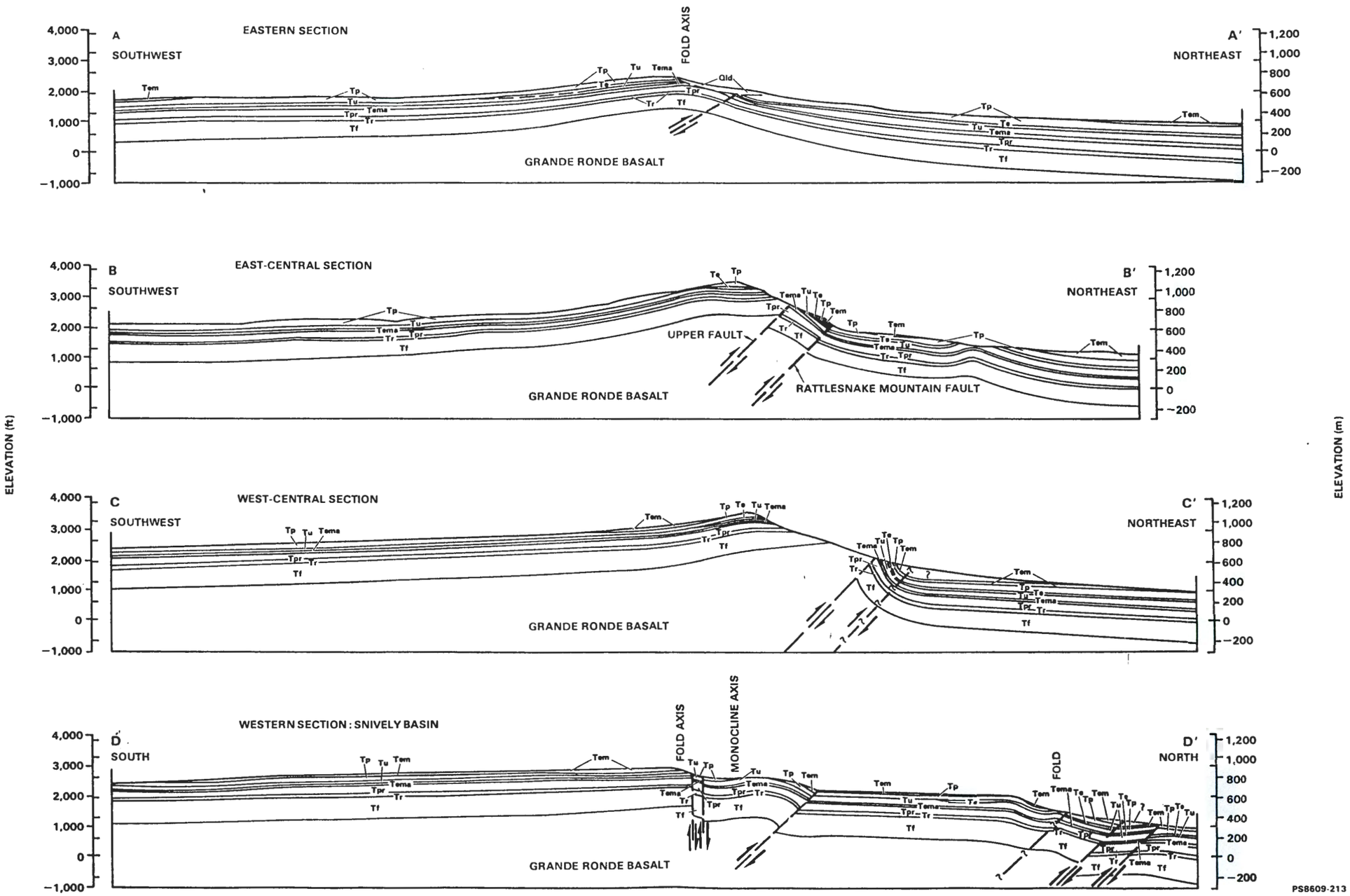

Figure 1.3-23. Cross sections through Rattlesnake Mountain (Fecht et al., 1984, pp. 33-34 and Plate I).

Quaternary movement also is possible along a splay of the Wallula Fault at Finley Quarry (Farooqui and Thoms, 1980, p. 7; see Table 1.3-2). This exposure is a 10-m- (33-ft-) wide fault zone on the northern flank of one of the doubly plunging anticlines that lie along the Rattlesnake-Wallula alignment. The fault juxtaposes colluvium of unknown age against older Miocene basalt along a high-angle reverse fault. Younger colluvium and loess overlying the fault are not displaced. These younger sediments are overlain by two caliche soil horizons, the higher of which was dated as at least 70,000 yr (WCC, 1981c, pp. 69-72); this indicates that the displacement occurred more than 70,000 yr ago. This fault may extend 3 km (2 mi) to the northwest of the Finley Quarry exposure, as suggested by a ground-magnetic survey (Cochran, 1981b, p. 1).

Relationship of the Rattlesnake-Wallula alignment to the Pasco Basin

The Rattlesnake-Wallula alignment is composed of anticlinal folds that have the same geometry as other Yakima folds but are oriented northwest rather than the general east-west trend of the Yakima Fold Belt. Several structural features, such as the Horse Heaven Hills and the Rattlesnake Hills, trend into the Rattlesnake-Wallula alignment, but the structural features cannot be traced to the northeast beyond the Rattlesnake-Wallula alignment (Myers/Price et al., 1979, pp. III-127 to III-135).

The Rattlesnake-Wallula alignment abruptly stops in the Snively Basin area with no apparent continuation to the northwest (Fecht et al., 1984). Deformation at the surface is discontinuous along the trace of the Rattlesnake-Wallula alignment, suggesting a complex history. Where the Yakima River cuts through the Rattlesnake-Wallula alignment, no deformation of basalt flows that are as old as 12 m.y.B.P. is evident, but immediately to the west on Rattlesnake Mountain, basalts as young as 8.5 m.y.B.P. have been folded and uplifted as much as 300 m (1,000 ft) or possibly more (Myers/Price et al., 1979, Plate III).

The Rattlesnake-Wallula alignment is only one segment of a zone known as the Cle Elum-Wallula disturbed zone. Along the trend of the Cle Elum-Wallula disturbed zone, three distinct sets of structural ridges occur in the Pasco Basin area (Myers/Price et al., 1979; Hagood, 1985): (1) the aforementioned Rattlesnake-Wallula alignment, (2) a set immediately in front (northeast) of it, and (3) a set immediately in back (southwest) of it (see Fig. 1.3-9). The northeastern ridges are a low-amplitude set (No. 14M through No. 14P) that terminate to the northwest near the Horn Rapids anticline and extend to the southeast as far as Badger Canyon. The southwestern ridges begin at Wallula Gap and trend initially west-northwest near Wallula Gap, but farther northwest this changes to N. 50° W., forming the front of the Horse Heaven Hills (Hagood, 1985). Along the southeastern trend, the amplitude decreases dramatically from several thousand feet to several hundred feet across the Yakima River at Benton City, Washington and continues as a minor fold on the south flank of Rattlesnake Mountain up to the Rattlesnake Hills (Myers/Price et al., 1979, Plate III). Mapping conducted for the BWIP by Bond et al. (1978b) does not show a continuation to the northwest.

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The northwest trend of the Rattlesnake-Wallula alignment is oblique to the Yakima folds and suggests a control different from the Yakima folds. One possible hypothesis is basement involvement and development above a fault; another is development above another type of discontinuity such as the edge of a lava flow. Still a third hypothesis (Barrash et al., 1983) is a changing stress field from the Miocene to the present. Development of both structural trends at the same time, however, does not support a changing stress field. Ridges (e.g., Rattlesnake Mountain and Red Mountain) display the classic features of a Yakima fold and apparently developed at the same time as the Yakima folds, but at a different trend (Reidel et al., 1980, 1981). The apparent termination of some Yakima folds into the Cle Elum-Wallula disturbed zone suggests differing structural trends in the subsurface that have influenced the fold trends. The Rattlesnake-Wallula alignment and Cle Elum-Wallula disturbed zone are examples of these subsurface structural trends.

The Rattlesnake-Wallula alignment has been interpreted as a zone of dextral strike-slip faulting resulting from north-south compression (Davis, 1977; Bentley, 1980c; Price, 1982). This interpretation is based on the assumption that the gross spatial arrangement of anticlinal domes between Wallula Gap and Rattlesnake Mountain resembles small domes along strike-slip faults in the western Columbia Plateau and in other wrench fault zones (Suppe, 1985, pp. 278-280). The lack of surface deformation along the Yakima River between Red Mountain and Rattlesnake Mountain (Myers/Price et al., 1979, Plate III) limits the youngest age of any continuous strike-slip movement. In fact, most deformation along the Rattlesnake-Wallula alignment appears to be compressional across the trend. This pattern, however, does not indicate if the structures of the Rattlesnake-Wallula alignment are controlled by a basement fault that was reactivated by north-south compression and, thus, developed Yakima folds. This interpretation is favored over that of Barrash et al. (1983), who suggest a changing stress field.

Further discussion of models for the structural development of the Pasco Basin is presented in Sections 1.3.2.2.2.7 and 1.5.2.4.1.

1.3.2.2.2.6 Other structural features

Secondary features that have been superimposed on the principal structural elements include faults that cut the folds; localized faults that are confined to the folds or fold segments; small, secondary, shear zones within individual layers; higher order folds superimposed on the principal structural elements; and folds that cross the structures and interfere with them.

Higher order folds

Higher order folds occur on several ridges in and around the Pasco Basin. Gable Mountain and Gable Butte, two of the most prominent en echelon folds, occur on the Umtanum Ridge anticline (Fecht, 1978, Plate I, p. 38; PSPL, 1982). On some structures such as the Saddle Mountains (Reidel, 1984, Fig. 3; 1987, Plate II) and Horse Heaven Hills (Hagood, 1985, Plate I), second-order en echelon folds can be explained by north-south compression on a northwest- or northeast-trending ridge. Secondary en echelon folds in the Horse Heaven

Hills mapped by Hagood (1985, Plate I) have east-west trends on the northeast- and northwest-trending segments. These secondary folds can be explained as small folds growing under north-south compression on a major fold that has developed on a basement structure oblique to the east-west trend. The origin of the second-order folds on Umtanum Ridge is less clear. Price (1982, pp. 166-171) interpreted the en echelon folds as rotation about a point east of the fold belt. The lack of any rotation in paleomagnetic data from Gable Mountain and Gable Butte, however, showed that rotation did not occur.

Northwest-trending strike-slip faults

Bentley and Farooqui (1979) suggest that northwest-trending strike-slip faults are pervasive throughout the Columbia Plateau. Such faults are found in the western portion of the Columbia Plateau (see Section 1.3.2.2.1.4), but similar strike-slip faults of regional extent have not been observed to cut across the Pasco Basin. Except for a possible component of dextral movement on the Rattlesnake-Wallula alignment (Davis, 1981, pp. 2.5N-29 to 2.5N-33; Price, 1982, p. 177; see Section 1.3.2.2.1.4) and perhaps on the interpreted fault for the hydrologic barrier (see Section 1.3.2.2.2.4), no strike-slip faults of regional extent, or anticlinal domes along wrench faults similar to those near The Dalles, Oregon, have been observed in the Pasco Basin (see Fig. 1.3-17).

West of the Hanford Site, several strike-slip faults have been mapped crossing the Rattlesnake Hills, Yakima Ridge, and Umtanum Ridge (see Fig. 1.3-12). These strike-slip faults are exposed on the anticlinal ridges, but not in the intervening synclines, although Swanson et al. (1979a, 1981) extrapolate the faults through the intervening syncline. These structures do not have any of the typical domal ridges developed along their trace, which are characteristic of acknowledged strike-slip faults on the western plateau (Swanson et al., 1979a). These and other faults that are mapped as having strike-slip movement are interpreted or presumed to be localized cross faults.

Cross faults are not uncommon; the Saddle Mountains display several that correspond to the segment boundaries, one of the most prominent being at Sentinel Gap (Reidel, 1984, Fig. 3; 1986). Others occur at the junction of the Sentinel Gap and Smyrna segments and at the Saddle Gap and Eagle Lakes segments. Cross faults also occur in Snively Basin (e.g., the 3,629 Fault of Bond et al. (1978b) in the Rattlesnake Hills). Yakima Ridge has two known cross faults: one on the extreme eastern portion of the exposed Yakima Ridge (see Fig. 1.3-12) and the fault interpreted by Cochran (1982, p. 77) on the subsurface extension to the east. The hydrologic barrier also may be a cross fault (see Section 1.3.2.2.2.4).

Strike-slip faults west of the Hanford Site (west of the Pasco Basin, see Fig. 1.3-12) proposed by Bentley (in Swanson et al., 1979a) do not display the domal characteristics of those near The Dalles, Oregon. Bentley interprets these faults to cross poorly exposed or unexposed synclinal areas; these faults resemble localized or cross faults similar to those mapped in the Pasco Basin and not regional strike-slip faults mapped farther west. The occurrence of cross faults in and around the Pasco Basin may suggest that many previously

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interpreted regional strike-slip faults, especially in poorly exposed areas such as synclines, may be localized cross faults confined to these anticlinal ridges. The inferred connection between ridges through synclines, where there is no exposure, may not be correct.

Focal mechanisms for earthquakes in and around the Pasco Basin (Section 1.4.1.2) are consistent with a response to nearly north-south compression and are reflected by thrust or reverse fault solutions on east-west striking fault planes (Rohay and Davis, 1983). Strike-slip focal plane solutions have been recorded farther west where strike-slip faults have been observed. This further suggests the presence of cross faults and possible absence of major strike-slip faults in the central Columbia Plateau.

Zones of tectonic brecciation and shearing

Field studies have revealed the occurrence of tectonic breccia and shear zones in geologic structures (Price, 1981; Gardner et al., 1981; Goff, 1981; Reidel, 1984; Barsotti, 1986). Price (1982, pp. 63-78) defined three types of breccias: shatter breccias, anastomosing breccias, and shear zone and fault breccias. Shatter breccias are simply shattered basalt in which the original primary features of the basalt are still preserved. Anastomosing breccias are composed of lenticular basalt fragments with a submicroscopic, pulverized, basalt matrix, and are nontabular basalt breccias of no apparent, measurable orientation (Goff, 1981). Shear zones and fault breccias are tabular breccia zones that have three stages of development (Price, 1982, pp. 66-68). The first stage is the development of a set of parallel, sigmoidal, extension fractures that are superimposed on primary structures. The second stage involves rigid rotation of millimeter-scale basalt blocks, causing the initial granulation of basalt. The third stage involves the development of discrete slip surfaces either within, or bounding, a tabular breccia.

Flow top breccias are distinguished from tectonic breccias by several characteristics. Tectonic breccia typically contains more angular clasts of smaller size, usually a few centimeters or less, than flow top breccia. Clasts in flow top breccia are often bound by original glass and are often an admixture of vesicular and nonvesicular basalt, whereas clasts in tectonic breccia have a homogeneous texture. When observed in core, tectonic breccia zones are typically bounded by fracturing, resulting in a distinct demarcation between the zone and the surrounding intact rock, in contrast to the often degradational contacts of flow top breccia zones. The presence of subparallel fracturing within a tectonic breccia zone results in clasts being arranged parallel to subparallel to each other, which also contrasts with the random, chaotic nature of clasts in flow top breccias. Slickensides are present on some surfaces in tectonic breccias and absent in flow top breccias without tectonic fracturing. Tectonic breccias typically display a crushed basalt matrix, while flow top breccias may be partially to fully filled with secondary minerals or palagonite between fragments, or the fragments may be welded together.

Investigations are being conducted in the Vantage, Washington, area as an analogue to the Cold Creek syncline to determine the properties of these zones, so that they may be incorporated into models for the Cold Creek

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syncline (see Section 8.3.1.2.2.3.2 and 8.3.1.2.4.3.2). Because the Cold Creek syncline is buried beneath Pliocene to Quaternary sediments, direct observation of breccias and faults can only be made from drill core. The Vantage analog study will provide direct observation of breccias from the field so that breccias in core can be interpreted. Major high angle reverse to thrust faults along anticlinal ridges are associated with very thick breccia zones. In the Saddle Mountains, these zones are very distinct and in Sentinel Gap consist of a several-hundred-meter-thick zone of shatter breccias (Reidel, 1984, p. 952). Similar breccia zones have been found in Umtanum Ridge (Price, 1982, pp. 63-112; Barsotti, 1986, pp. 33-82, 107-114), at Wallula Gap (Gardner et al., 1981, pp. 34-77), and perhaps as much as 607 m (2,000 ft) in borehole RSH-1 on Rattlesnake Mountain (Raymond and Tillson, 1968, pp. 37-39). An examination of most anticlinal ridges shows this to be consistently true.

The greatest amount of brecciation and shearing occurs in the hinge zone of the anticlinal folds and decreases progressing down the flanks. Studies of several south-dipping limbs support these observations (e.g., see Price, 1982; Barsotti, 1986; Reidel et al., 1984). Detailed studies on Umtanum Ridge found that the degree of brecciation is related spatially to the dip of the layering (Price, 1982, pp. 18-112). The greatest amount of tectonic jointing and faulting occurs in the hinge zone and in steeply dipping beds. On the flanks of the folds, faults with low dips (less than 45°) and limited extent often occur as conjugate shear zones (Price, 1982, Fig. 85).

On the well-exposed south limb of the Frenchman Hills, sparse, locally developed, but widely disseminated fault zones and shear zones can be observed (Price, 1982, pp. 149-157). These features typically have small displacements and the apparent maximum displacement of 1 to 2 cm (0.4 to 0.8 in.) decreases to no recognizable displacement at a lateral distance of 1 m (3.3 ft). Faulting is principally confined to the individual basalt layers.

Tectonic breccia zones in the Cold Creek syncline are infrequent in all the thousands of feet of core drilled into the Columbia River basalt (Table 1.3-4). The breccia zones that do occur are generally intact and less than 10 cm (4 in.) in apparent thickness, although some may be thicker (Moak, 1981, pp. 6.1 to 6.13).

Because no oriented cores were drilled, the orientation of tectonic breccias is not known. The limited size of the core and general lack of well-defined planar features in the breccia make the sense of shear difficult to determine. In several zones that have crudely developed planar features, tectonic breccias appear to dip ~30° to 45° and have a reversed sense of movement, based on the last movement indicated on poorly defined slickensides. Slickensides, however, are poor indicators of movement because more typically there appears to be no preferred direction.

Breccia zones do not appear to be restricted to any single stratigraphic zone or depth. As shown in Table 3.1-4, the infrequent breccia zones that do occur are most common in the Grande Ronde Basalt, followed by Wanapum Basalt, and then Saddle Mountains Basalt; no breccia zones have been observed in core

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Table 1.3-4. Tectonic breccia and fractures in core (sheet 1 of 2)

Borehole	Breccia/fracture depth interval, m(ft)	Stratigraphic unit (flow)	Comments	Breccia	Fracture
DC-2-A1	847.3 (2,780)	Sentinel Bluffs	Possibly a small tectonic feature; altered to hard clay		
	929.9 (3,051)	Schwana (Umtanum)	2.5-cm (1-in.) thick zone	X	
	1,011.6 (3,319)	Schwana	15.2-cm (6-in.) clay zone	X	
DC-2-A2	929.0 (3,048) to 929.9 (3,051)	Schwana (Umtanum)	Altered to hard clay along high-angle zone; small breccia clasts	X	
DC-4	499.3 (1,638) to 499.6 (1,639)	Priest Rapids (Lolo)	Well-healed; 7.6-cm- (3-in.-) wide zone	X	
	504.8 (1,656)	Priest Rapids (Lolo)	Small-scale slickensided feature	X	
	505.4 (1,658)	Priest Rapids (Lolo)	12.7-cm (5-in.) zone	X	
DC-6	384.1 (1,260)	Priest Rapids (Rosalia)	5.1-cm (2-in.) tectonic shear zone; cemented	X	
	385.0 (1,263)	Priest Rapids (Rosalia)	7.6-cm (3-in.) zone		X
	799.8 (2,624) to 800.7 (2,627)	Sentinel Bluffs (Cohassett)			X
	813.8 (2,670)	Sentinel Bluffs	Breccia and associated slickensides; possibly tectonic		X
DC-7	1,264.0 (4,147) to 1,264.3 (4,148)	Schwana (GR-16)	Associated with flow top; probably not tectonic	X	
	1273.5 (4,178)	Schwana (GR-17)	Primary feature associated with flow top	X	
	1,280.6 (4,201.5) to 1,283.2 (4,210)	Schwana (GR-18)	Shattered and fractured; appears tectonic but may be associated with upper flow contact at 1,278.9 m (4,196 ft)	X	
	1,443.5 (4,736)	Schwana (GR-29)	Atypical tectonic clasts; probably of primary origin	X	
DC-8	530.6 (1,741)	Priest Rapids (Rosalia)	1.3-cm (0.5-in.) tectonic breccia zone with slickensides; minor fracturing	X	
	1,164.0 (3,819) to 1,164.6 (3,821)	Schwana (GR-13)	30.5-cm (12-in.) tectonic breccia zone; 45° dip	X	
	1,188.1 (3,898)	Schwana (GR-13)		X	
	1,197.9 (3,930)	Schwana (GR-14)	Probably a primary feature associated with flow top	X	
DC-12	226.8 (744) to 229.8 (754)	Umatilla	Primary vesicular zone in middle of flow	X	
	615.7 (2,020) to 616.6 (2,023)	Frenchman Springs (FS-7)	Slickensides; appears tectonic		X

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Table 1.3-4. Tectonic breccia and fractures in core (sheet 2 of 2)

Borehole	Breccia/fracture depth interval, m(ft)	Stratigraphic unit (flow)	Comments	Breccia	Fracture
DC-12 (cont.)	678.8 (2,227)	Unnamed interbed between Frenchman Springs	Slickensided clay, contains a few basalt inclusions; may be due to loading		X
DC-14	423.4 (1,389)	Roza	12.7-cm (5-in.) zone; low-angle fractures for several feet; slickensides		X
	923.5 (3,030) to 923.9 (3,031)	Sentinel Bluffs (McCoy Canyon)	2.5-cm (1-in.) tectonic breccia zone with slickensides; fractures for several feet	X	X
	970.8 (3,185) to 972.0 (3,189)	Schwana (Umtanum)	Fracturing with 2.5-cm (1-in.) zone of clay and breccia; bounded by a few meters of low-angle fractures; probably tectonic origin	X	X
DC-15	600.8 (1,971)	Frenchman Springs (FS-7)	2.5-cm (1-in.) zone; breccia and subhorizontal slickensides in clay-filled matrix	X	X
	609.6 (2,000)	Frenchman Springs (FS-8)	7.6-cm (3-in.) zone; numerous slickensides in clay matrix	X	
	940.9 (3,087) to 946.1 (3,104)	Schwana (Umtanum)	Silica cemented breccia; no gouge or slickensides; questionable origin	X	
DDH-3	826.9 (2,713)	Sentinel Bluffs (Cohassett)	12.7-cm (5-in.) breccia zone; clay matrix; adjacent shattering; probably tectonic	X	
	855.9 (2,808) to 856.5 (2,810)	Sentinel Bluffs	Brecciation associated with flow contact; some small zones may be tectonic	X	
DH-4	1,179.3 (3,869) to 1,182.3 (3,879)	Schwana (GR-24)	Probably primary, but not associated with a flow top	X	
DH-5	1,222.3 (4,010)	Schwana (GR-29)	Primary brecciation	X	
DB-10	120 (400); 175 (575)	Pomona, Esquatzel, Asotin	Two reverse faults with about 55 m (180 ft) of combined displacement. Slickensides, gouge	X	X
DB-11	222.5 (730) to 224.6 (737)	Umatilla	Shattered up to 221.9 m (728 ft)	X	
DB-15	335.1 (1,165) to 356.6 (1,170)	Roza		X	X
RRL-2	613.9 (2,014) to 615.1 (2,018)	Frenchman Springs (FS-1)			X
RRL-6	573.0 (1,880) to 573.3 (1,881)	Roza			X
	647.1 (2,123) to 651.1 (2,136)	Frenchman Springs (FS-1)		X	
	654.1 (2,146) to 655.0 (2,149)	Frenchman Springs (FS-1)		X	
	741.0 (2,431) to 741.3 (2,432)	Frenchman Springs (FS-4)			X
DH-27	121.2 (397.6)	Middle Ringold	10-cm (3.9-in.) clay zone within semi-consolidated gravel; well-developed slickensides		X

Source: Moak (1981).

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from suprabasalt units, although a thin zone of slickensides, thought to be of tectonic origin, is present in the middle Ringold unit in borehole DH-27 (see Table 1.3-4). There may be a correlation between total amount of core from a particular formation penetrated and the number of breccia zones. Alternative interpretations could include an inverse correlation between number of breccia zones and age (i.e., fewer breccia zones in younger units); still another interpretation could be that more breccia zones occur in rock with fewer weakness zones (interbeds and flow tops), suggesting a correlation with the strength of the rock.

Tectonic breccias that have been observed in boreholes in the Cold Creek syncline are similar in appearance to the widely disseminated fault and shear zones described on the gently-dipping south limb of the Frenchman Hills anticline (Price, 1982, pp. 149-157; see above). This suggests that their occurrence is not necessarily associated with areas of greatest deformation in a fold. An alternative interpretation is that they are associated with other, possibly larger faults. The repeated stratigraphic interval in borehole DB-10 is a candidate for such a fault, although similar repeats in section are not observed in adjacent boreholes; so the magnitude of the feature observed in borehole DB-10 is uncertain at this time. The absence of detailed information on the orientation, sense of shear, and extent of tectonic breccias precludes a well-constrained interpretation of their origin and estimate of their frequency of occurrence in the Cold Creek syncline.

Core disking, the fracturing of core into thin saddle-shaped disks, is a drilling-induced phenomena observed in some cores from the Cold Creek syncline that is apparently related to de-stressing of zones with high ratios of horizontal to vertical stress (Paillet and Kim, 1987, pp. 6,223-6,234; Section 2.6.2.1). Numerical modeling of core-disking indicates that it results from effects of shear and unloading as the bit penetrates rock under substantial horizontal stress. Paillet and Kim (1987, p. 6,231) note an imperfect correlation between core-disking and borehole breakouts. Both tend to be confined to dense flow interiors. The imperfect correlation is attributed to differences in failure mechanisms. No correlation has been observed among borehole breakouts, core-disking, and tectonic breccia zones. Paillet and Kim (1987, p. 6,233) suggest that breakouts and core-disking within the interiors of individual flows "may indicate that substantial stresses are being produced by concentration of regional stresses in relatively hard and thick basalt flows embedded within softer, more easily deformable sediments and altered flow top breccias."

In boreholes DC-4, RRL-6, and DC-12, a comparison of zones of tectonic breccias and fractures (Table 1.3-4) to zones of core-disking and breakouts (Paillet and Kim, 1987, Fig. 10 and Table 2.6-1, Chapter 2) shows that breccias are confined to the Wanapum and Saddle Mountains Basalt (atypical compared to other boreholes) where core-disking and breakouts are in the Grande Ronde Basalt. In the other boreholes in Table 1.3-4, brecciation occurs in the Grande Ronde Basalt. Tectonic breccias result from localized fractures of in-place rock in response to regional tectonic forces; core disking and borehole breakout are localized mechanisms of deformation in response to high in situ stress. It is not clear how these two types of deformation are related.

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Tectonic joint sets

Regional joint sets that form independent of the folding process (see Section 1.3.2.2.2.7) have not been thoroughly studied in the Pasco Basin. Identifying joint sets on remote sensing imagery--a method commonly used for study--is complicated by the sedimentary cover that overlies the basalt bedrock. Their study is also made more difficult by the presence of ubiquitous cooling joints, which are difficult to distinguish from tectonic joints, both in outcrop and core samples (see Section 1.2.1.2.3). A complete compilation of tectonic joint sets, either as a map or in tabular form, cannot be completed at present using available data. Several compilations of photolineaments and topographic lineaments have been completed for various purposes, however, and many of these lineaments may represent tectonic joint sets.

One such photolineament compilation for the entire Columbia Plateau is presented in Sandness et al. (1982). They analyzed satellite imagery and aerial photography, and categorized each lineament according to the feature that caused it. Their categories included features such as color or vegetation discontinuities, straight drainage features, known mapped faults, alignment of topographic features, and probable joints. The result of their work is a series of 1:250,000 quadrangle maps that contain a composite overlay of all lineaments, regardless of origin.

The most prominent joint sets that they note on the Walla Walla quadrangle occur along the Palouse River about 120 km (75 mi) to the east of the reference repository location (Sandness et al., 1982, p. 84). They mention other joint sets west of Connell, at Wallula Gap, along the Yakima River northwest of Prosser, near O'Sullivan Dam, and along Crab Creek along the north side of the Saddle Mountains. There is no discussion of the tectonic significance of any of these joint sets.

A second compilation of lineaments was completed as part of the licensing investigations for the Washington Public Power Supply System's nuclear plants (Glass and Slemmons, 1977). The objective of this project was to identify features that might possibly aid in locating the epicenter of the 1872 "Chelan" earthquake. They used topographic maps as well as remote sensing imagery to identify possible surface faulting features. There is no discussion of regional joints sets per se.

To the south of the Pasco Basin, in north-central Oregon, regional joint set patterns in Columbia River basalt have been determined from remote sensing imagery and have been interpreted relative to their tectonic significance (Lawrence, 1979, pp. 33-42). Lawrence analyzed the direction and length of photo lineaments interpreted as joint sets and related these characteristics to folding in the Ochoco and Blue Mountains. He distinguishes between regional and local joint sets on the basis of whether the joints extend through more than one flow, and notes the difficulty of attempting to identify joints in outcrops because of the abundance of primary cooling joints.

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The patterns of regional joint sets can provide evidence for the stress regime that produced them. Knowledge of the age of the rocks containing or bounding the extent of the joints can be used to demonstrate possible changes in orientation of the stress regime with time--information that is useful for making predictions. Also, joints may act as groundwater pathways to connect aquifers at various depths; they may act as barriers to groundwater flow as well (Newcomb, 1959, pp. 10-12; see Section 3.9.3.1.2 for a discussion of groundwater pathways from the repository to the accessible environment).

1.3.2.2.2.7 Relationship between folding and faulting

Most deformation on the Columbia Plateau has been attributed to north-south compression (Sections 1.3.2.4 and 1.5.2.4.1). This section discusses the relationship among folds, faults, and tectonic joints and places them in the structural framework of the Pasco Basin.

The deformation mechanisms by which folds, faults, and tectonic fractures develop is not yet fully understood. A structural analysis of part of Umtanum Ridge near Priest Rapids Dam by Price (1981, pp. 7-18) has led to a working hypothesis for deformation in the Pasco Basin. This hypothesis contends that deformation occurred by faulting, folding, and development of tectonic joints in the anticlinal crests during regional compression with substantially less deformation in the synclinal troughs. The gently dipping limbs of the anticlines contain widely disseminated, discrete shear zones and (or) faults. Steep strata on the north limbs of Yakima folds contain the more extensive faults or breccia zones (Price, 1982).

Price's (1982, pp. 18-115) study of the Umtanum Ridge anticline revealed that folding included localized intralayer faulting, extensive shattering, and limited interlayer faulting. Most strain is cataclastic, but glassy flow tops appear to have been more ductile. Price determined that four tectonic joint sets are dominant. Two sets have vertical dips and strike perpendicular to and parallel to the fold axis, respectively. The other two sets are conjugate sets that strike perpendicular to the fold axis and dip to the east or west. These sets represent extension parallel to the fold axis and extension perpendicular to the fold axis during folding. Joints are most pronounced and abundant in the core of the fold; they decrease upward in the structure to where they are not recognized above the Vantage horizon. Because joints are systematically related to folds, joints within Umtanum Ridge are interpreted to be the same age as the folds (Price, 1982, p. 111).

The strain distributions and structural geometries agree well with a flexural-flow-buckle model. However, the internal cataclastic flow is not inherently penetrative and limited flexural slip has occurred. Price's (1981) fold model suggests that most strain in the fold is by simple shear and that it took place above the topographic surface of adjacent synclinal valleys. Large reverse faults associated with the anticlines are interpreted to be the faulting strain that is required by the folding, and they are interpreted to have propagated to the surface late in the folding process. Therefore, the observed folding strain and its distribution are interpreted to be the result of local stresses and resultant strains related to fold geometry and are the direct results of regional plateau shortening.

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Recent publications by Suppe (1983, 1985) on large-scale folds that formed at shallow crustal levels about the brittle-plastic transition and are related to slip on adjacent faults, may be applicable to the Yakima folds. Suppe identifies three classes of fault-related folds: (1) buckling, caused by compression above a bedding plane decollement; (2) fault-bend folding, caused by bending of a fault block over a nonplanar surface; and (3) fault-propagation folding, caused by compression in front of a fault tip during fault propagation. Fault-bend folding and fault-propagation folding models are among possible explanations for the origin of Yakima folds. The fault-propagation folding model is generally compatible with that proposed by Price (1981) and Reidel (1984) but with potentially significant differences. The presence or absense of a decollement is the major uncertainty. More work will be necessary to resolve this question (see Section 8.3.1.2.3.3.4).

Price's (1981, pp. 7-17 to 7-19) work suggests that relatively few tectonic fractures should be found in synclines. Those fractures present are inferred to strike either perpendicular to or parallel to the fold axis, to be nearly vertical, and to cross flow contacts at a high angle. Most tectonic fractures encountered at the reference repository location should be similar to those observed on the southern flank of the Frenchman Hills (Price, 1981, pp. 7-17 to 7-19; 1982, pp. 149-157). They will probably be of limited extent; confined to a single flow or, at the most, several flows; occur in conjugate sets; and have no detectable stratigraphic offset (within the resolution of the data set--see Fecht et al. (1986) for resolution of boreholes). Field studies in the Burbank Creek syncline and the syncline directly north of Umtanum Ridge show that synclines exhibit the least strain of any parts of a fold (Price, 1981, p. 7-17).

Tectonic breccias are present in many deep boreholes in synclinal folds on the Hanford Site (see Section 1.3.2.2.2.6), but breccia zones are infrequent in each borehole, typically intact, and generally less than 10 cm (4 in.) thick (Moak, 1981, p. 6.3). The relatively infrequent occurrence of tectonic breccia in borehole supports Price's (1981, pp. 7-17 to 7-19) model of fewer tectonic fractures in synclinal areas than in anticlinal areas, where strain appears to be concentrated. Tectonic breccias encountered in boreholes do not seem to be concentrated at any particular depth or interval. Alternatives to Price's previously described model are discussed in Section 1.5. Acquisition of data necessary to test this and alternative models is the objective of studies discussed in Section 8.3.1.2.4.3.1.

Further insight into the mechanics of folding and faulting and the development of tectonic joints has been gained by analyzing paleomagnetic data from the Pasco Basin. Reidel et al. (1984, pp. 251-273) have found that paleomagnetic data from the Pomona flow in the Yakima Fold Belt show clockwise rotation of sample sites from the anticlinal ridges relative to the synclinal valleys. Two geographic patterns of rotation are present: (1) a primary one in which greatest rotation occurs in the crest-hinge area of the anticlines and decreases toward the synclines and (2) a secondary pattern in which the amount of rotation is controlled by the geometric segments of the folds. They interpret the rotation mechanism to involve two axes: (1) a generally east-west horizontal axis corresponding to the fold axis of the anticlines and (2) a vertical axis.

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Further study by Barsotti (1986, pp. 115-139) supports this interpretation, but also shows that the inclination angle of the paleomagnetic vector can be rotated by shear during folding. Rotation of the declination probably occurred along a closely spaced, northwest-trending, right-lateral shear system (Price's (1981) conjugated set that strikes perpendicular to the fold axis) that developed in the anticlines as they grew under north-south compression. The confinement of rotation to the anticlines indicates that this shear system is principally limited to the anticlines. These data are consistent with Price's structural analysis of anticlinal ridges and interpretations of limited strain effects in the synclinal areas. Although the persistent clockwise rotation was not predicted by Price's tectonic model (Price, 1981, pp. 7-1 to 7-19), it supports his structural model and provides additional data to interpret the mechanical evolution of the folds.

1.3.2.2.2.8 The Yakima folds: a nonunique fold geometry and possible comparisons

The Yakima folds are not unique geologic structures on the Earth or, for that matter, on the other terrestrial planets. Wrinkle ridges or volcanic plains anticlinal ridges on the terrestrial planets (Basaltic Volcanism Study Project, 1981, pp. 868-883), which form as a result of basement involvement or detachment, are interpreted as geometric analogs of the Yakima folds (Waters and Maxwell, 1985, p. 745). The surface geometry of Yakima folds resemble typical folds in a thrust belt. They formed under generally north-south compression, based on geometry (Davis, 1977, p. 2R, C-24), focal mechanisms (Rohay and Davis, 1983, pp. 6-12 to 6-15), and in situ stress measurements (Kim et al., 1986, Table 6), by brittle deformation, and at the surface of the Earth. Confining pressure is within the horizontal plane with minimal vertical confining pressure. When north-south compression was applied to the Columbia Plateau, the result was shortening of the crust, accomplished principally by uplift and folding. Rock was forced over the uppermost lava flow at the surface (Reidel, 1984, pp. 973-975) with the surface of this flow top becoming the fault plane. This surface is a low-angle thrust fault, because the flow is nearly horizontal. Less is known, however, about the fault orientation in the subsurface. Only two exposures of these faults can be seen in canyons adjacent to ridges in the plateau: 45° for the Frenchman Hills along the Columbia River near Vantage (Grolier and Bingham, 1971) and 70° for the Columbia Hills in Rock Creek (Anderson, in Swanson et al., 1979a). No information is present concerning the presence of a detachment surface at depth.

Most synclinal valleys are not true synclines, in that they represent the gentle south-dipping limb of an anticline that has been overridden by the next anticline to the south. The upper Cold Creek syncline west of the Hanford Site is a tight, faulted, southern limb of Umtanum Ridge that is overridden by the north limb of Yakima Ridge. The Cold Creek syncline in the vicinity of the Hanford Site has a width of over 10 km (6 mi) and is a broad trough that has apparently undergone little deformation relative to anticlinal areas (see Section 1.3.2.2.2.4). It is an area that has been undergoing subsidence since the beginning of Columbia River Basalt Group volcanism.

1.3.2.2.3 Subsurface structural features: a synopsis of geophysical investigations

This section describes the geophysical investigations that have been conducted to characterize regional and local structural features in the subsurface. Surface geologic mapping can only provide a partial description of the structural features that are significant to site characterization, design of a repository, and performance assessment. Direct observation of subsurface features, using borehole investigations, is limited by the number of boreholes that reasonably can be drilled. Thus, geophysical methods, integrated with borehole and surface geology studies, provide the best means of determining the structural features and physical properties of the subsurface at the candidate site.

Geophysical methods involve measuring various physical parameters in the Earth. These are the Earth's natural fields (e.g., gravity, magnetic, and electrical) and discrete rock-mass properties (e.g., seismic velocity, density, bulk modulus, resistivity, and radioactivity). The natural fields are measured directly. Other rock parameters are derived by measuring the effects produced by the Earth when energy is induced into the Earth. Types of energy utilized typically include seismic, electric, and electromagnetic. Geophysical techniques detect discontinuities, layering, or regions in the Earth where the rock properties differ from the surrounding rocks.

Individual geophysical methods provide information that typically does not have a unique interpretation. By integrating several types of geophysical data with geologic information, a model can be developed. In this way, a more reliable interpretation can be developed. With each new input of data, the values of some parameters are adjusted, and the model is modified until the model best satisfies the greatest number of parameters and measured fields.

The science of geophysics, specifically field techniques, processing techniques, and interpretation methods, is developing rapidly. In particular, the major advances in digital computers over the last 10 yr has provided the power to look at large, complex data sets in a variety of ways. The data base for the BWIP reflects a combination of older and newer advances in technology by virtue of the time the BWIP has been in existence. The following sections discuss the data and the interpretations carried out and present a picture of the needed data to characterize the site adequately.

1.3.2.2.3.1 Gravity studies

Several authors have compiled data that form a fairly complete regional data set for the Pacific Northwest. Smaller scale data sets exist in the oil industry and power industries. Several detailed surveys have been conducted on the Hanford Site and some of these were conducted by the BWIP.

Gravity data can be used to constrain structural models on both a regional and site-specific scale. Some of the effects in the data collected for the Hanford Site are the result of stratigraphic features in the

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suprabasalt sedimentary layers, such as channel cut and fill. The gravity data used for these studies, which range from broad, regional structural interpretations to detailed investigations of shallow sedimentary layers, are summarized below.

Regional gravity setting

Several major gravity compilations that include the Pacific Northwest have been completed in recent years. The compilations by Eaton et al. (1978, Plate 3-1) and the Society of Exploration Geophysicists (SEG, 1982, Map) provide a general overview of the gravity characteristics of the Columbia Plateau and adjacent areas. These maps do not, however, include British Columbia. Compilations by the Washington Public Power Supply System (WPPSS, 1981, Fig. 2.5L-22) and Riddihough and Seemann (1982, Map) include the southern portion of British Columbia, but do not extend significantly eastward into Idaho. A combination of these compilations is used to define the gross gravity features of the Pacific Northwest.

The Columbia Plateau is a relative gravity high (Fig. 1.3-24 and 1.3-25) on the regional Bouguer anomaly maps of WPPSS (1981, Fig. 2.5L-22), Riddihough and Seemann (1982), Bonini et al. (1974), Finn et al. (1984, Sheet 13), and the Society of Exploration Geophysicists (SEG, 1982). A 40- to 80-mgal gravity gradient along the trend of the Blue Mountains is considered to be the northwestern extent of the Basin and Range Province by Eaton et al. (1978, p. 77) and Riddihough et al. (1986, p. 530). To the east lies the gravity low of the Idaho Batholith, while to the north the gradient is relatively gentle as the basalts overlap the Omineca crystalline belt of northern Washington and southern British Columbia (Cady, 1980, p. 328). The western margin of the Columbia Plateau is separated from the Cascade Range low (described by Danes, 1969, pp. 548-549), by a gradient that may represent a rapid decrease in basalt thickness (Konicek, 1975, pp. 111-112).

Gravity features of the Columbia Plateau

The Washington Public Power Supply System (WPPSS, 1977, Table 2RE-20) described the residual gravity features of the Columbia Plateau as having broad gravity highs over basalts, broad gravity lows over areas with thick sediment accumulation, and no obvious structural trends. In the western part of the Columbia Plateau, Konicek (1975, p. 115) and Robbins et al. (1975, pp. E5 and E6) noted that Umtanum Ridge, Ahtanum Ridge, and the Rattlesnake Hills are associated with positive anomalies. Konicek (1975, p. 115) noted that the Cowiche Mountains also are expressed with a positive anomaly, but the anomaly is 5 km (3 mi) north of the topographic expression. Toppenish Ridge, by contrast, has a related gravity high that is south of its surface expression. Konicek also noted that a change in these anomalies occurred along the north-south regional gravity gradient discussed above. The Ellensburg, Wenas, Yakima, and Toppenish Basins are expressed by gravity lows (Konicek, 1975, p. 115; Robbins et al., 1975, p. E-4).

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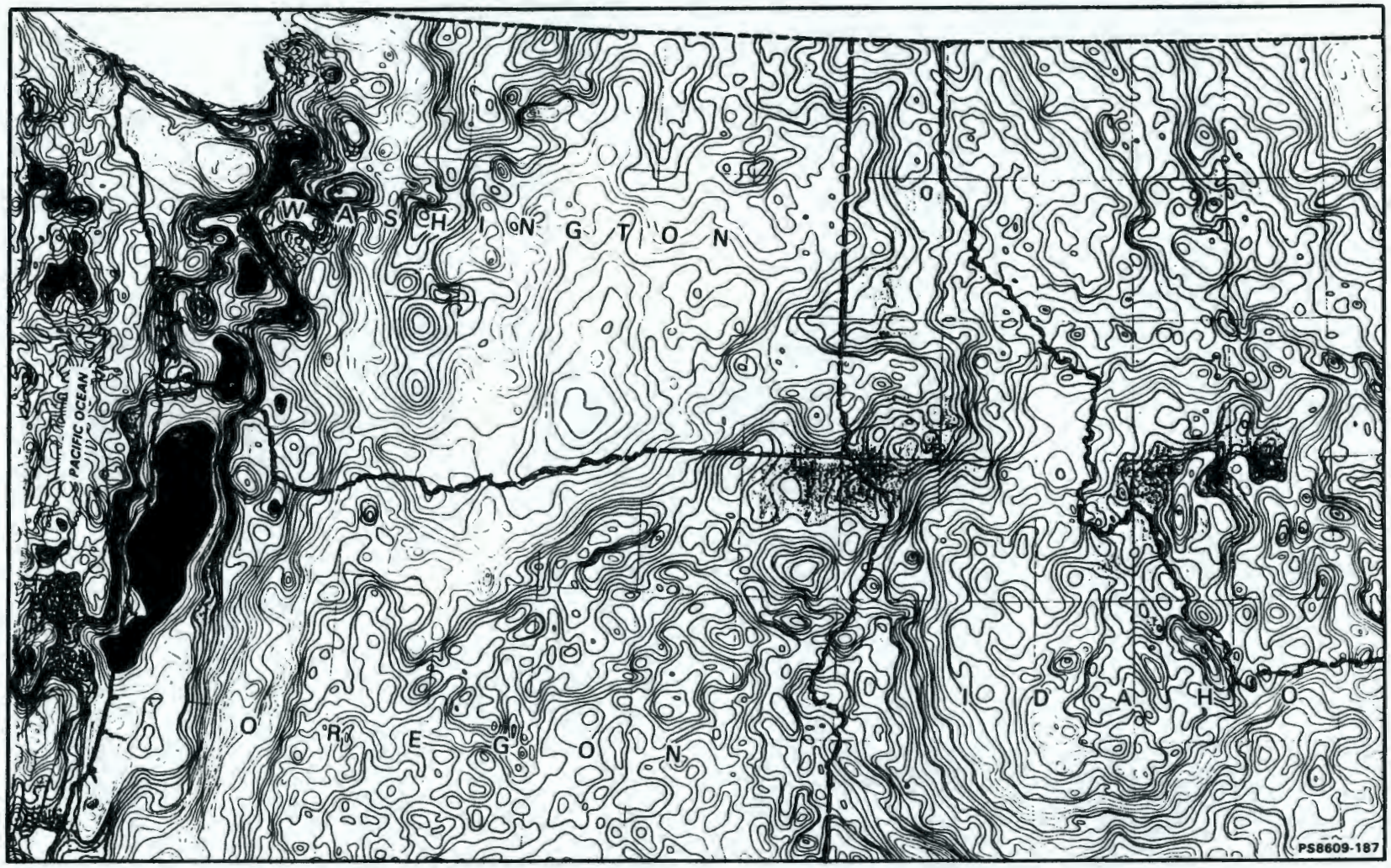

Figure 1.3-24. Bouguer gravity map of the Pacific Northwest (SEG, 1982).

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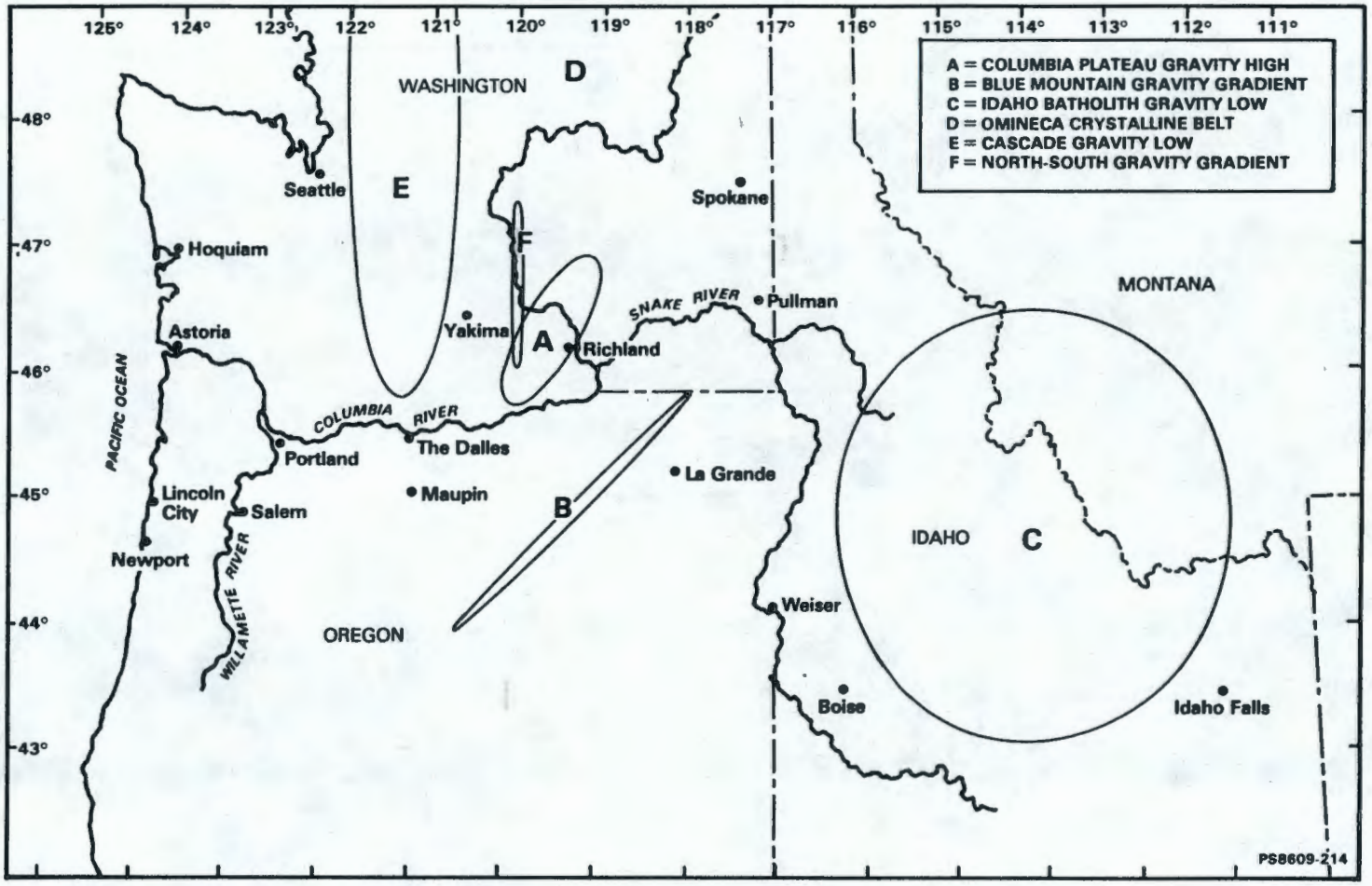

Figure 1.3-25. Major gravity features of the Pacific Northwest.

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Several structural models have been proposed using gravity data along profiles in the northern part of the Columbia Plateau (Cady, 1980, p. 330; WPPSS, 1981, Appendix 2.5L-1; Prieto et al., 1985, pp. 2709-2719). The north-south profile of Cady extends from east-central Oregon to east-central British Columbia and shows a 10-km- (6.2-mi-) thick section of basalts that gently laps onto the Omineca crystalline belt. The east-west profiles of WPPSS (1981, Appendix 2.5L-1) and Prieto et al., 1985, p. 2718), which are located north of the Pasco Basin, show a thinner section of basalt. However, the profiles disagree as to the amount, because of differences in density contrasts used to model the data.

Based on gravity analyses, Mohl and Thiessen (1985, p. 26) extended the edge of the cratonic margin, as defined by strontium isotope data, underneath the basalt cover of the eastern Columbia Plateau. Continuation of studies such as these may yield significant information for unraveling the tectonics of the Hite Fault region.

The Olympic-Wallowa lineament of Raisz (1945, pp. 479-482) is not evident on Bouguer gravity maps (Konicek, 1975, p. 114; Riddihough et al., 1986, p. 528). This does not preclude the possibility of the Olympic-Wallowa lineament from being a major tectonic structure, although it does lessen the possibility of significant vertical displacement at depth.

During the Washington Public Power Supply System's investigations (WPPSS, 1981, pp. 2.5L-16 and 2.5L-17) the gravity effect of several simple models was calculated to constrain possible strike-slip offset along the Cle Elum to Wallowa segment of the Olympic-Wallow lineament, where it crosses the north-south regional gravity gradient along the western margin of the Pasco Basin. They concluded that any fault at the base of the basalt that crosses the gradient with a strike between N. 45° W. and S. 45° W. would be restricted to a maximum horizontal displacement of 2 to 3 km (1.2 to 1.9 mi). The Washington Public Power Supply System however did not address the structural significance of the north-south gravity gradient relative to other structures (e.g., the Hog Ranch anticline and other Yakima folds).

Along the central portion of the Cle Elum to Wallula, magnetotelluric data indicate as much as 1 km (0.6 mi) of relief at the base of the basalt near Rattlesnake Mountain (see Section 1.3.2.2.3.3). The Washington Public Power Supply System (WPPSS, 1981, p. 2.5L-2) restricts the maximum vertical displacement to less than approximately 100 m (300 ft) using their gravity data; however, the gravity data coverage is probably not adequate to make such determinations.

Pasco Basin and reference repository location

Gravity data have been used extensively during siting investigations for nuclear powerplants in the Pasco Basin (Weston, 1978a; WPPSS, 1981, Appendix 2.5L and Appendix 2.5L-1; PSPL, 1982, Appendix 2K and Appendix 2L). The gravity data obtained for these studies are incorporated into the BWIP gravity data base. The additional data acquired by the BWIP are generally located near or in the reference repository location.

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The Washington Public Power Supply System noted that the Saddle Mountains, which form the northern boundary of the Pasco Basin, display no obvious gravity expression (WPPSS, 1981, p. 2.5L-17); however, the density of gravity data points in the area is low. This is in contrast to the Umtanum Ridge-Gable Mountain structure (PSPL, 1982, Appendix 2K) and the Yakima Ridge structure (Cochran, 1982, p. 85), including their respective subsurface extensions, that have obvious expressions in the gravity data.

Table 1.3-5 lists gravity anomalies that are located within the Pasco Basin, and Figure 1.3-26 is the gravity map. The locations for the anomalies can be found on Figure 1.3-27. Most of the anomalies are associated with geologic features at or above the top of the basalt surface. The analysis of the gravity data for deeper structural information will proceed during site characterization activities. The buried extension of Yakima Ridge needs additional investigation of its structural nature, its relationship to several aeromagnetic linears, and its structural relationship to the surface expression of Yakima Ridge (Section 8.3.1.2.3.3.4).

The BWIP has established a 152- by 152-m (500- by 500-ft) grid of gravity stations within the reference repository location (Fig. 1.3-28). Several areas are present that have little or no gravity data due to restricted access, the largest being the 200 West Area. The reference repository location is relatively well covered, while very sparse data exist south, west, and southeast of it.

1.3.2.2.3.2 Magnetic studies

Ground-level site-specific, basinwide, regional, and satellite-acquired magnetic data have been collected by various organizations. Originally, each data set was acquired and used in a somewhat different sense, but, for the purposes of the BWIP, all are complementary. For the discussion here, the data have been grouped into two sets: a regional set and the central Columbia Plateau.

Regional magnetic setting

Magnetic data for the region that includes the Columbia Plateau include data from satellite, aerial, and land surveys. Continent-scale magnetic data from POGO and MAGSAT satellites and aeromagnetic data from Project MAGNET (Table 1.3-6) are discussed in Mayhew (1982a, 1982b, 1985), Mayhew and Galliher (1982), Won and Son (1982), and Sexton et al. (1982). Reasonable agreement exists between the MAGNET and MAGSAT data, although there is greater detail in the MAGNET data (Won and Son, 1982). The amount of detail added to the regional trends varies, depending on the acquisition parameters, filtering wavelengths that were used, and surface-fitting formulas.

Trends in the POGO data are also apparent in the MAGSAT data, but a significant amount of detail is added. The MAGNET data generally are better correlated with known surface geology than are the MAGSAT data and offer the best representation of upper crustal geology. The MAGSAT data have potential for providing information on the deep crust, although techniques for its

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Table 1.3-5. Gravity anomalies of the Pasco Basin

Anomaly	Description	Reference
May Junction monocline	North-south trending gradient located southeast of Gable Mountain	PSPL (1982) p. 2K-27
White Bluffs gradient	Northwest trending gradient located along White Bluffs, artifact of Bouguer correction	WPPSS (1981) pp. 2.5L-9 - 2.5L-10
Southeast anticline	West-northwest trending residual high due to the bedrock high	PSPL (1982) pp. 2K-30 - 2K-31
Buried Yakima Ridge	Residual gravity high due to subsurface extension of ridge	Cochran (1982) pp. 68-69
Cold Creek syncline	Gravity low due to sediment fill in syncline	Richard and Deju (1977) p. 63
Borehole DC-3 gradient	Steep gradient trending northeast located near borehole DC-3, due to erosion of Middle Ringold	Kunk and Ault (1986)
Yakima Barricade gradient	North-south trending gradient located near Yakima Barricade due to termination of Elephant Mountain flow, possible faulting	Kunk and Ault (1986)
Borehole DC-4, DC-5 anomaly	Perturbation of Bouguer gravity northeasterly trend from boreholes DC-4 and DC-5 toward RRL-14 probably due to erosional channel in sediments	Kunk and Ault (1986)
Borehole RRL-9 gravity high	Gravity high centered about borehole RRL-9, due to high near-surface density	Kunk and Ault (1986)

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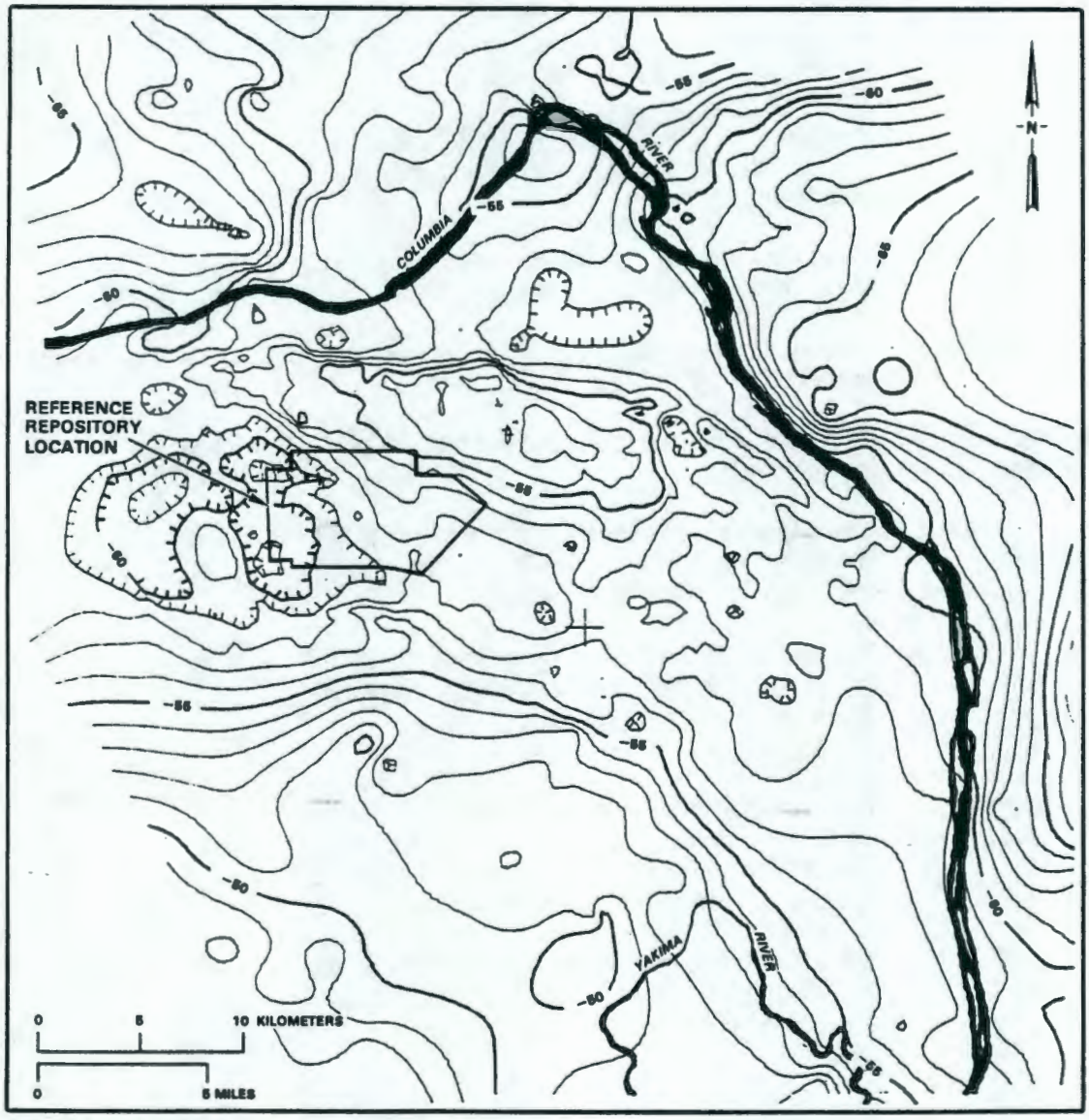

CONTOUR INTERVAL = 1.0 mGAL
REDUCTION DENSITY = 2.67 gm/cm^3

TO CONVERT gm/cm^3 TO lb/ft^3, MULTIPLY BY 62.4

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Figure 1.3-26. Gravity in the vicinity of the reference repository location.

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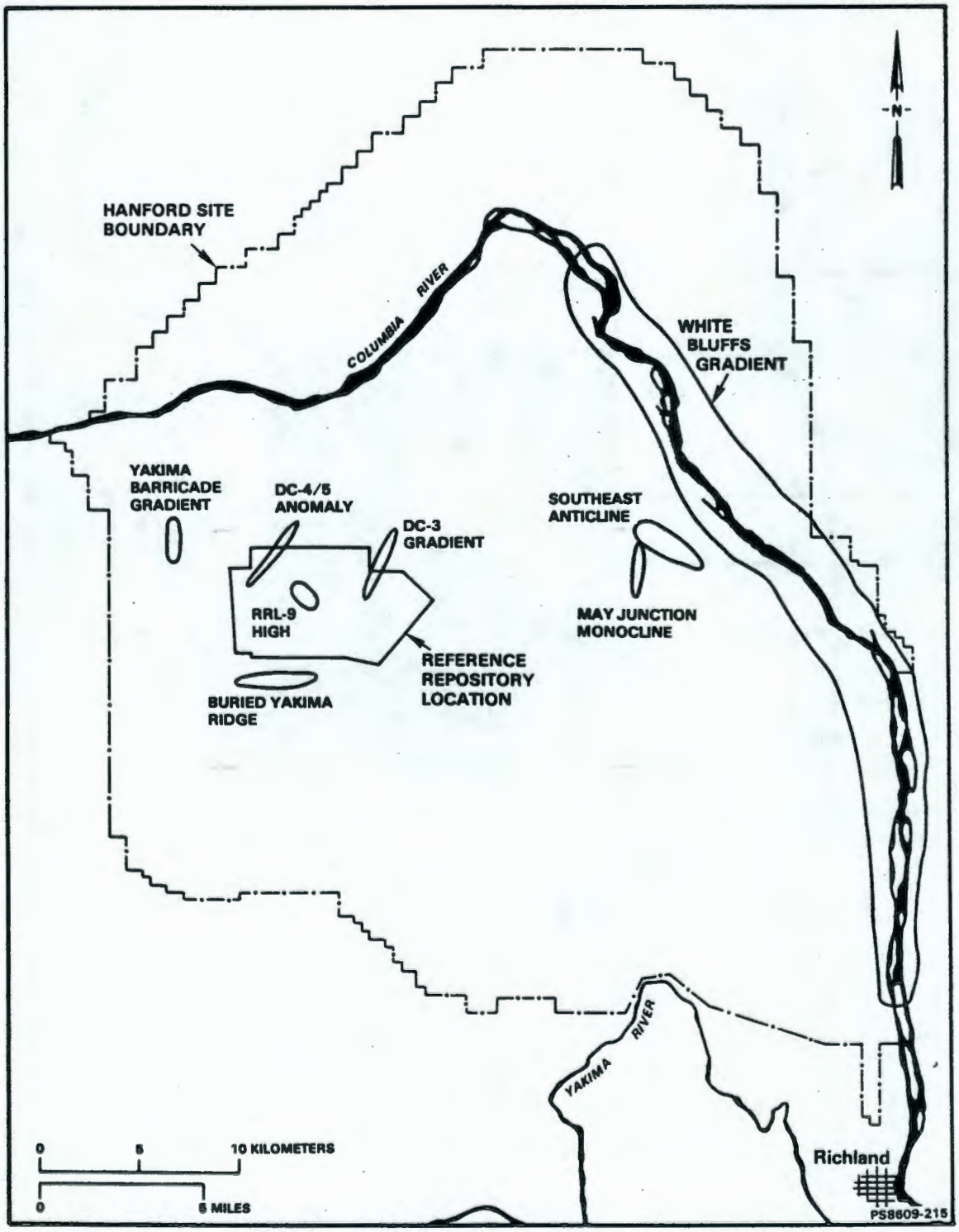

Figure 1.3-27. Gravity features in the vicinity of the reference repository location. See Table 1.3-5 for further description of features.

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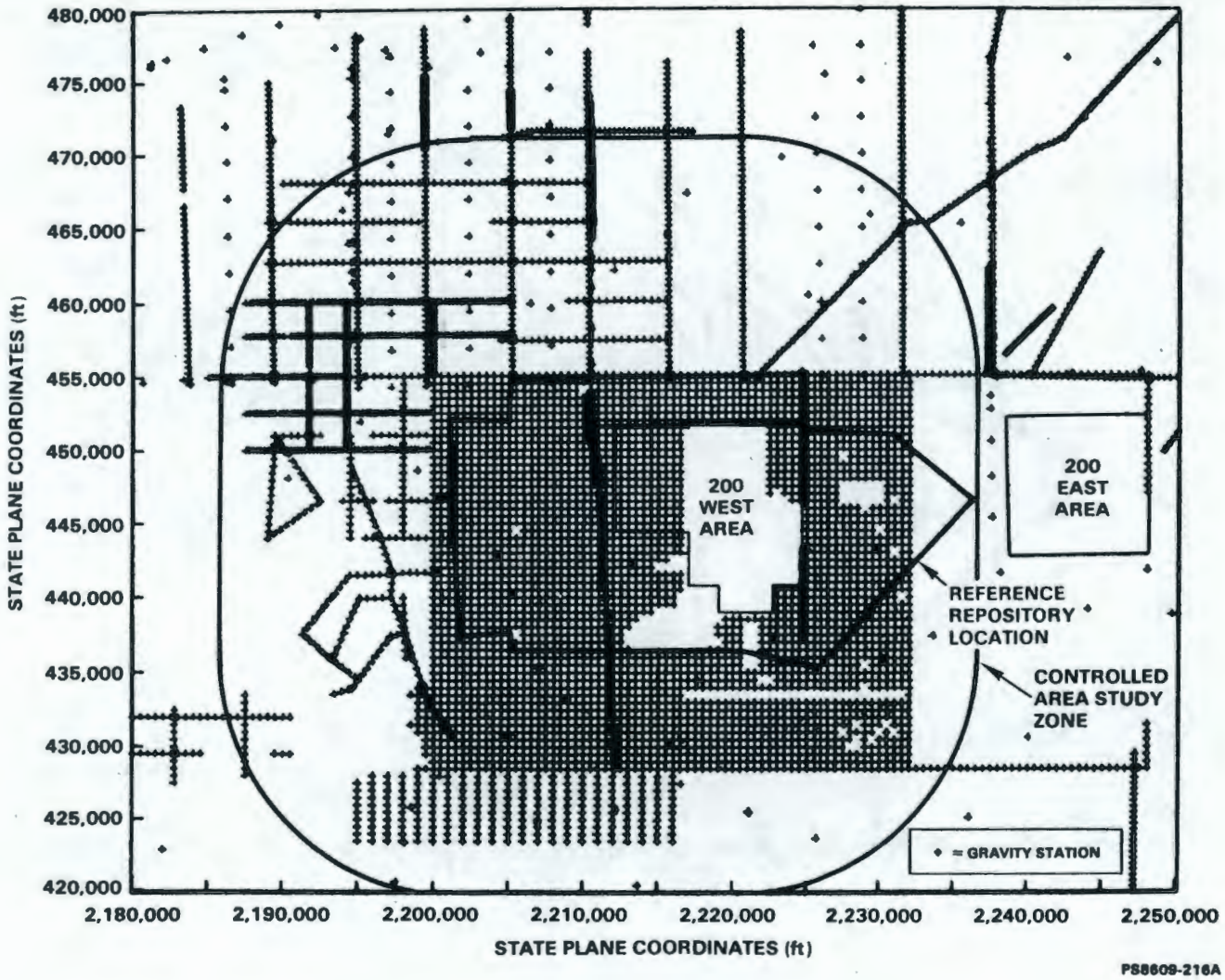

Figure 1.3-28. Gravity stations in the reference repository location area.

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Table 1.3-6. Aeromagnetic surveys

Map area[a]	Survey reference	Survey altitude	Survey line spacing and orientation	Magnetometer
A	Raymond and McGhan (1963)	150-m (500-ft) terrain clearance	1.6 km (1 mi) north-south	Fluxgate
H	Zietz et al. (1971)	4,575-m (15,000-ft) constant elevation above sea level (barometric)	8.0 km (5 mi) east-west	Alkali vapor and fluxgate
A	Blume (1971)	275- and 455-m (900- and 1,500-ft) barometric	3.2 x 3.2 km (2 x 2 mi) northeast-southwest, northwest-southeast	Proton precession
F	USGS (1974)	2,134-m (7,000-ft) barometric	1.6 km (1 mi), east-west, tie lines north-south	Unspecified
D	Robbins et al. (1975)	150-m (500-ft) terrain clearance	3.2 km (2 mi) north-south traverses, 1.6 km (1 mi) flight line spacing	Modified AN-ASQ/3A
E	Weston (1978c); WPPSS (1977)	305- and 455-m (1,000- and 1,500-ft) terrain clearance	0.8 x 0.8 km (0.5 x 0.5 mi) northeast-southwest traverse lines, northwest-southeast tie lines	Optically pumped cesium vapor
C	Swanson et al. (1979c)	150-m (500-ft) terrain clearance	1.5 km (1 mi) north-south	Fluxgate
A	Myers/Price et al. (1979)	1,220-m (4,000-ft) barometric	0.8 x 0.8 km (0.5 x 0.5 mi) northeast-southwest, northwest-southeast	Proton precession
G	USGS (1979)	150-m (500-ft) terrain clearance	1.5 km (1 mi) north-south	Proton precession
B	Holmes and Mitchell (1981); AERO (1980)	760; 990; 1,220; 1,450; and 1,680 m (2,500; 3,750; 4,000; 4,750; 5,500 ft)	0.8 x 0.8 km (0.5 x 0.5 mi) northeast-southwest northwest-southeast	Optically pumped cesium vapor
N/A[b]	Sexton et al. (1982); Won and Son (1982)	500 to 1,600 m (1,640 to 5,250 ft)	1° north-south Project MAGNET	Optically pumped helium 4SQ-81
N/A	Mayhew (1982a)	400 to 700 km (250 to 435 mi)	Pogo Satellite	
N/A	Mayhew and Galliher (1982)	300 to 500 km (185 to 310 mi)	MAGSAT Satellite	

[a]See Figure 1.3-27.
[b]N/A = not applicable.

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analysis must be further refined. The Columbia Plateau does not exhibit any strong magnetic response in the above-mentioned data sets, although regional trends are apparent.

Zeitz et al. (1971) present the results of an aeromagnetic survey that was flown at 4,600 m (15,000 ft) over the Columbia Plateau and surrounding regions. Their data reveal the same general characterisics as the MAGNET aeromagnetic data reported by Sexton et al. (1982), except that the data compiled by Zeitz et al. exhibit higher amplitude anomalies. Higher frequency anomalies have been removed from the MAGNET data by low-pass filtering. Zeitz et al. note the subdued nature of anomalies over the Columbia Plateau, in spite of the high magnetization of the basalts, and speculate that this is due to a canceling effect brought on by alternating normal and reversed polarity in the basalt layers (Zeitz et al., 1971, p. 3351). Zeitz et al. also speculated that the characteristics of the magnetic field over the Columbia Plateau are more influenced by the sub-basalt rocks than by the basalts, and they base this interpretation on the relatively long wavelengths and low amplitudes of anomalies that are observed.

General magnetic characteristics of the area surrounding the Columbia Plateau include a broad, magnetic low associated with most of Idaho (Sexton et al., 1982, p. 368, Fig. 3; Mayhew and Galliher, 1982, p. 812, Fig. 3). The extension of this low into the Columbia Plateau (see Zietz et al., 1971, Fig. 1) suggests similarities between the subsurface lithologies of Idaho and the Columbia Plateau as far as 120° W. longitude.

South of the Columbia Plateau, a relative high is detected on the satellite and MAGNET surveys. This trend continues diagonally across southeastern Oregon to northern California. Mayhew (1985, p. 2648, Fig. 2) shows a minor northwest excursion of this high that trends across southeastern Washington, reflecting the position of the Rattlesnake-Wallula alignment segment of the Olympic-Wallowa lineament proposed by Raisz (1945). Zietz et al. (1971, Fig. 1) also show generally higher magnetic intensities in this area that extends from near Yakima, Washington, toward the Walla Walla, Washington, and Pendleton, Oregon, areas, and then northeastward to Clarkston, Washington. Zietz et al. refer to this feature as the Columbia arc and attribute the eastern high to the presence of pre-Tertiary basement lithologies (e.g., Clearwater Embayment of Swanson et al., 1981). The presence of these highs suggests that a different lithology exists south of the central Columbia Plateau, which has implications regarding the nature of the Olympic-Wallowa lineament. Magnetic data, along with other geophysical data, will be integrated with geologic information to further characterize these features in the vicinity of the Pasco Basin (Section 8.3.1.2.3.3.4).

A magnetic low lies north of the Columbia Plateau and corresponds to the North Cascades and Okanogan Highlands. Satellite data (Mayhew, 1985, p. 2648, Fig. 2) suggest that this low is connected with the similar low in Idaho. This interconnection is not as apparent in the MAGNET data set (Sexton et al., 1982, p. 368, Fig. 3).

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The westward edge of the Columbia Plateau exhibits the most striking differences between satellite and aeromagnetic data. Sexton et al. (1982, p. 3, Fig. 3) and Won and Son (1982, p. 297, Fig. 2) show a distinct magnetic low in the Cascade Range province. The apparent magnetization map from satellite data of Mayhew and Galliher (1982, p. 312, Fig. 3) shows only a gradual trend toward higher magnetization, reaching a maximum near the Pacific Coast. The Zeitz et al. (1971) survey shows a general low in the Cascade Range with localized highs.

Central Columbia Plateau

Table 1.3-6 shows a summary of the magnetic information available that covers the Hanford Site. Total field aeromagnetic maps from various surveys over the central Columbia Plateau all give comparable results, when differences in survey design are considered. Figure 1.3-29 shows the locations of the various surveys over the central Columbia Plateau.

Zietz et al. (1971, p. 3,353 and Fig. 1) noted a broad, arcuate, magnetic low that passes through the central Columbia Plateau (Fig. 1.3-30). This low extends from Ellensburg, Washington, to the Blue Mountains, near Waitsburg, Washington, then to the northeast of Clarkston, Washington, where it connects with a magnetic low in Idaho. The magnetic low transects the topographic expression of the Blue Mountains, which precludes a purely topographic explanation for the feature. South of this low, the map shows a magnetic high centered near Richland, Washington. Subsequent magnetic surveys for the Washington Public Power Supply System and the BWIP show numerous anomalies superimposed on these larger features. Zietz et al. (1971) detected a prominant high in the northeastern Pasco Basin, at approximate latitude 46°45'N., longitude 118°45'W. (see Fig. 1.3-30). Prieto et al. (1985, p. 2,717) attribute this magnetic high to metamorphic basement material, which supports the Zietz et al. (1971) idea of basement influence in the magnetic field.

Weston Geophysical, using the Washington Public Power Supply System data set, interpreted aeromagnetic intensity maps and described several linears that cross the Pasco Basin (Fig. 1.3-31; Weston, 1978c). Werner deconvolution solutions of aeromagnetic profile data collected for the BWIP provide limited help in interpreting the geologic significance of these features (Holmes and Mitchell, 1981, pp. B-23 to B-24; AERO, 1980). Specific Werner deconvolution solutions are discussed in Section 1.3.2.2.3.7.

Two of the aeromagnetic linears identified by Weston Geophysical have received more attention than others because of their proximity to the Washington Public Power Supply System reactor sites. The Nancy and the Juniper Springs aeromagnetic linears are discontinuous features on the Weston magnetic intensity contour map. They transect the northern Pasco Basin on a northeast by trend. The tectonic significance of these linears is not presently known. Weston Geophysical interpreted the Juniper Springs linear as most probably related to a fault that is younger than Umtanum Ridge, Yakima Ridge, and the Rattlesnake Hills-Wallula Gap structures (WPPSS, 1977; Weston, 1978c). This interpretation is based on apparent offsets in magnetic anomalies associated with Umtanum Ridge, Yakima Ridge, and Rattlesnake Hills

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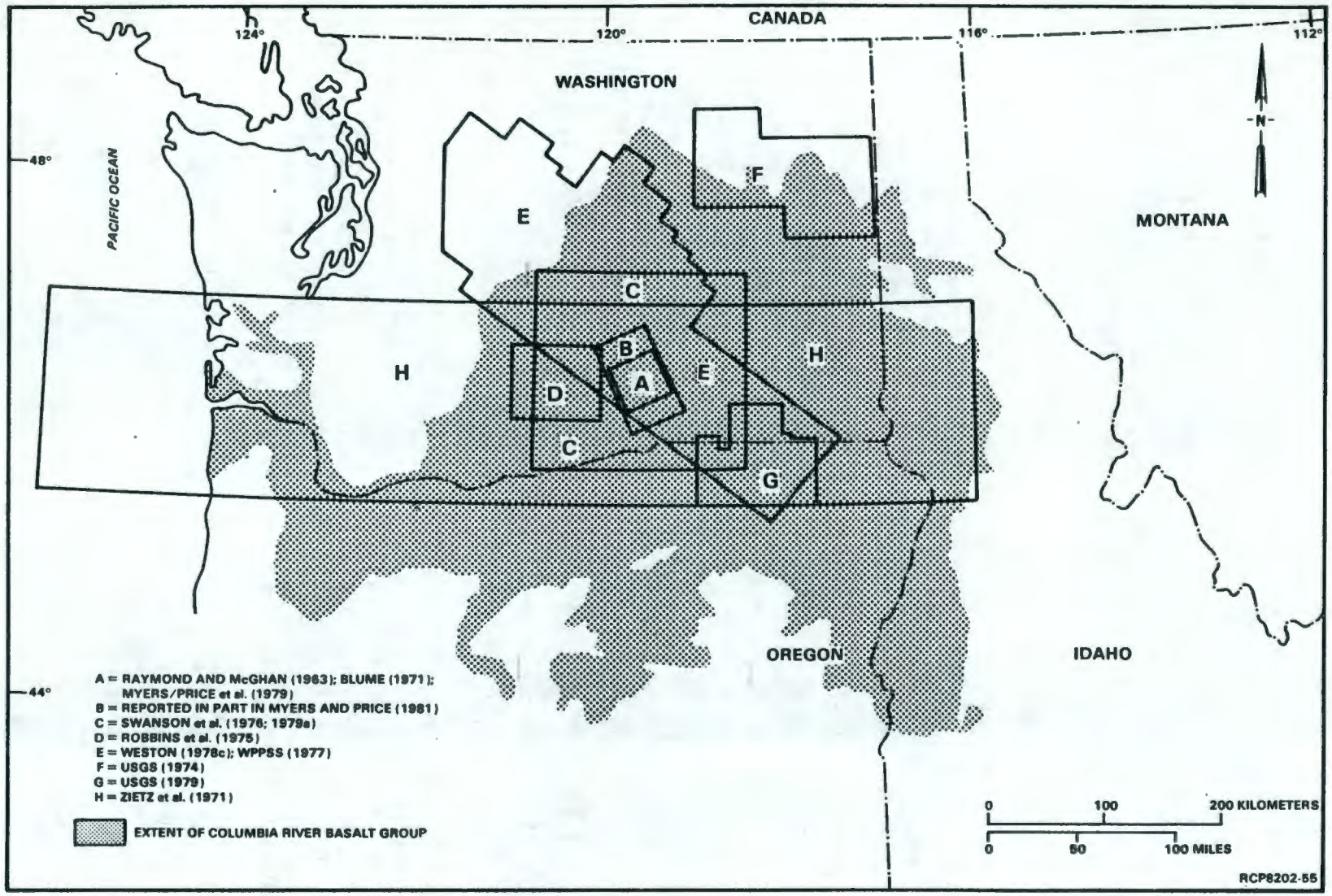

Figure 1.3-29. Aeromagnetic surveys over the Columbia Plateau.

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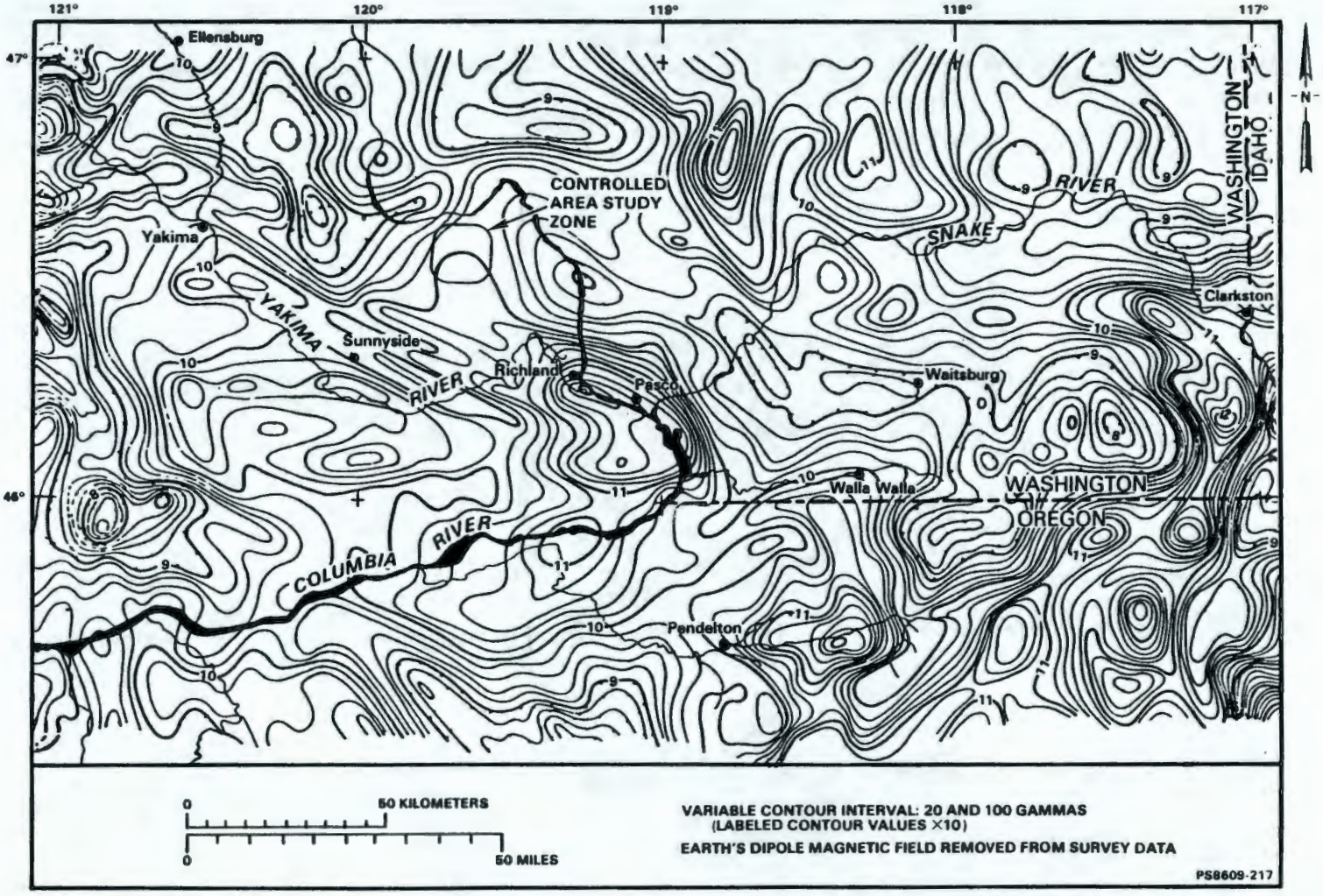

Figure 1.3-30. Aeromagnetic map of central Washington flown at 4,572 m (15,000 ft) barometric altitude (from Zeitz et al., 1971).

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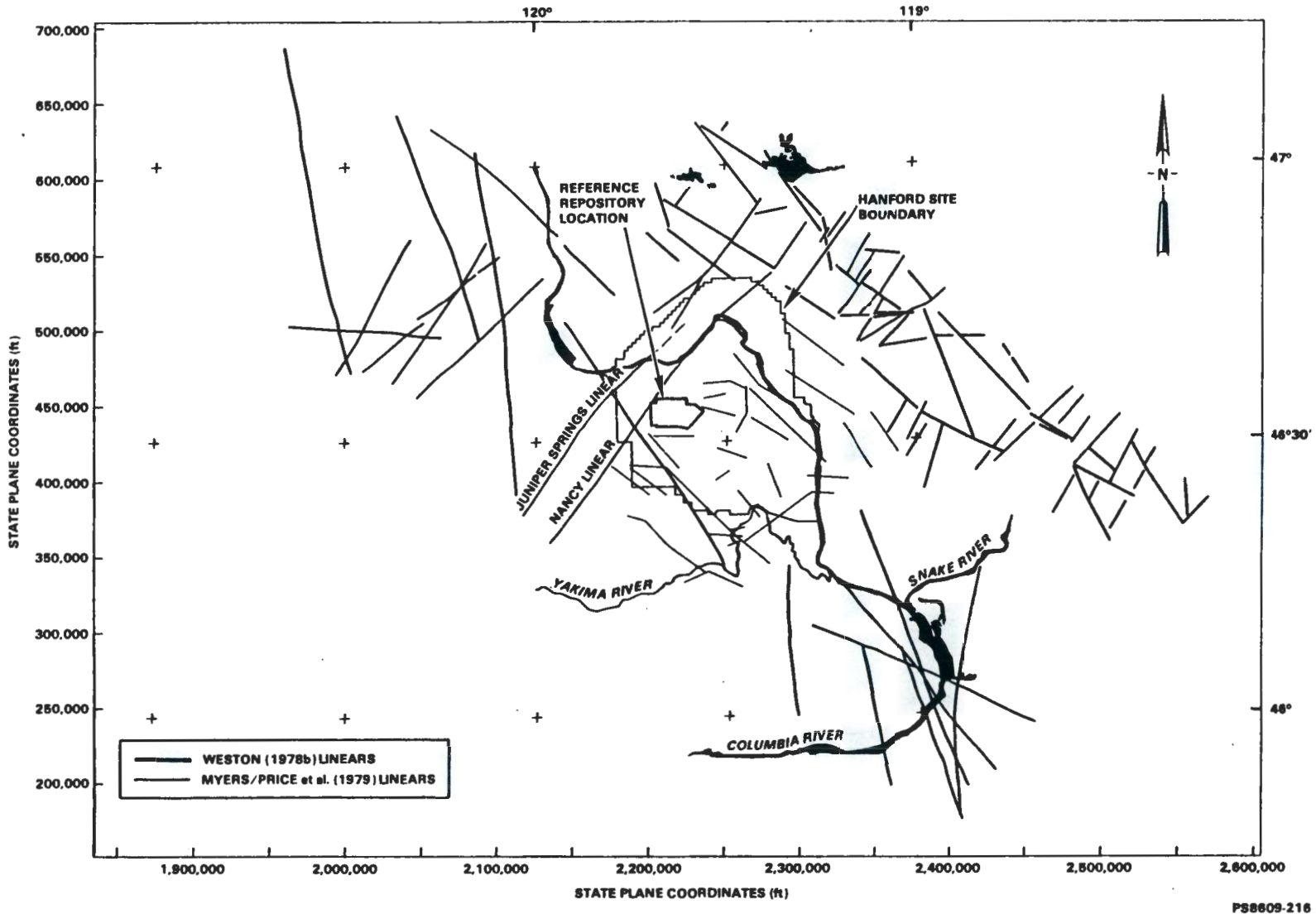

Figure 1.3-31. Summary of aeromagnetic linears in the central Columbia Plateau.

CONSULTATION DRAFT

at their intersections with this linear. However, no geologic explanation for the Nancy linear, which lies to the east of and parallel to the Juniper Springs linear, is presented in their report. Rather, the Nancy linear is defined only as a line on a magnetic intensity contour map (Weston, 1978c).

The character of the total magnetic field along the trace of the proposed Nancy linear is variable and discontinuous. Along its trend it is represented by an isolated magnetic high; a high to the west associated with a low to the east; and a high to the east adjacent to a low to the west. There are no trends in gravity data that correlate with the Nancy linear where it crosses the Cold Creek Valley, nor does the linear correlate with any of the faults that are mapped on the Rattlesnake Hills or the Saddle Mountains. However, a few of the Werner deconvolution solutions are coincident with the linear (Fig. 1.3-32). The trace of the Nancy linear is also coincident in a general fashion with several geologic and geomorphic features. They include the Coyote Rapids microseismic swarm area (see Sections 1.4.1.1.1 and 1.4.2.1.3) and an intracanyon flow interpreted from other aeromagnetic data, which trends from north of the Saddle Mountains to approximately Gable Butte (Swanson et al., 1979c).

The information gathered to date does not support an interpretation of the Nancy linear as a continuous geologic structure. This feature, like many other subtle features in the Pasco Basin, requires further study to provide more substantial evidence for its potential geologic origin. Planned studies are discussed in Section 8.3.1.2.3.3.4.

Swanson et al. (1976, p. 12; 1979c, Map GP-917), using data collected at an altitude of 150 m (500 ft) above ground level, noted a zone of northward-trending anomalies east of the Pasco Basin and associated the zone with the Ice Harbor dike system. They interpret the southern termination of these anomalies, at the intersection of the Olympic-Wallowa lineament, as strike-slip faulting.

Myers and Price (1981, Plate III-6) and AERO (1980, p. 54) noted northeast-trending aeromagnetic linears in the southeastern Pasco Basin (see Fig. 1.3-32). The linears were interpreted from trends and disruptions of trends in total field magnetic contours, and from Werner deconvolution features generated from the total field data. These trends apparently disrupt the trace of the Ice Harbor dikes and other northwest-trending linears and may represent previously undetected strike-slip faulting. The presence of this strike-slip faulting has not been corroborated by other geologic or geophysical data to date. The magnetic responses have alternate geologic interpretations that are not related to faulting. Many of the major magnetic features that exhibit apparent northeast-trending disruptions are themselves not well understood and must be investigated more fully before the more subtle disruptions can be understood (see Section 8.3.1.2.3.3.4). The significance of these northeast trends and the potential for their presence in the reference repository location are uncertain and will be addressed during site characterization (Section 8.3.1.2.3.3.4).

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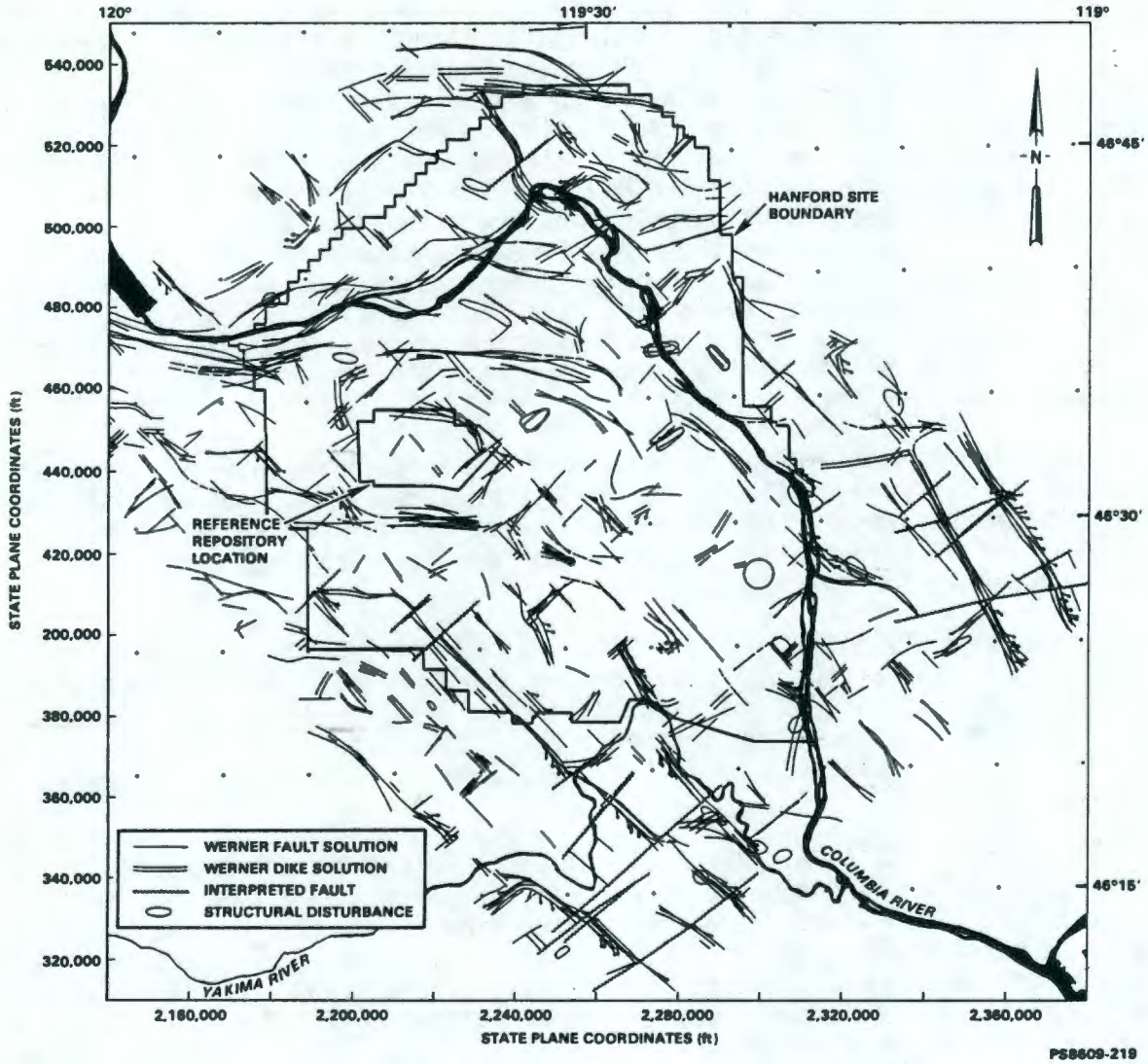

Figure 1.3-32. Summary of Werner deconvolution solutions for aeromagnetic survey data (AERO, 1980).

AERO (1980) flew an aeromagnetic survey at five different levels over the Pasco Basin and used the flight-line profiles to calculate Werner deconvolution solutions for the BWIP (see Fig. 1.3-32). Myers and Price (1981, pp. 8-1 to 8-25) discuss these solutions and qualitative interpretations of the results in the Cold Creek syncline area. Additional evaluations are presented in Holmes and Mitchell (1981, pp. B-14 to B-56) and DOE (1987c, pp. C.5-133 to C.5-145). Representative total-field magnetic contour and Werner deconvolution maps also are presented in Holmes and Mitchell (1981, Fig. B-8 through B-12).

Werner deconvolution (Werner, 1953; Kilty, 1983) is a mathematical analysis that detects magnetization contrasts. These contrasts can result from the influence of structural, stratigraphic, erosional, or topographic features. The number and scatter of Werner solutions in a given area are measures of the confidence in the existence and location of a geologic feature. Additional geologic and geophysical investigations are required to verify the interpretation of Werner solutions.

Several magnetic surveys of the land surface have been conducted in and around the reference repository location (Ault, 1981; Cochran, 1981a, 1981b, 1982; Kunk, 1981; Kunk and Ault, 1986). The magnetic-field contour maps generated from these surveys depict the same general features as the aeromagnetic surveys discussed above, but in more detail. The geologic interpretation of this detail is uncertain, and existing top-of-basalt maps (e.g., Myers and Price, 1981, Fig. 8-3; Landon and Bjornstad, 1986, Fig. 4) do not help, since these maps are low in resolution due to limited data. Improving the interpretation of magnetic data will require an improved understanding of (1) the effect of suprabasalt sediments on the magnetic field, (2) the magnetic susceptibilities and natural remanent magnetism of the sediments and basalts; and (3) the structures in the basalt that are not revealed on existing top-of-basalt maps.

The general ranges for magnetic properties of basalts and suprabasalt sediments in the Pasco Basin are shown in Table 1.3-7. The contrast between the susceptibility of the sediments and basalt is large, and the basalt dominates the magnetic field in most cases. An exception may occur at the reference repository location, where suprabasalt sedimentary units are up to 180 m (590 ft) thick. These areas of relatively deeply buried basalt may allow variations in the sedimentary units to be expressed in the magnetic data.

There is considerable variability in susceptibility and natural remanent magnetism within the magnetostratigraphic units, which precludes detailed modeling and interpretation of the data sets. Van Alstine and Gillette (1981, 1982) discuss the magnetic variability of the basalts and conclude that comprehensive sampling programs are required to describe this variability adequately. Deriving parameters on the basis of occasional samples from outcrops and boreholes may not produce representative values for the Pasco Basin, which will result in less-than-accurate modeling of the data. Numerous magnetic polarity reversals also complicate the interpretation of magnetic data. See Section 8.3.1.2.3.3.1 for a discussion of site characterization plans that are designed to reduce the uncertainty in interpreting magnetic intensity data.

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Table 1.3-7. Magnetic properties of basalts and suprabasalt sediments, Pasco Basin

Lithologic unit	Susceptibility (cgs units)	Natural remanent magnetism intensity (emu/cm^3)	Reference
Sediments (Ringold Formation)	--	0.00001 to 0.0000001	WCC, 1978
Sediments (Ellensburg Formation)	0.0001 to 0.00001	--	Djuth, 1983
Basalt	0.001 to 0.0001	0.01 to 0.0001	Van Alstine and Gillette, 1982

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1.3.2.2.3.3 Magnetotelluric studies

Magnetotelluric techniques have been used extensively, primarily by hydrocarbon exploration companies, on the Columbia Plateau since approximately 1980. While magnetotelluric surveys typically provide less resolution than seismic reflection data, their extensive use is due, in part, to initially poor success with seismic reflection techniques in determining structure and stratigraphy beneath the basalts. Apparent recent success with seismic methods by hydrocarbon exploration companies suggests that magnetotelluric methods may no longer be the most effective technique for detailed deep exploration on the Columbia Plateau. However, magnetotelluric exploration will still be used, because it provides cost-effective reconnaissance investigations of the deeply buried rocks. In many areas, it may remain the most effective exploration method.

Due to the acquisition parameters and state of technology at the time, most of the data collected prior to 1983 are not useful for detailed structural interpretations. Fortunately, the quality of data has improved significantly over the last few years because of advances in magnetotelluric technology. Therefore, the following interpretations rely more on recently acquired data, although the entire data set is still useful for the regional setting and geoelectric stratigraphy.

Five surveys (Czimer and Edwards, 1978; Senturion, 1979; Argonaut, 1980; Geotronics, 1982; Z-Axis, 1985) have been conducted by the BWIP and three proprietary regional data sets have been purchased (Geotronics, 1982; Z-Axis 1983; Phoenix, 1983; Fig. 1.3-33). A regional magnetotelluric profile by the U.S. Geological Survey (Stanley, 1982) also is part of the BWIP data base.

For regional analysis beyond the Pasco Basin, the BWIP purchased the Phoenix (1983) and Z-Axis (1983) proprietary data. These data reflect the improvements in data collection technology (e.g., remote referencing and

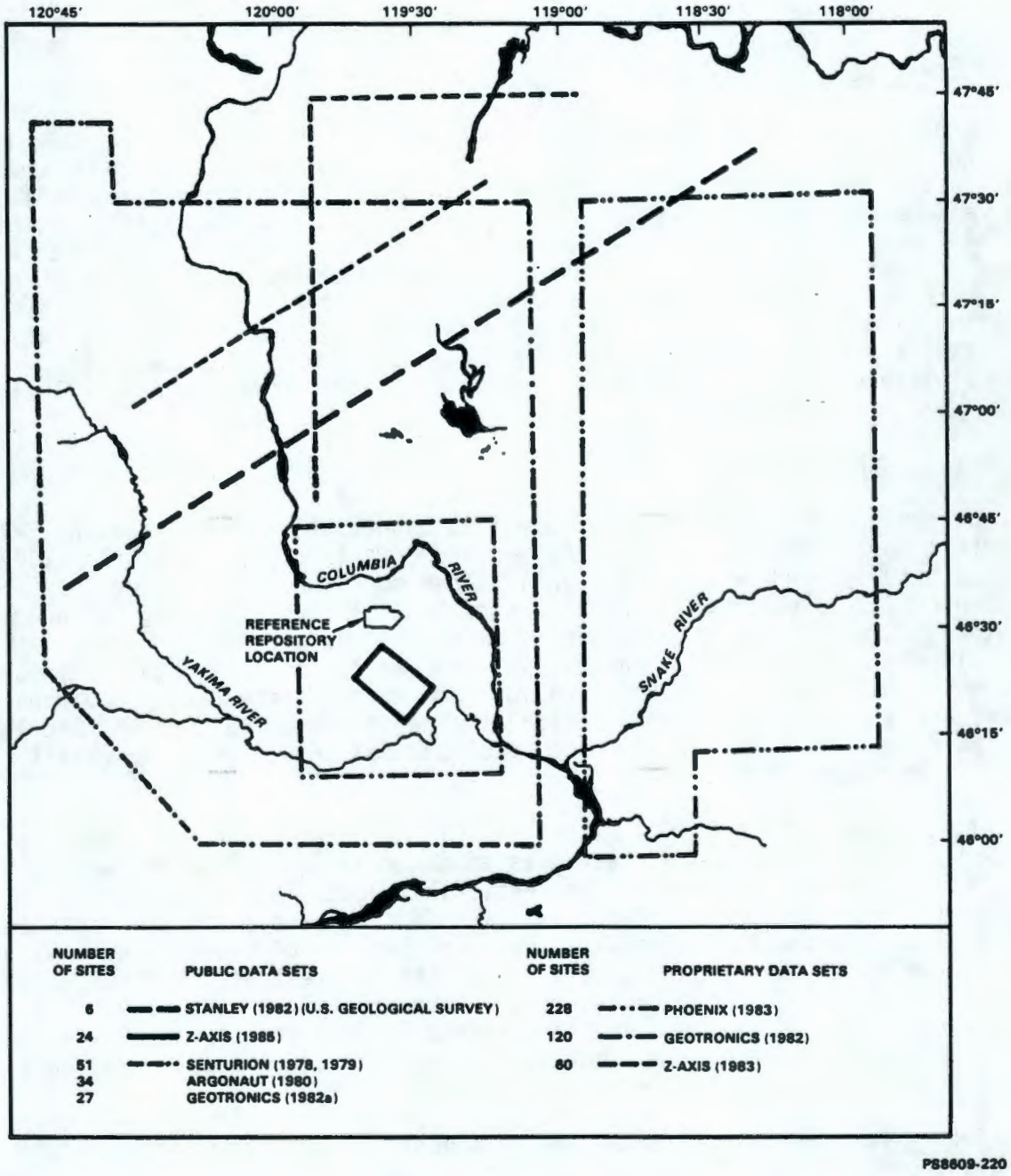

Figure 1.3-33. Magnetotelluric survey data available to the Basalt Waste Isolation Project.

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in-field processing) and provide adequate regional control to the east of the Pasco Basin and marginal control to the north. To the west and south of the Pasco Basin, more magnetotelluric data are necessary to develop a complete regional magnetotelluric setting (Section 8.3.1.2.3.3.4).

Geoelectric stratigraphy

Crustal rocks have been grouped into five layers using magnetotelluric data for the central Columbia Plateau (Fig. 1.3-34). Layer 1 includes the suprabasalt sediments, the uppermost basalt flows, and the interbeds of the Saddle Mountains Basalt. Layer 2 is the basalt section, and layer 3 is the sediment section underlying the basalts. Layer 4 presently has a rather wide range of resistivities, depending on the location of the measurements throughout the plateau. This is believed to be caused by the variety of rock types that are associated with it. The Pasco Basin data indicate a layer 4 resistivity of approximately 100 Ω·m (Berkman et al., 1986). The lowermost, crustal layer, layer 5, is deep and not well defined in the magnetotelluric data.

Sub-basalt structures

Orange and Berkman (1985, pp. 156-159) quantitatively analyzed the BWIP magnetotelluric data collected by Czimer and Edwards (1978), Senturion (1979), Argonaut (1980), and Geotronics (1984). They confirmed the findings of Geotronics (1981, p. 5) that detailed structural interpretations, based on pre-1982 data, were not warranted because of poor data quality. Their analysis also indicated that the quality and density of data acquired in 1982 were not sufficient for the detailed interpretations presented by Geotronics (1984) and Mitchell and Bergstrom (1983). They recommended that the pre-1982 data be used only to define the gross geologic features of the sub-basalt rocks in the Pasco Basin.

Orange and Berkman (1985, Plates 11-16) interpreted the Geotronics data set for the central Columbia Plateau as an accumulation of basalt ranging from 3 to 4.6 km (1.9 to 2.9 mi) in thickness. This accumulation is asymmetric in cross section and thins rapidly to the west of the Pasco Basin and more gently to the east (Section 1.5). Most of the thick section of basalt occurs within the boundaries of the Pasco Basin, although the thickest accumulation appears to occur slightly to the southwest of the boundary. They made no attempt to address the relationship between the observed surface structures and the base of the basalt. They concluded that additional, closely spaced, high-quality data are needed for detailed structural analysis.

Twenty-four relatively close-spaced magnetotelluric sites were occupied along two profiles across part of the Rattlesnake-Wallula alignment in 1985 (Z-Axis, 1985). This study was the first attempt by the BWIP at a detailed investigation of a possible sub-basalt structure. The data are significantly better than previous data sets. Berkman et al. (1986) interpreted the data and concluded that there is approximately 1 km (0.6 mi) of relief at the base of the basalt beneath Rattlesnake Mountain. This is approximately the same amount of relief observed at the surface. They were not able to determine

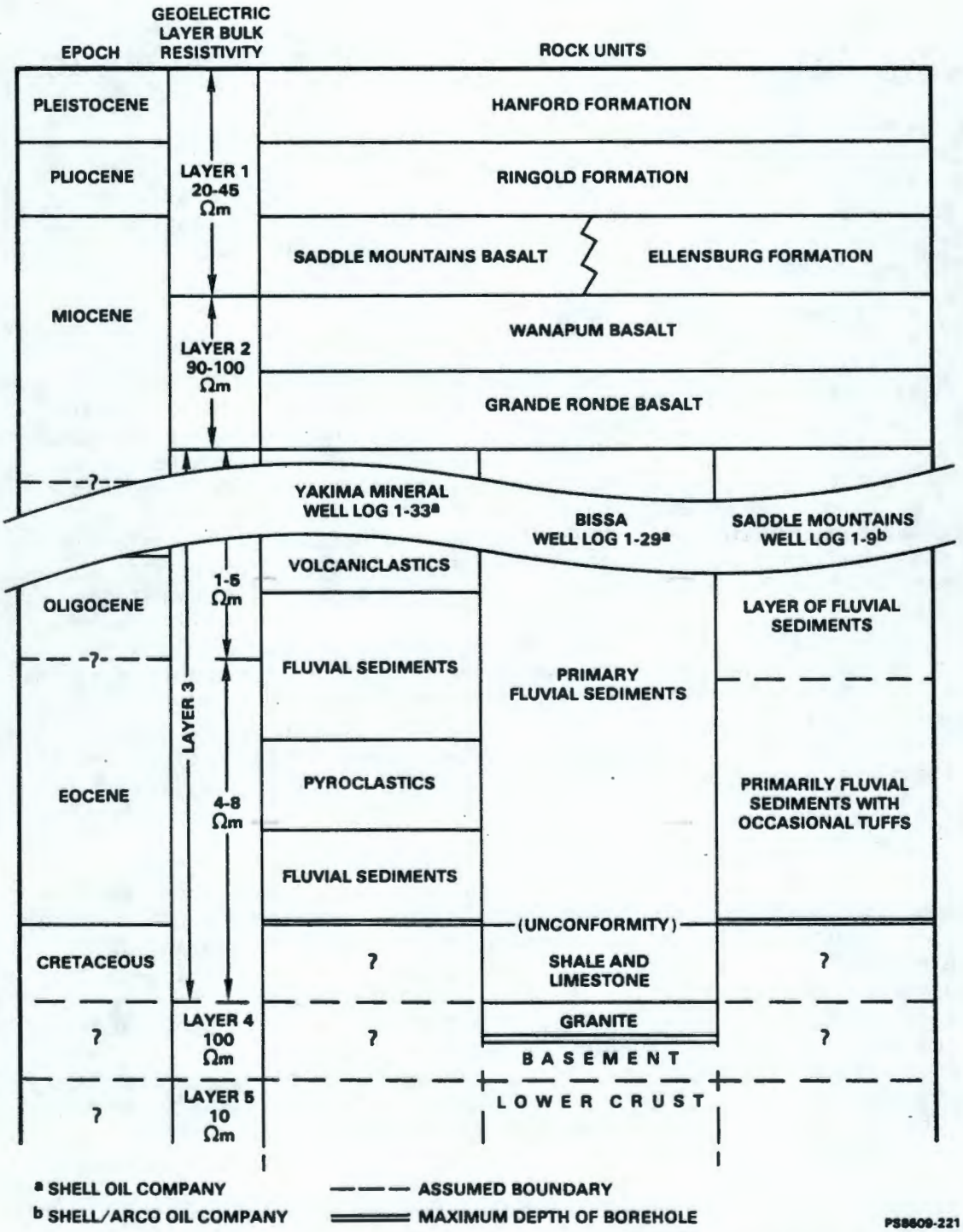

Figure 1.3-34. Stratigraphic correlations with geoelectric layers defined by magnetotelluric data (from Berkman et al., 1986).

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whether the base of the basalt was faulted, but indicated that with additional, carefully selected sites, the feature may be resolved with the magnetotelluric method.

To date, the BWIP has defined the gross setting of the Pasco Basin. No large, unexpected sub-basalt structures have been identified, but large gaps still exist between high-quality magnetotelluric sites. To improve the interpretation of basement structures and stratigraphy in the Pasco Basin, additional high-quality magnetotelluric data will be collected (Section 8.3.1.2.3.3.4).

1.3.2.2.3.4 Seismic refraction surveys

The purposes of large-scale refraction surveys conducted by the BWIP have been to define the regional structures to assist in determining a tectonic model for the area of the reference repository location, to define a crustal model that better constrains earthquake locations, and to determine station corrections for the earthquake recording network. Surveys also have been conducted by other investigators to determine the regional variation of structures within the Columbia Plateau and Pacific Northwest. Additional surveys have been conducted to support siting and licensing of nuclear powerplants, engineering and foundation studies, and general exploration.

Seismic refraction results have given a general picture of the upper crustal variations in the region of the Pasco Basin. The refraction data need to be subjected to additional interpretation and these results need to be integrated with gravity, magnetic, magnetotelluric, borehole, and geologic data to determine a consistent structural model. This integration effort is part of the site characterization plans discussed in Section 8.3.1.2.3.3.6.

Long-range refraction surveys

Surveys conducted over and near the Columbia Plateau have been reported by Dehlinger et al. (1965), White and Savage (1965), Johnson and Couch (1970), Hill (1972), and Crosson (1972). A summary of crustal thickness and upper mantle velocities in the western United States, shown in Figures 1.3-35 and 1.3-36 was given by Smith (1978). The data used to constrain the interpretation for the Columbia Plateau came from the previous work noted above, from Hill (1978), and from inferences from magnetotelluric measurements. Velocity models used by the University of Washington to locate earthquakes have a crustal thickness of 40 km (25 mi) beneath the Puget Sound region. The crustal thickness thins to 25 km (16 mi) in northeastern Washington.

A seismic refraction experiment was conducted by the BWIP and the University of Washington using blast data recorded by seismic networks. Rohay and Malone (1983), using a time-term analysis of these data, reported depths to the 6-km/s (2.0×10^4-ft/s) layer, probably the crystalline basement, shown in Figures 1.3-37 and 1.3-38. These data indicate that the basement is deepest beneath the Hanford Site and to the south. Although Figure 1.3-37 indicates a possible shallowing of the basement to the west, there are not

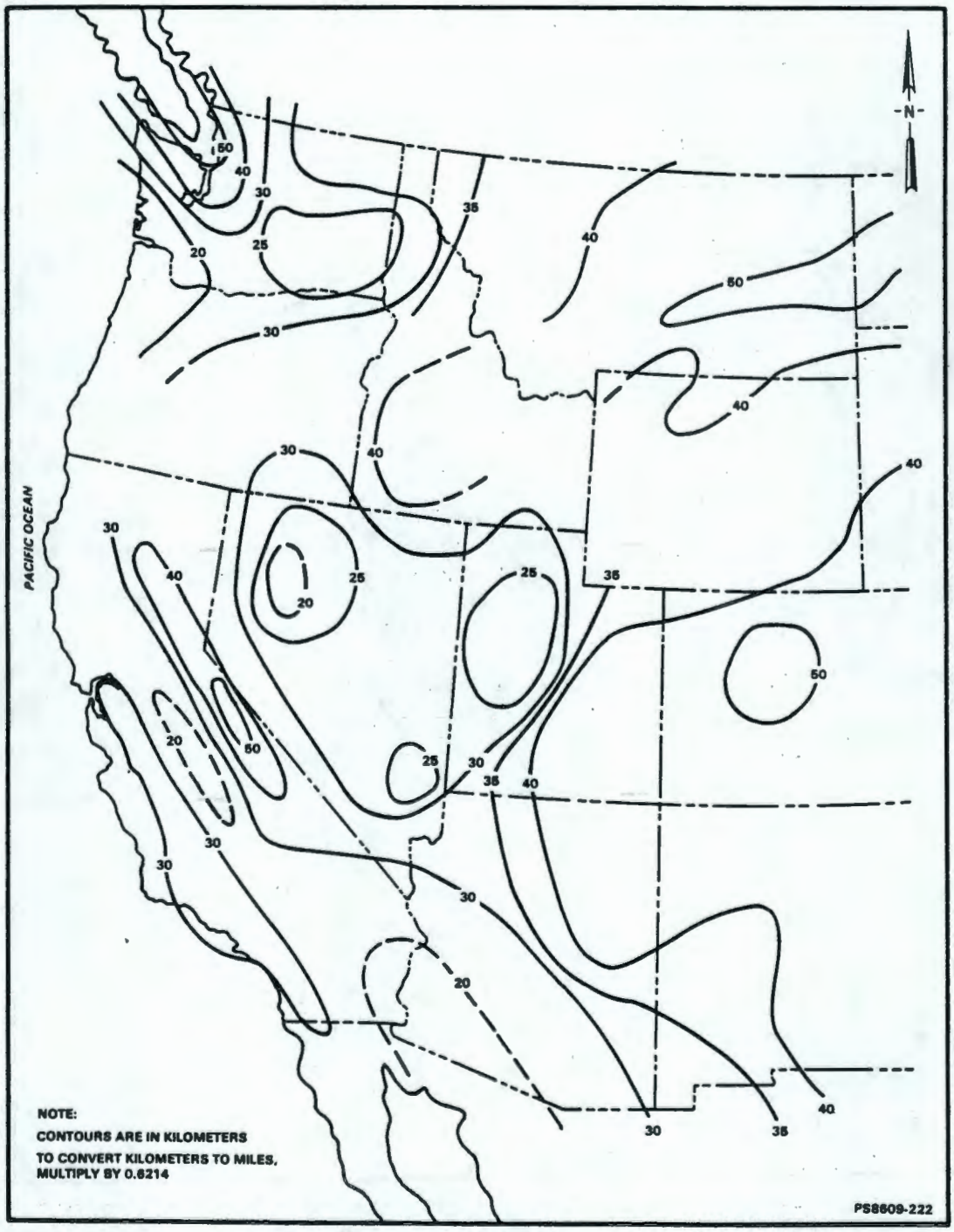

Figure 1.3-35. Isopach map of crustal thicknesses for the western United States (compiled from various sources by Smith, 1978).

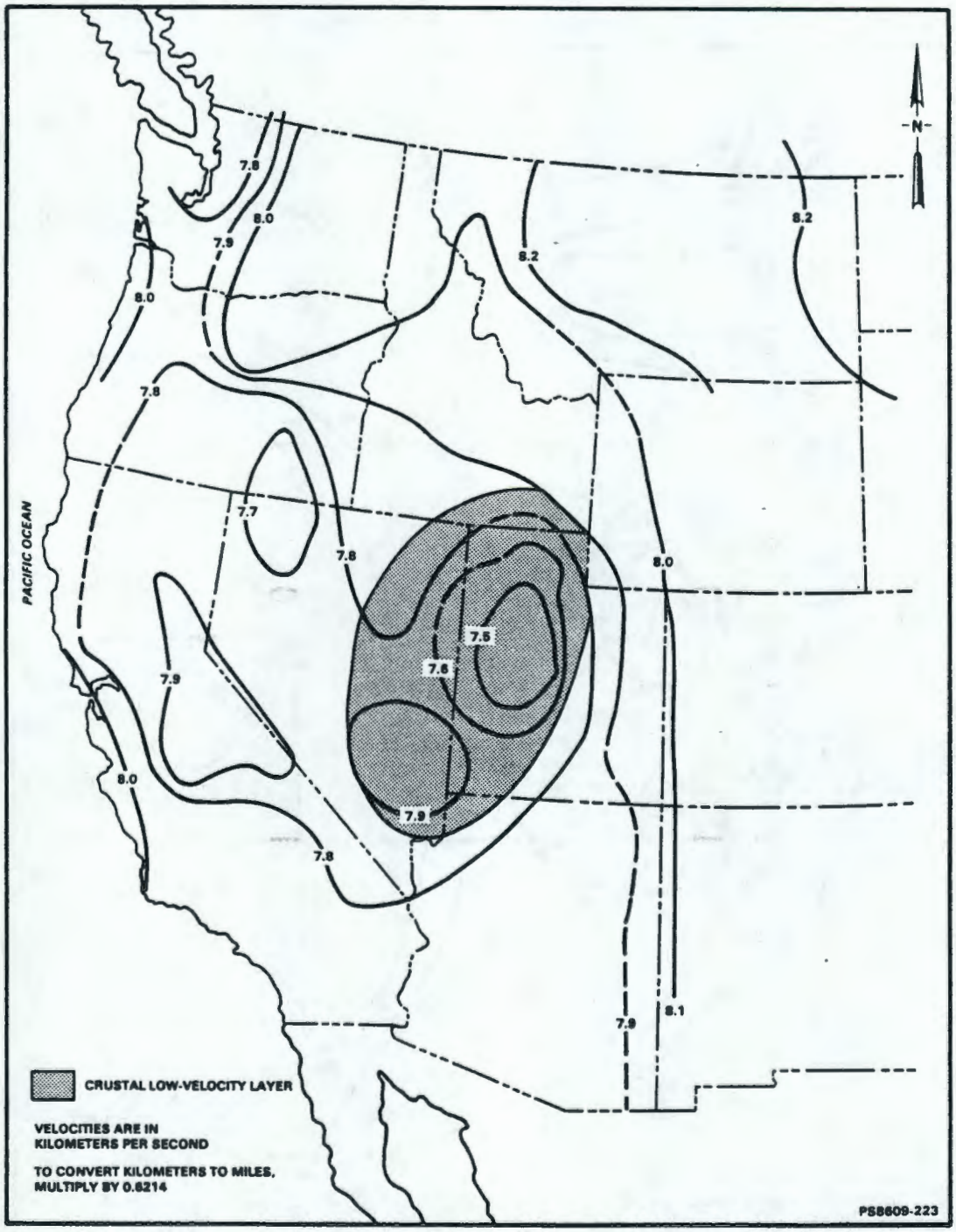

Figure 1.3-36. Map of upper mantle velocities immediately below the crust for the western United States (compiled from various sources by Smith, 1978).

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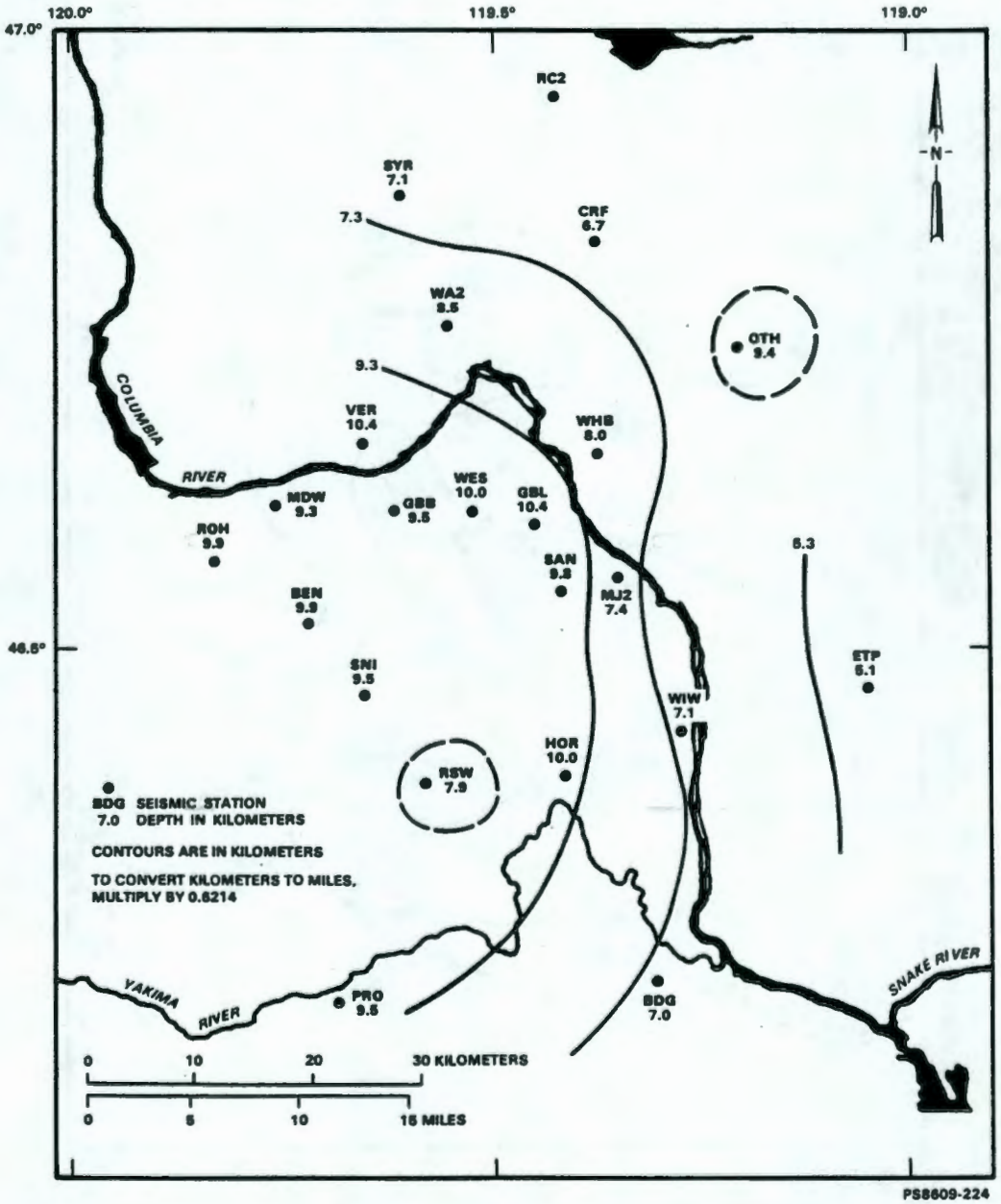

Figure 1.3-37. Depth to top of 6.0-km/s (3.7-mi/s) layer beneath the Pasco Basin (from Rohay and Malone, 1983). Dashed lines around stations RSW and OTH indicate inconsistent results.

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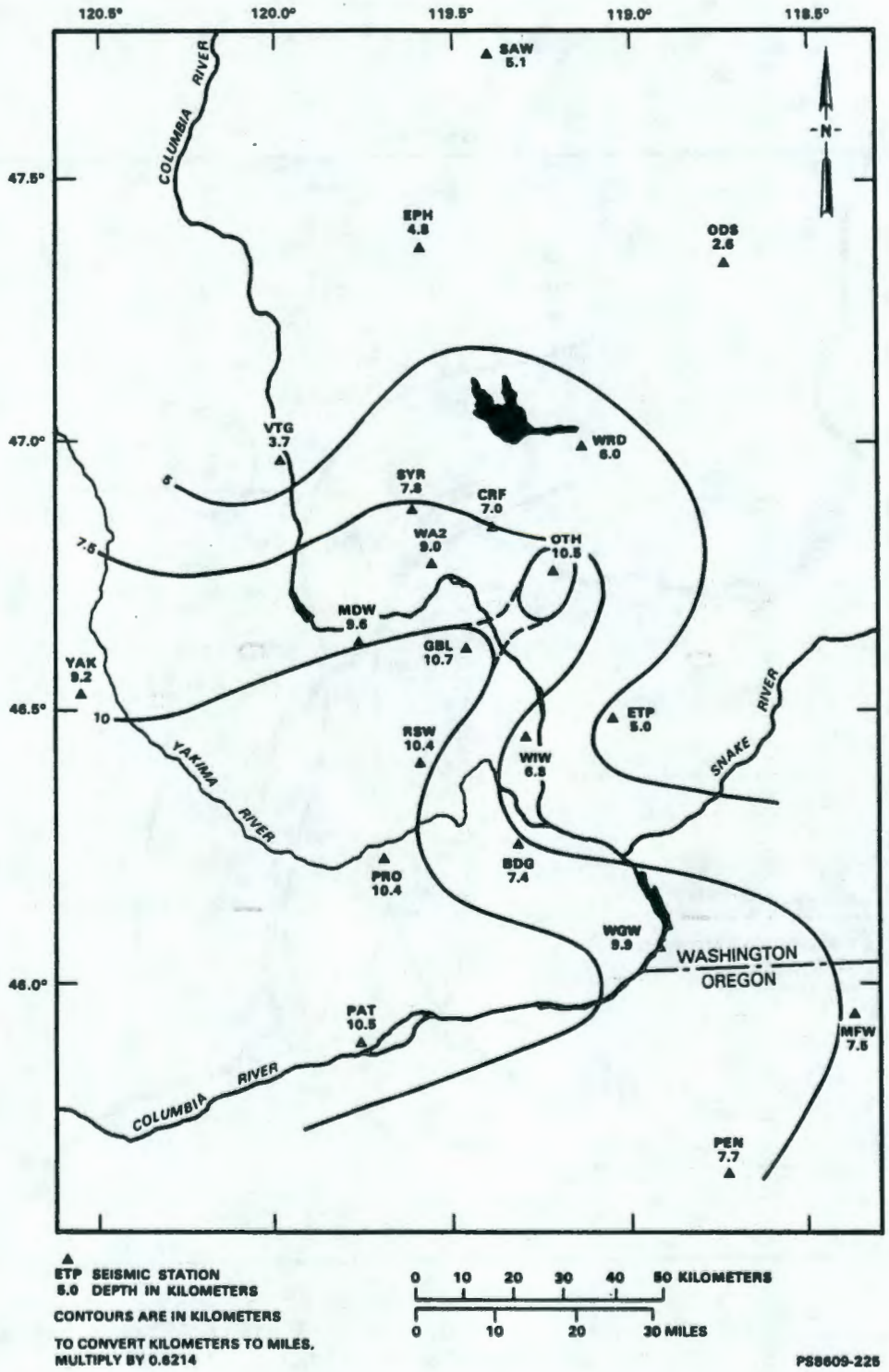

Figure 1.3-38. Variation of depth to top of 6.0-km/s (3.7-mi/s) layer in the southwestern section of the Columbia Plateau (Rohay and Malone, 1983).

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sufficient data to constrain this. A portion of these data recorded over the Pasco Basin also was inverted by Odegard and Mitchell (1987) using a single-ended refraction inversion program. The results of this inversion are shown in Figure 1.3-39. This inversion was consistent with analyses by Rohay and Malone (1983), except that a low-velocity zone was included and two basalt layers were found. The depth to basement for this inversion is nonunique, since the velocity of the low-velocity zone for the sediments (the 4.6-km/s (1.5×10^4-ft/s) layer) is assumed. The thickness of this 4.6-km/s layer is partially determined by the assumed velocity of this zone.

In 1984, a long refraction survey was conducted for the BWIP by the U.S. Geological Survey, the University of Washington, and the BWIP. Data were recorded along a 260-km (162-mi) transect from 8 points. The University of Washington and the BWIP recorded cross-line data from these shots with temporary seismograph stations. The University of Washington and the BWIP also recorded additional data using earthquake seismograph networks. Initial results from the long-line experiment were presented by Catchings et al. (1984) and are shown in Figure 1.3-40. (This profile was developed from the northeast-southwest line A-A' in Fig. 1.3-41.) These data agree with the previous work of Rohay and Malone (1983), showing the deep basement beneath the Hanford Site but show it to be somewhat deeper. In the Catchings et al. (1984) model, the basin does not extend as far to the south. The major discrepancy is between the Catchings et al. model, which has a 40-km- (25-mi-) thick crust with an 8.4-km/s (2.75×10^4 ft/s) upper mantle velocity, and the

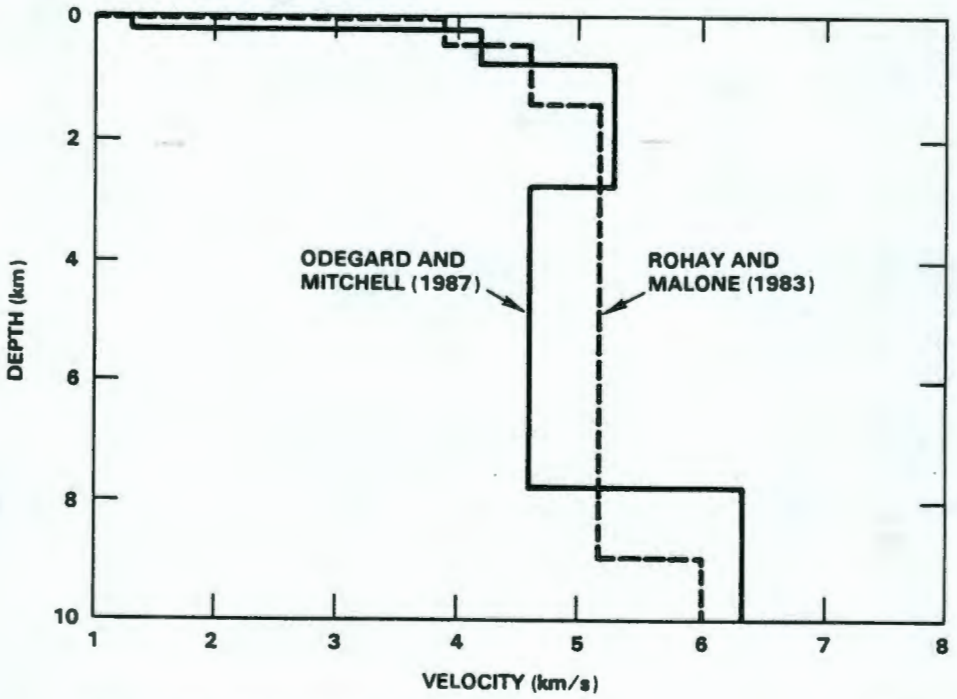

Figure 1.3-39. Upper crustal velocity structure models for the Pasco Basin (Odegard and Mitchell, 1987; Rohay and Malone, 1983).

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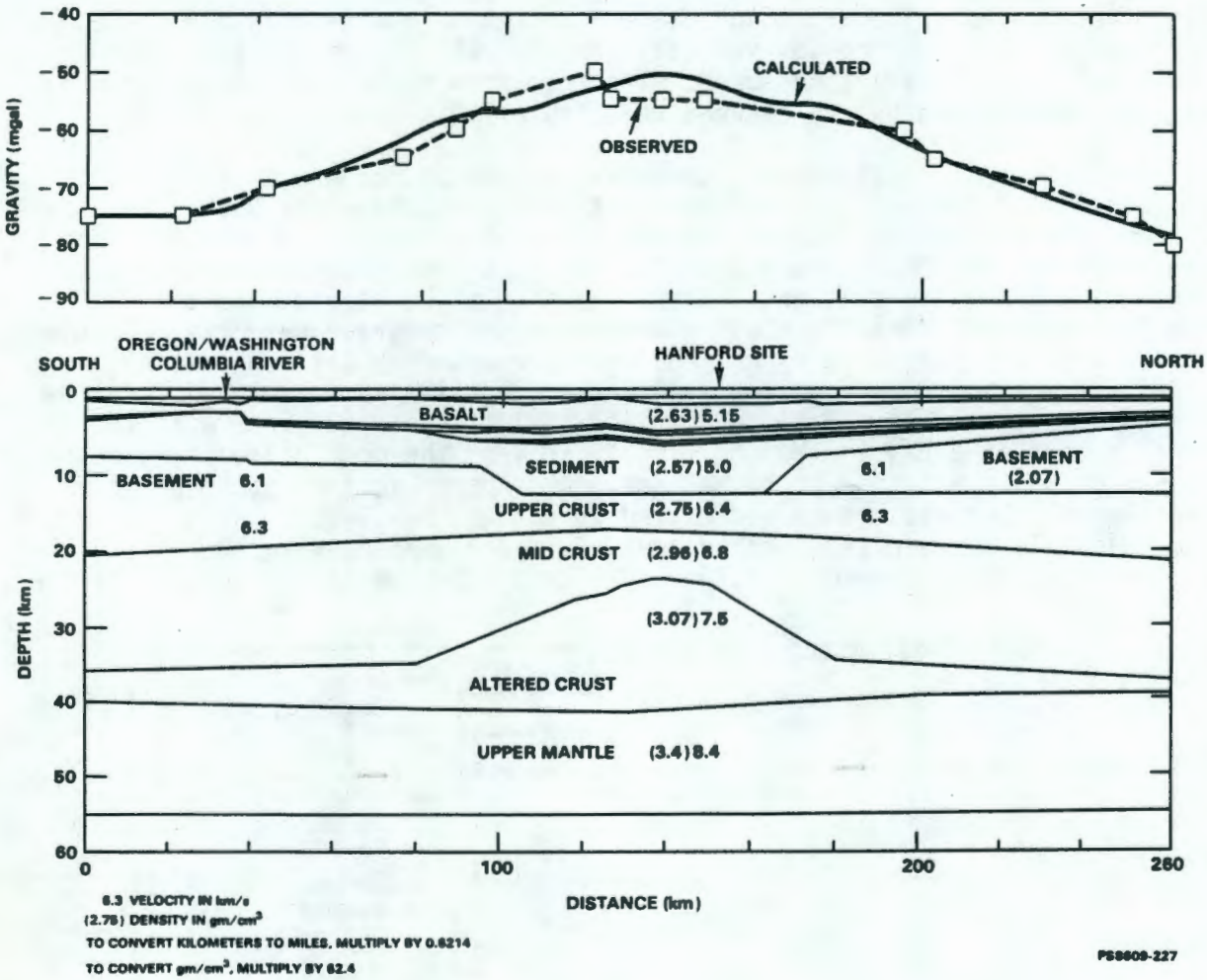

Figure 1.3-40. Velocity and density structure of the crust beneath the southwestern section of the Columbia Plateau (from Catchings et al., 1984). Velocities are in kilometers per second and densities (values in parentheses) are in grams per cubic centimeter. The upper part of the figure shows the fit of gravity calculated from the model to the observed gravity.

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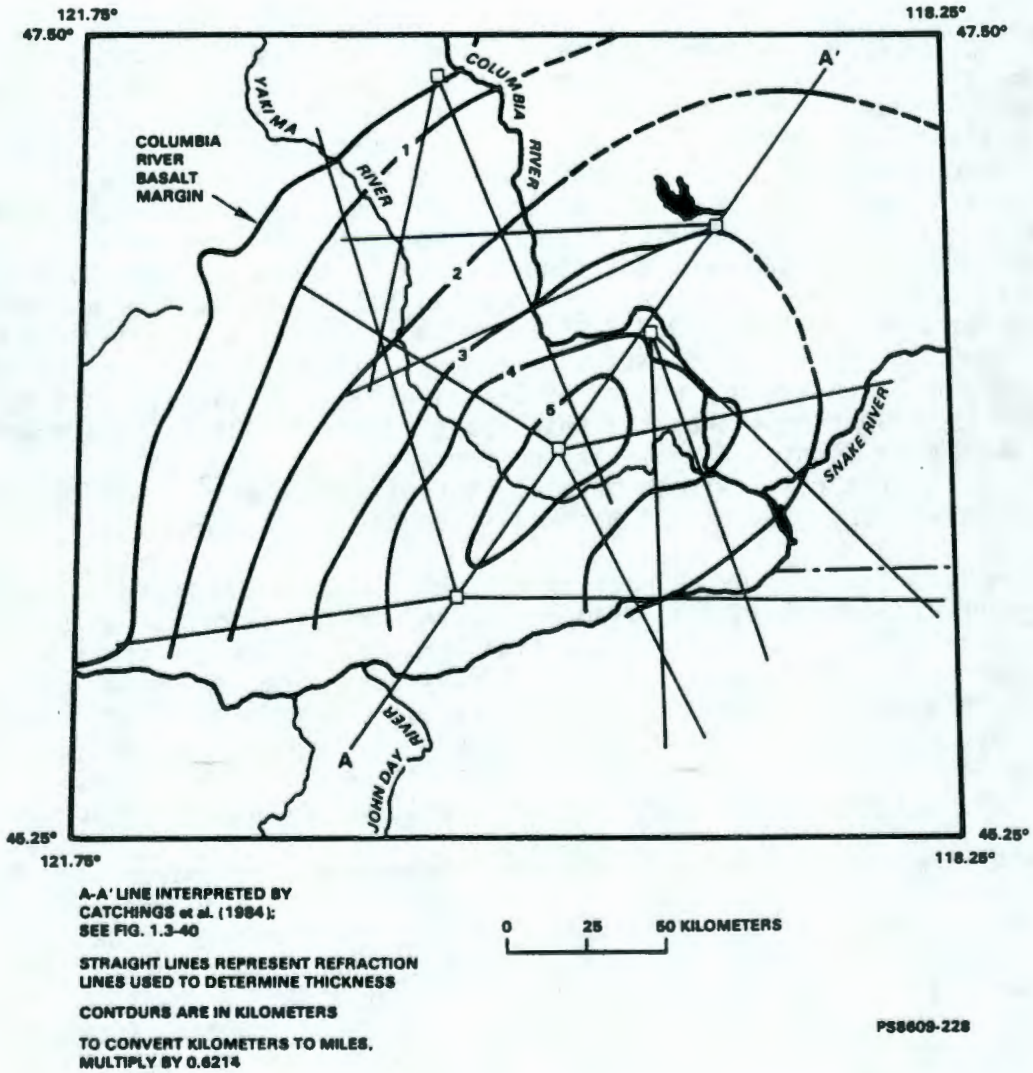

Figure 1.3-41. Isopach map showing thickness of basalt and supra-basalt sediments for the southwestern section of the Columbia Plateau (from Glover, 1985).

Hill (1972) model, which has a 25-km (16-mi) crust and a 7.9-km/s (2.6×10^4-ft/s) upper mantle. This may be due (Glover, 1985) to Hill's misinterpretation of data with an apparent velocity of 7.2 km/s (2.35×10^4-ft/s) as being propagated through the upper mantle. It also may be due to the lack of a more detailed interpretation incorporating intracrustal structures.

Using the off-line data recorded by the University of Washington and the BWIP, Glover (1985) used iterative ray tracing in laterally varying structures to determine the thickness of basalt and the depth to basement. Results of these analyses are shown in Figures 1.3-41 through 1.3-43. Figure 1.3-41 shows the thickness of basalts, including the surface sediment layer. Figure 1.3-42 shows the thickness of the sediment layer beneath the basalt. Figure 1.3-43 shows the depth to basement, which is the summation of the thicknesses from the two previous figures. The thickness of basalt and the depth to basement are in general agreement with the results from magneto-telluric surveys (Section 1.3.2.3.3) and with the results of Rohay and Malone (1983) described above. The data are, however, inconsistent with the rift model for the Pasco Basin proposed by Catchings et al. (1984). This is because one would expect that the thick part of the basalt and sediments would have a much more elongated shape if the depression were caused by incipient rifting. Glover's results seem more consistent with simple basin development caused, perhaps, by the loss of material from the upper mantle.

Time-term analysis of refracting arrivals from earthquakes recorded by seismograph stations have been used by several investigators to determine upper mantle velocities and relative time-term delays for the crust in the Washington area. McCollom and Crosson (1975) determined the upper mantle velocity to average 7.8 km/s (2.55×10^4 ft/s) in western Washington and to average 8.2 km/s (2.7×10^4 ft/s) in eastern Washington. Rohay (1982) analyzed data from refraction profiles to estimate upper mantle velocities of 7.8 to 7.9 km/s (2.55×10^4 to 2.6×10^4 ft/s) for the North Cascades.

Data from the BWIP refraction survey recorded by the University of Washington and the BWIP earthquake seismograph networks also were analyzed by Rohay et al. (1985). They used time-term analysis primarily to determine depth to basement. Results of this analysis are shown in Figure 1.3-44. These results are consistent with those of Glover (1985) and with Catchings et al. (1984) but do not include information on the thickness of the crust. In addition, this work gives a better picture of the regional variation in depth to basement. The results indicate that the depth to basement shallows to the southwest but may continue as a deeper feature to the northwest. This is along the general strike of the Cle Elum-Wallula disturbed zone.

Zervas and Crosson (1986) analyzed refraction data from earthquakes recorded in Washington using time-term analysis to estimate upper mantle velocities and crustal thickness variation. They found an average mantle velocity of 8.2 km/s (2.7×10^4 ft/s) and evidence for a 1° dip of the crust mantle boundary from eastern Washington to the Cascade Range. They also found evidence for anisotropy in the upper mantle, with the fastest velocities in

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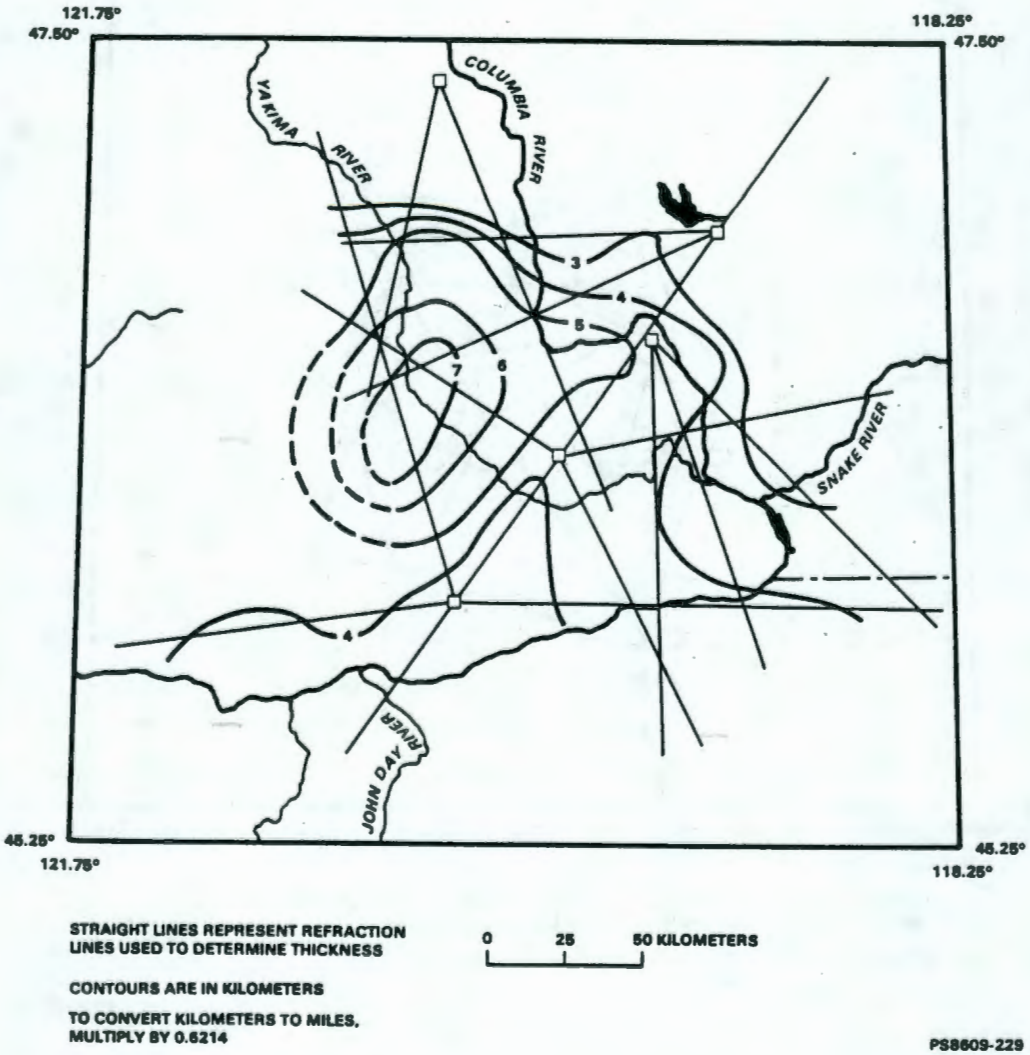

Figure 1.3-42. Isopach map of sediment thickness from base of basalt to top of crystalline basement (from Glover, 1985).

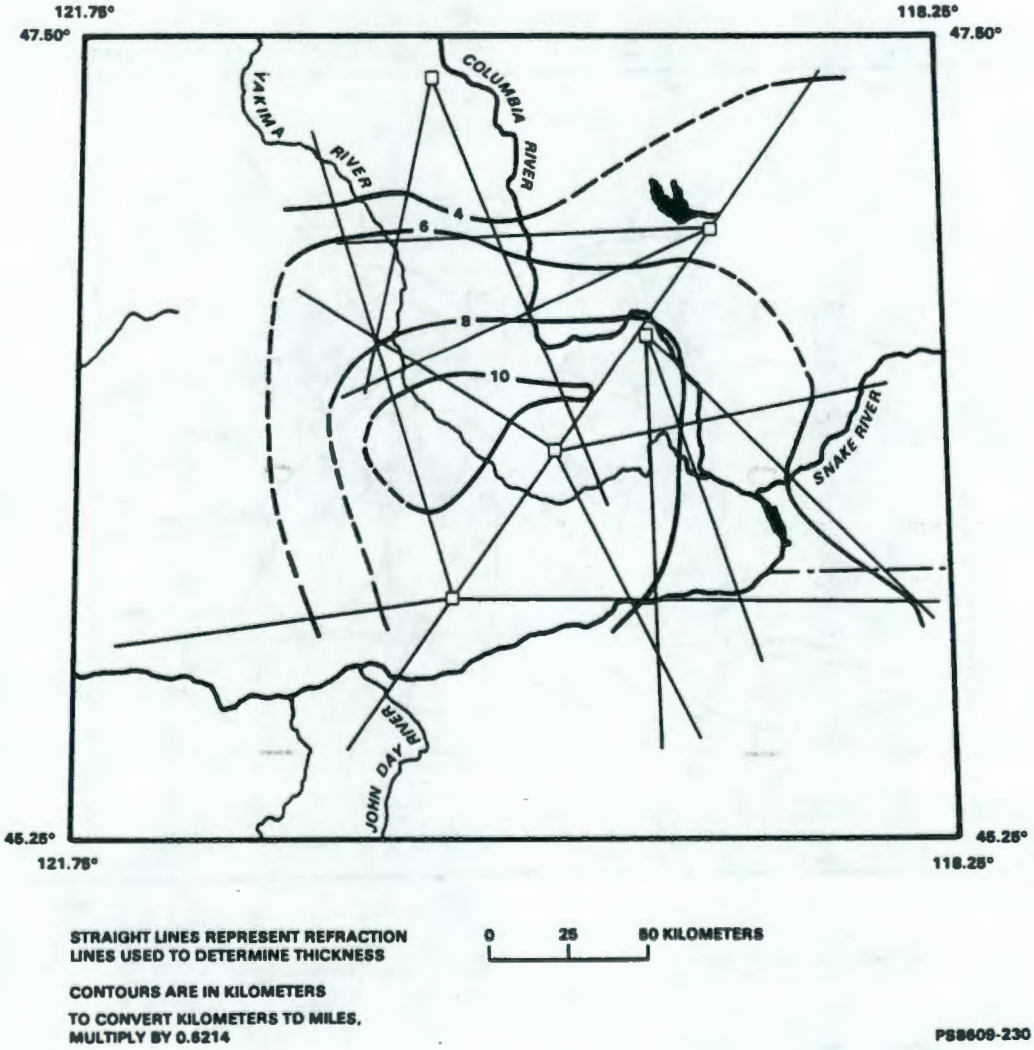

Figure 1.3-43. Contour map showing depth to top of crystalline basement below surface (from Glover, 1985).

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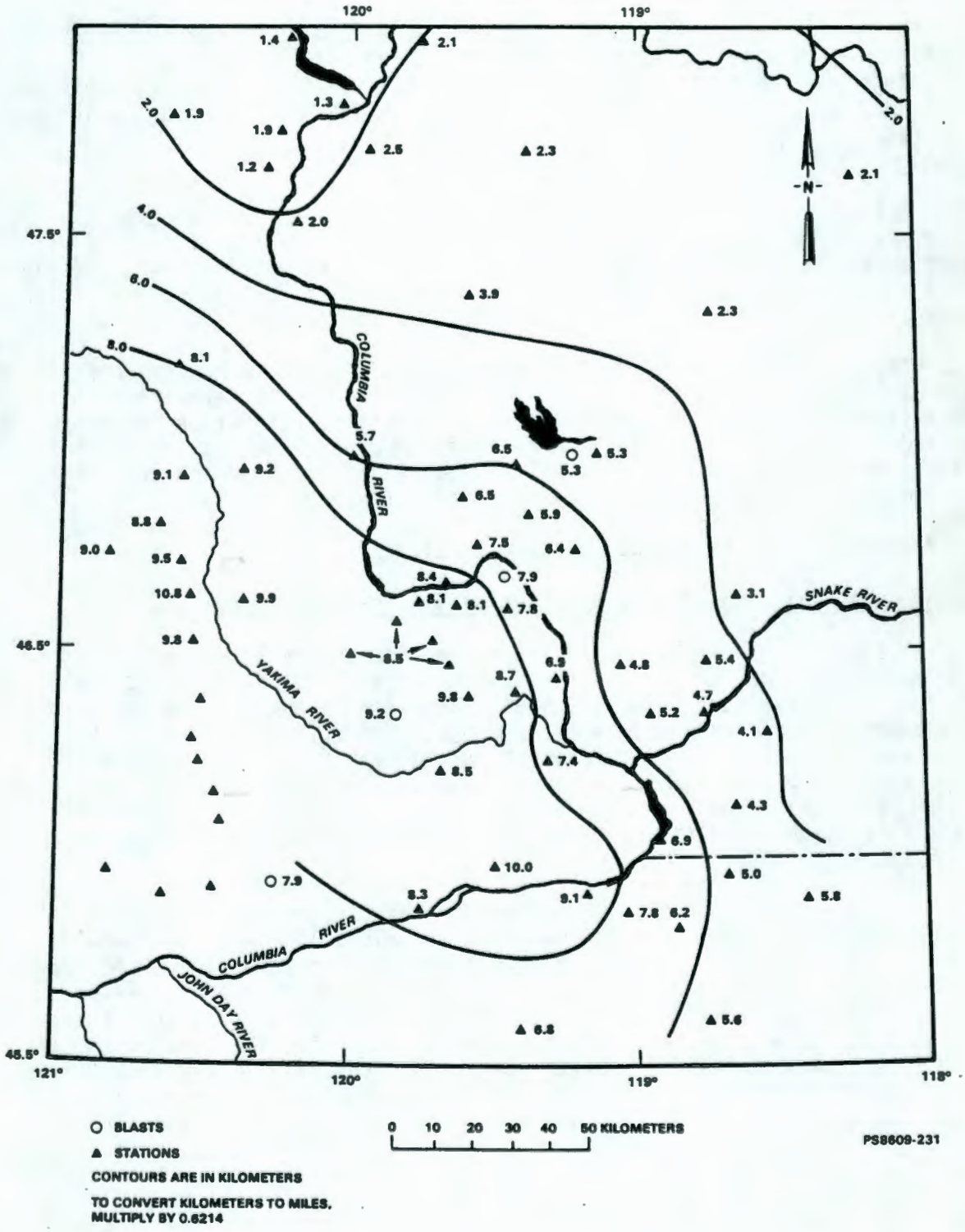

Figure 1.3-44. Contour map of depth from surface to crystalline basement (from Rohay et al., 1985).

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the northwest and southeast directions. These results do not support the unusually high velocities (8.4 km/s (2.75 x 10^4 ft/s)) shown by Catchings et al. (1984). The 8.4-km/s (2.75 x 10^4-ft/s) velocity could be revised if the crustal model were thinner or had a higher average velocity.

Local refraction surveys

Active seismic surveys on the Hanford Site have been conducted intermittently since 1959. These surveys consisted mainly of short (less than 1 km (0.6 mi)) seismic refraction profiles. They were conducted primarily for site investigations in support of engineering and foundation studies. Other surveys were conducted to test the method and for general exploration.

In 1959, a small test of the method was conducted by Raymond and Ratcliffe (1959) in support of defense radioactive waste management activities. In 1963, a development test of seismic reflection and refraction methods was conducted to test the feasibility of determining the depth to the basalt beneath the Hanford Site. Donaldson (1963) recommended that drilling and seismic refraction be combined to obtain the required data. Additional work was conducted for the Fast Flux Test Facility for foundation studies and to determine depth to bedrock (Blume, 1971).

Washington Public Power Supply System seismic refraction surveys

A significant amount of seismic refraction surveying was conducted for the Washington Public Power Supply System Nuclear Project 2 (WPPSS, 1981) and Nuclear Projects 1 and 4 (WPPSS, 1986), and for the Puget Sound Power and Light Company Skagit/Hanford Nuclear Project (PSPL, 1982). Over 50 km (31 mi) of seismic refraction lines were shot for Nuclear Project 2 (WPPSS 1981, Appendix 2 5D). Some of these lines are shown in Figure 1.3-45. Most of these data were either low resolution for depth-to-bedrock determinations or relatively high resolution for shallow studies to determine overburden material velocities.

The best general purpose data from the Washington Public Power Supply System Nuclear Project 2 survey was obtained along line 1 in the Hanford Road survey area (see Fig. 1.3-45), which was designed to investigate the possible extension of Yakima Ridge. The surface densities of shot and receiver locations were sufficient to give a somewhat detailed picture of not only the top of basalt, but the suprabasalt sediments as well. The results of this survey are shown in Figure 1.3-46. Because of the nature of the sediments and top-of-basalt velocity structures, the contractor-estimated depth errors of approximately 6 m (20 ft) seem to be somewhat optimistic. A more reasonable estimate might be 10% of the depth or velocity, approximately 15 to 20 m (49 to 66 ft) for top of basalt. The ability of the seismic refraction method to detect a fault of the size (6 m (20 ft)) mentioned in the report also should be questioned, because the seismic refraction method averages out variations in the refracting horizon.

Nineteen seismic refraction lines were run for siting the Washington Public Power Supply System Nuclear Projects 1 and 4 (WPPSS, 1986). Four of these lines were low resolution with large shot spacings and determined depth

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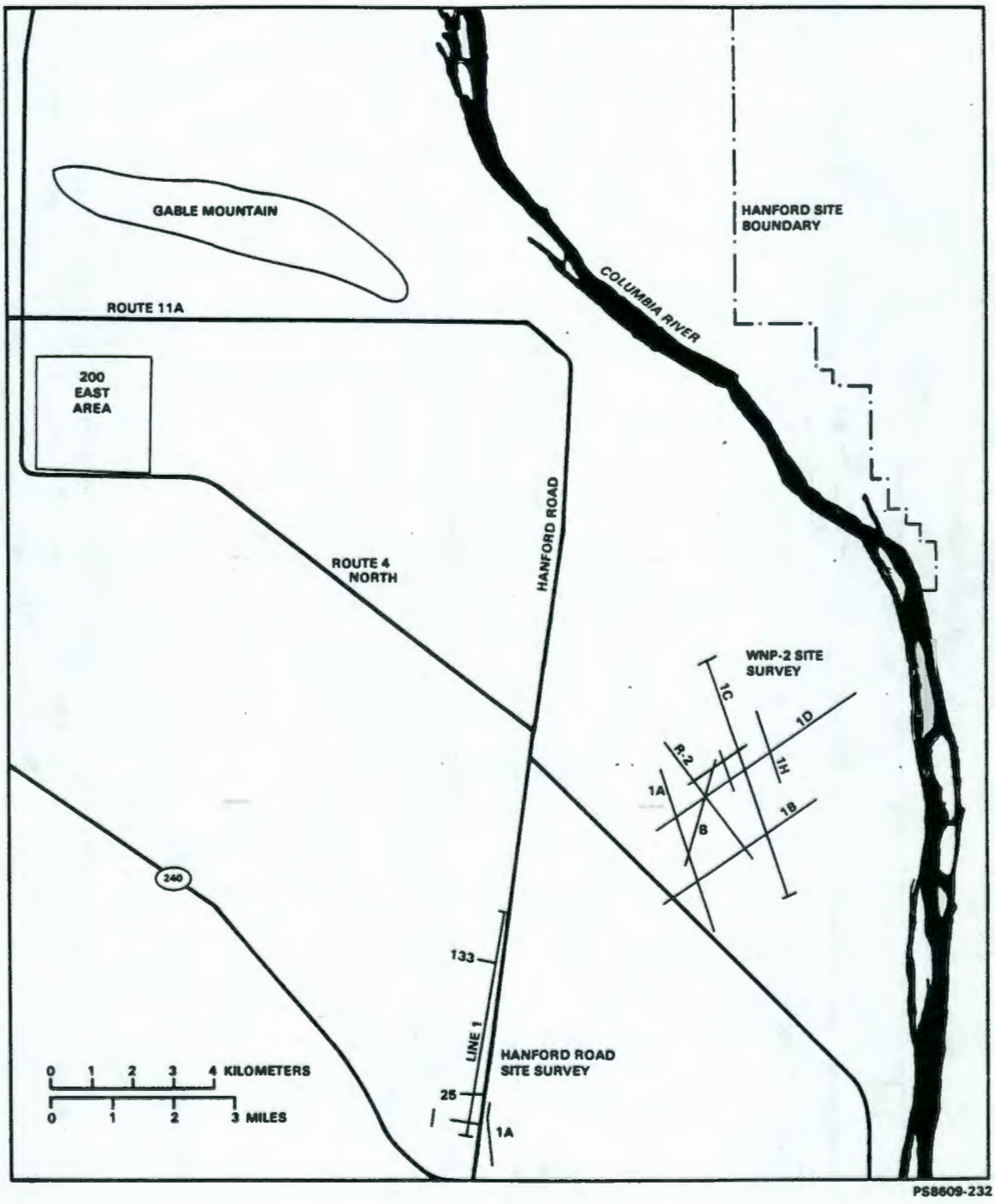

Figure 1.3-45. Locations of seismic refraction lines shot for the Washington Public Power Supply System Nuclear Project 2 (WPPSS, 1981, App. 2.5D).

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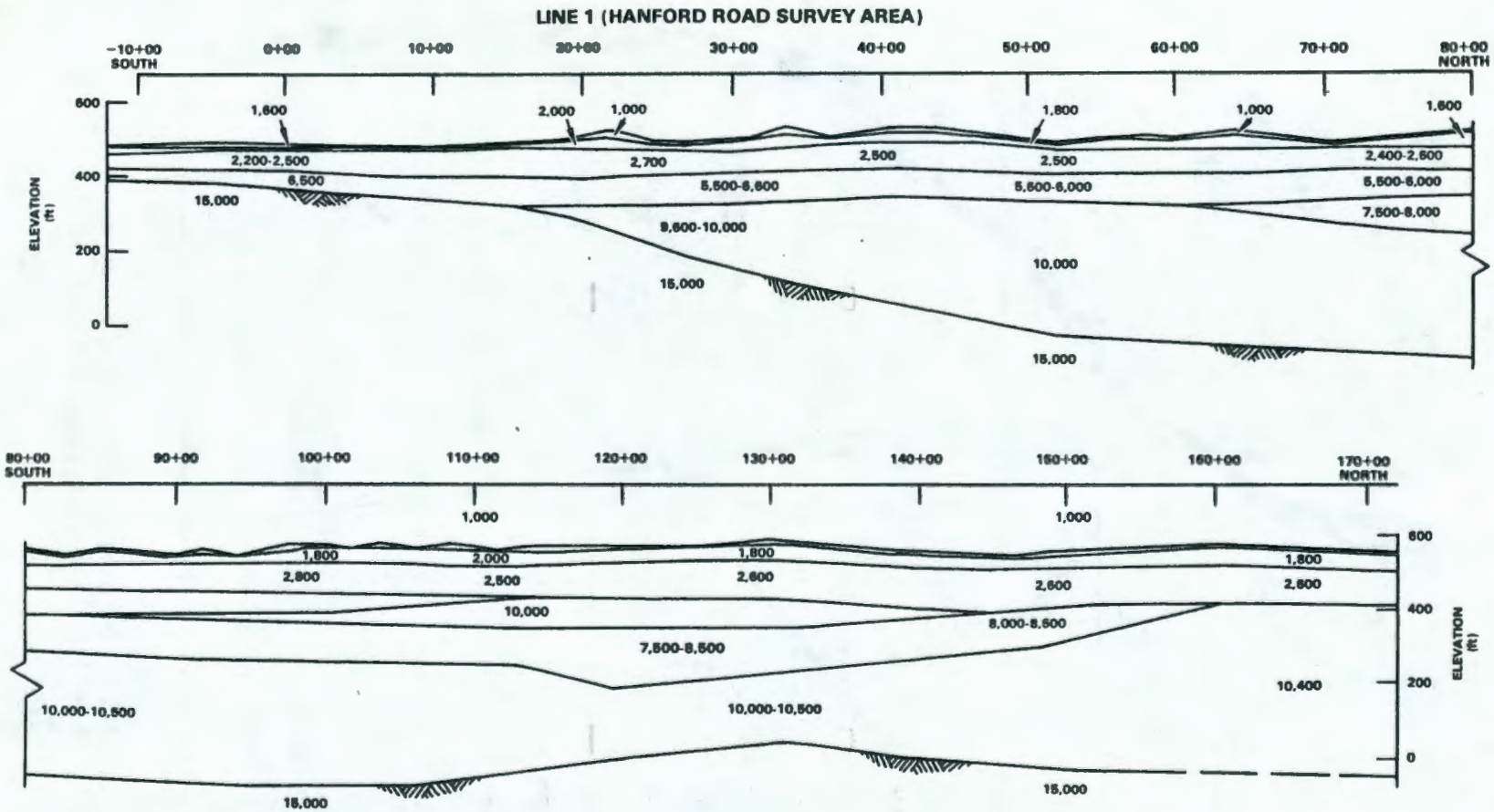

LAYERS ARE LABELED WITH COMPRESSIONAL VELOCITIES IN FEET PER SECOND

TO CONVERT FEET TO METERS, MULTIPLY BY 0.3048

PS8609-233

Figure 1.3-46. Results of seismic refraction survey along Line 1 and crosslines of the Hanford Road survey area (from WPPSS, 1981, App. 2.5D). Elevations are above mean sea level. See Figure 1.3-45 for location of Line 1 and crosslines. (sheet 1 of 2)

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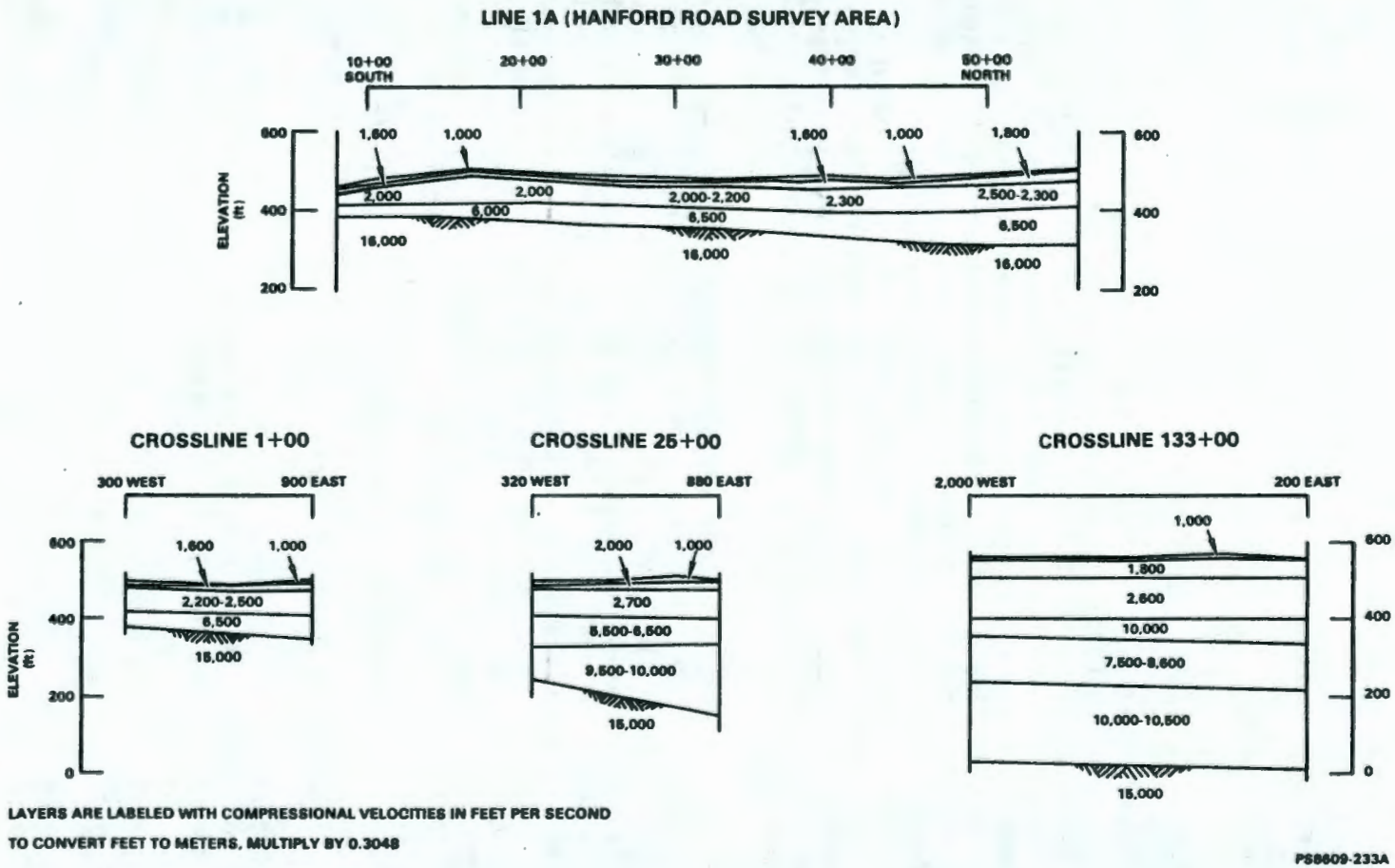

Figure 1.3-46. Results of seismic refraction survey along Line 1 and crosslines of the Hanford Road survey area (from WPPSS, 1981, App. 2.5D). Elevations are above mean sea level. See Figure 1.3-45 for location of Line 1 and crosslines. (sheet 2 of 2)

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to bedrock. No sediment or basalt velocity values were given on these sections. No significant features were observed in the bedrock. The 4 low-resolution lines and the other 15 lines were used to determine the velocity structure of the sediments. A high-velocity refractor was observed in the Ringold Formation, but no anomalous features were observed. This high-velocity refractor apparently corresponds to the upper-middle Ringold Formation found in the BWIP survey discussed below.

Skagit/Hanford seismic refraction surveys

The Skagit/Hanford Nuclear Project conducted over 115 km (71 mi) of seismic refraction surveys to determine the velocity structure of the suprabasalt sediments, the depth to top of basalt, and the geologic character of structural features in the area. Except for a few lines in the area of the proposed reference repository location (south of Gable Mountain), most of the lines were used to investigate the Gable Mountain structure and its extensions (PSPL, 1982). A survey, comprising 30 refraction lines, was conducted on a portion of Gable Mountain to investigate a northeast-trending fault reported by Fecht (1978) and a possible pull-apart feature in the same location. The fault could not be traced effectively with the seismic lines, but the seismic lines were subsequently used to plan a trenching survey. The pull-apart feature was hypothesized to be a gravity slide, but was found to be a fractured and weathered zone.

Other lines in the Skagit/Hanford Nuclear Project survey were used to examine the May Junction linear, which was originally defined in BWIP gravity and magnetic data (Myers/Price et al., 1979). This linear is a north-south-trending disturbance in gravity and magnetic features between Gable Mountain and the Southeast anticline described below. It also appears to terminate the DB-10 ridge/anticline described below. The refraction lines, series 7 and 8 in Figure 1.3-47, did not indicate that this feature was fault controlled. As indicated by the central Gable Mountain survey, it is, however, difficult for the seismic refraction method to delineate buried fault features. The seismic reflection data on line FY 79-3 near refraction line 8, described in Section 1.3.2.2.3.5, did show a possible fault feature, which is indicated in Figure 1.3-48, at vibrator point 340. The trend of this fault feature is not known, however, because there are no parallel reflection lines; consequently, its association with the May Junction linear is unknown.

Seismic refraction lines to the northwest of the May Junction linear lines were used to investigate two faults identified by Myers/Price et al. (1979) in borehole DB-10 (see Fig. 1.3-47). These lines, together with other boreholes, showed that the upper fault had a north-south strike with a 32° dip. The lower fault was not encountered in the other boreholes. This would seem to require that it have a northwest-southeast strike. The refraction lines also confirmed a buried anticline that is in line with the west anticline of Gable Mountain. This anticline would be parallel to the lower fault strike. The refraction data, as expected, were unable to confirm the existence of the fault features shown in Figure 1.3-49 (from Myers/Price et al., 1979). The location of these features correspond to the sides of the buried anticline, and the feature at vibrator point 435 could correspond to the lower fault found in borehole DB-10.

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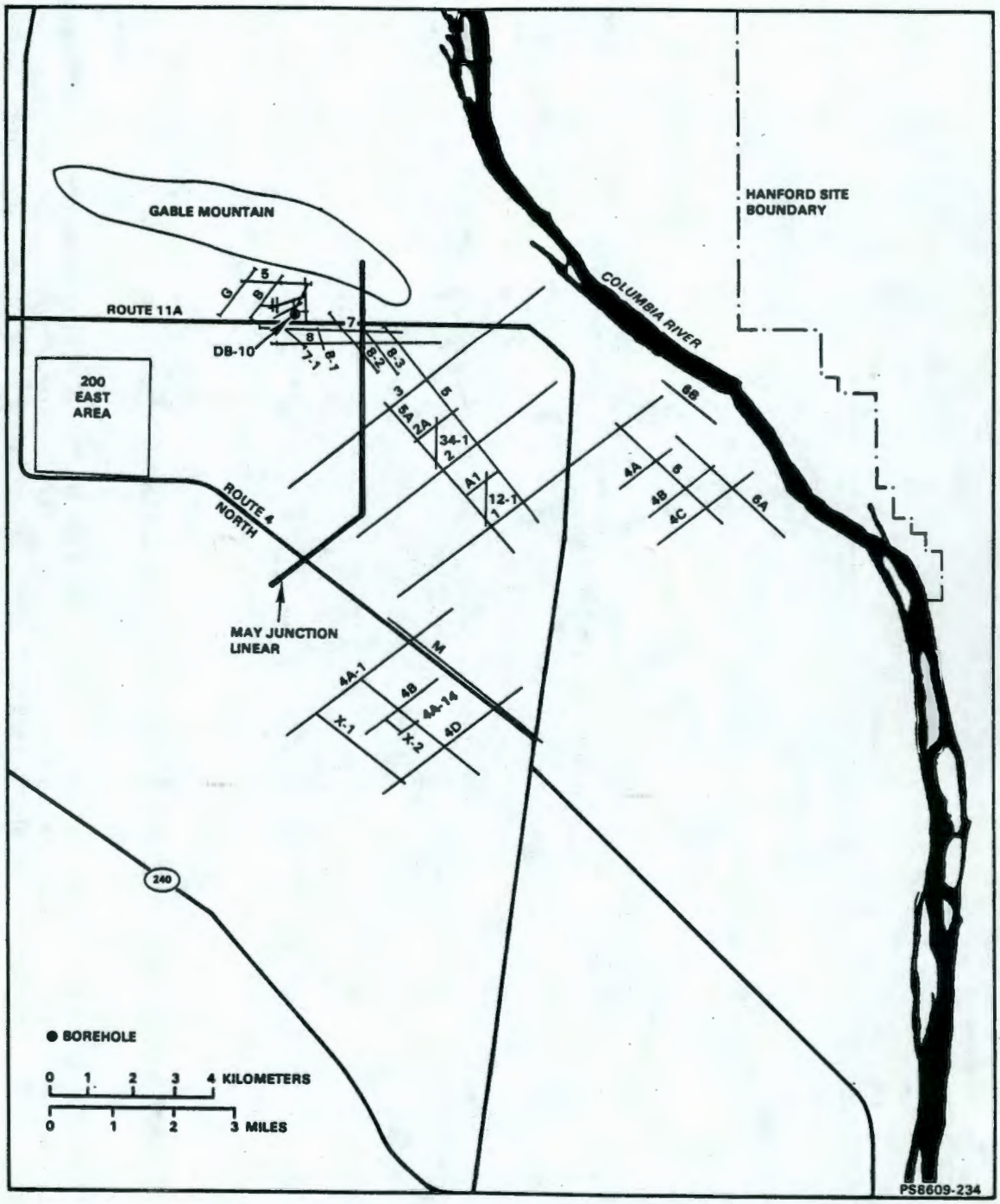

Figure 1.3-47. Location of Skagit/Hanford Nuclear Project seismic refraction survey lines (from PSPL, 1982).

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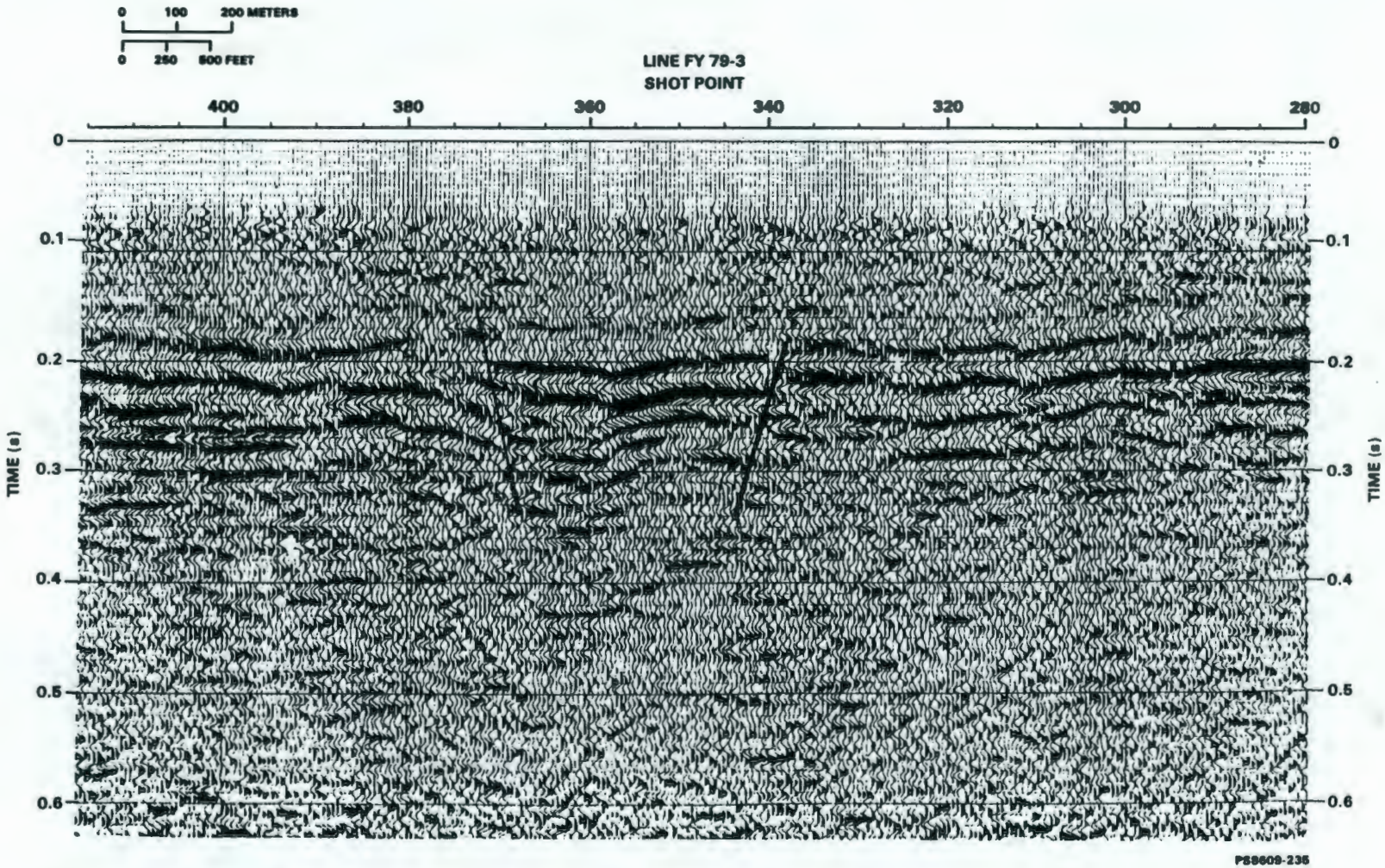

Figure 1.3-48. Seismic reflection line crossing location of May Junction linear from the Basalt Waste Isolation Project seismic reflection survey (SSC, 1979). See FIgure 1.3-54 for location of line FY 79-3. The feature at shot point 340 may be associated with the May Junction linear.

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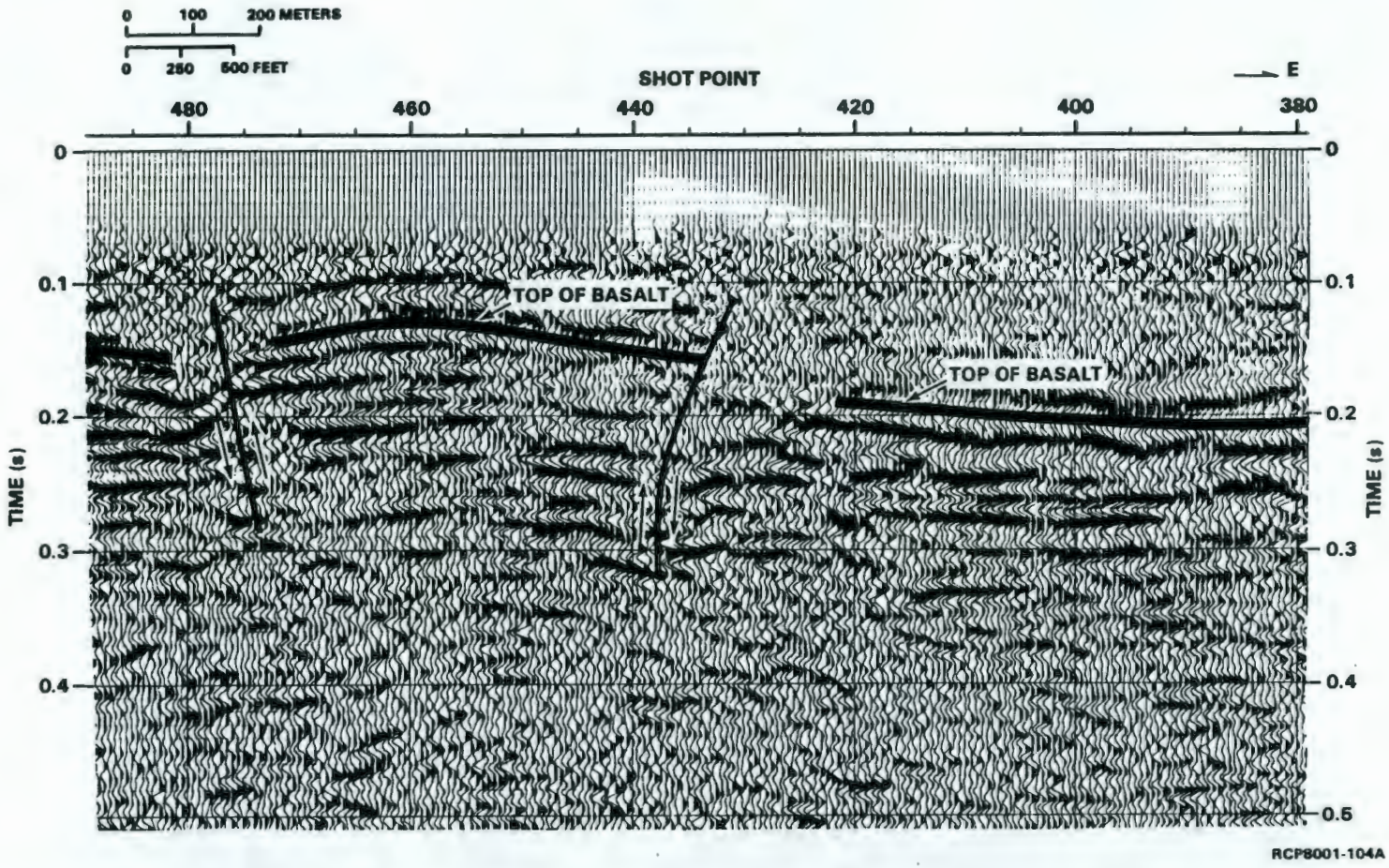

Figure 1.3-49. Seismic relection line crossing location of the borehole DB-10 ridge/anticline from the Basalt Waste Isolation Project reflection survey (SSC, 1979).

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Refraction-line series 1 through 6 was used to investigate the Southeast anticline. The top-of-basalt contours from these data show a linear anticlinal feature that appears to be an extension of the Gable Mountain anticline. These anticlines separate areas of sediments with a high-velocity interior layer located in the southwest from areas without this layer located to the northeast. This layer is discussed in detail in Section 1.3.2.2.3.6.

Basalt Waste Isolation Project seismic refraction surveys

Refraction surveys were conducted for the BWIP by Seismograph Service Corporation. Data were collected over eight lines with a total length of 32 km (20 mi) in the vicinity of the reference repository location, as shown in Figure 1.3-50. A low-powered energy source, the Betsy Seisgun (trademark of Mapco, Inc.), was used with 36 shots usually detonated at each shot point. The resulting data do not reveal penetration to the top of the basalt except in certain areas.

The initial interpretation of the data was made by Weston (1982). The interpretation consisted of cross sections of the velocity structure and static correction tables for a 168-m (550-ft) datum above mean sea level. These static data were used in subsequent reflection processing (Berkman, 1984).

A more detailed analysis of the refraction data along line 15 is presented in Mitchell and Odegard (1984) and Odegard and Mitchell (1987). They constructed a velocity-versus-depth section for this line and related it to lithology, using borehole data as shown in Figure 1.3-51. The interpretation of the data also incorporated the vertical seismic profiling data, which are discussed in Section 1.3.2.2.3.6. A comparison was made between the velocity model from the vertical seismic profiling data from borehole RRL-2 and an average of the seismic refraction profiles located around this borehole. The lithologic and stratigraphic interpretation of the borehole core superimposed on the average refraction and vertical seismic profiling velocity data is shown in Figure 1.3-52.

The velocity data have resulted in the middle Ringold unit being subdivided into upper and lower units. (These data also are consistent with the Skagit/Hanford Nuclear Project data (PSPL, 1982, Fig. 2L-2G)). The striking feature of the section shown in Figure 1.3-51 is the relatively large discontinuities in the velocity contours in the middle Ringold. Erosion of the middle Ringold unit, known to exist in the area, appears to be the cause of these discontinuities, although they may be the result of deformation by faulting.

Summary of results

The results to date of the local seismic refraction surveys have been the determination of depths to top of basalt and the delineation of the structure and stratigraphy of the suprabasalt sediments. The results of these surveys have assisted in better interpretations of geologic problems. In addition, they have allowed investigators to extend these solutions into areas

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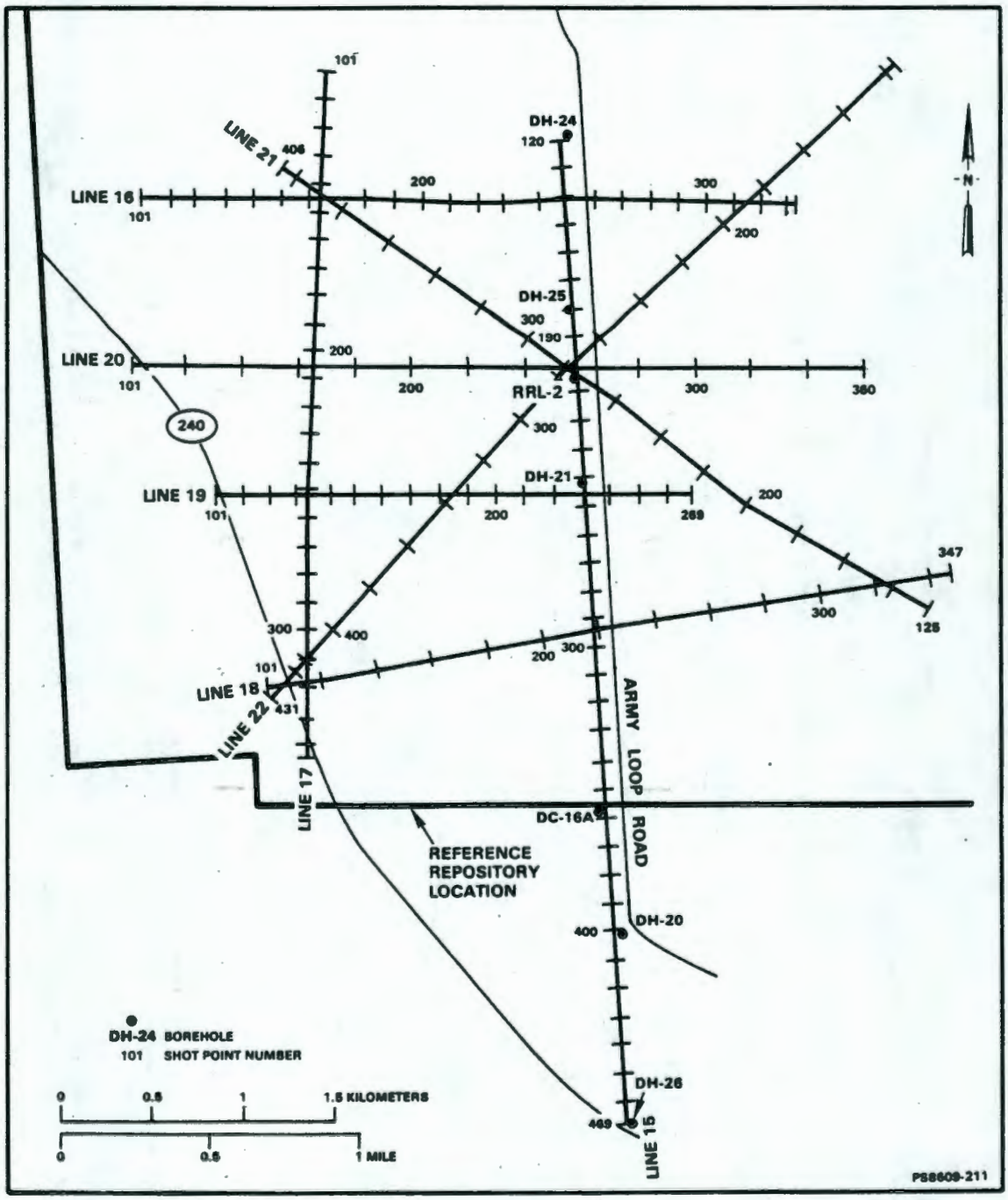

Figure 1.3-50. Location map for refraction lines shot during the Weston geophysical survey (Weston, 1982).

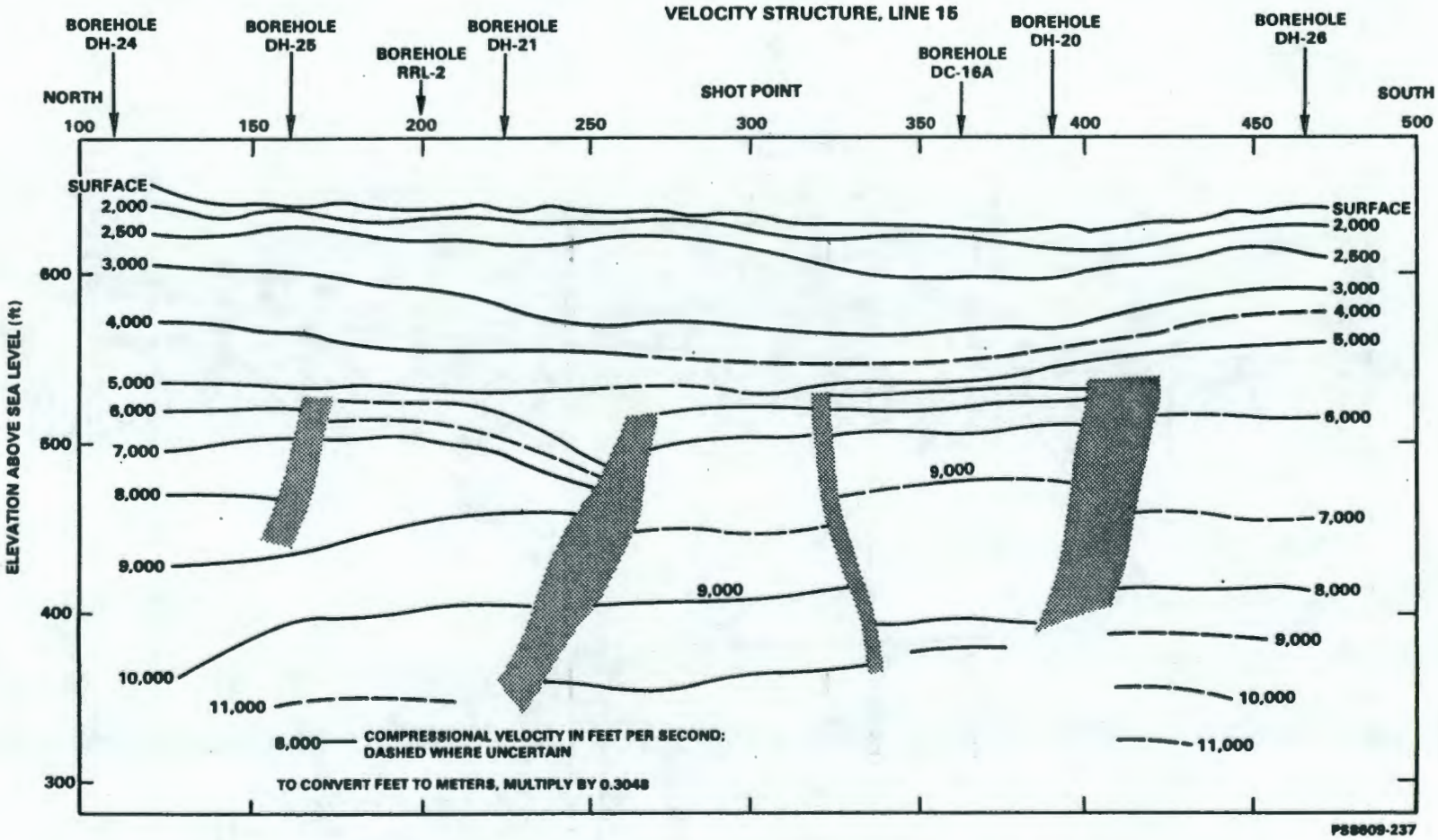

Figure 1.3-51. Interpreted section for Line 15 of the Basalt Waste Isolation Project seismic refraction survey (from Odegard and Mitchell, 1987). See Figure 1.3-50 for location of Line 15.

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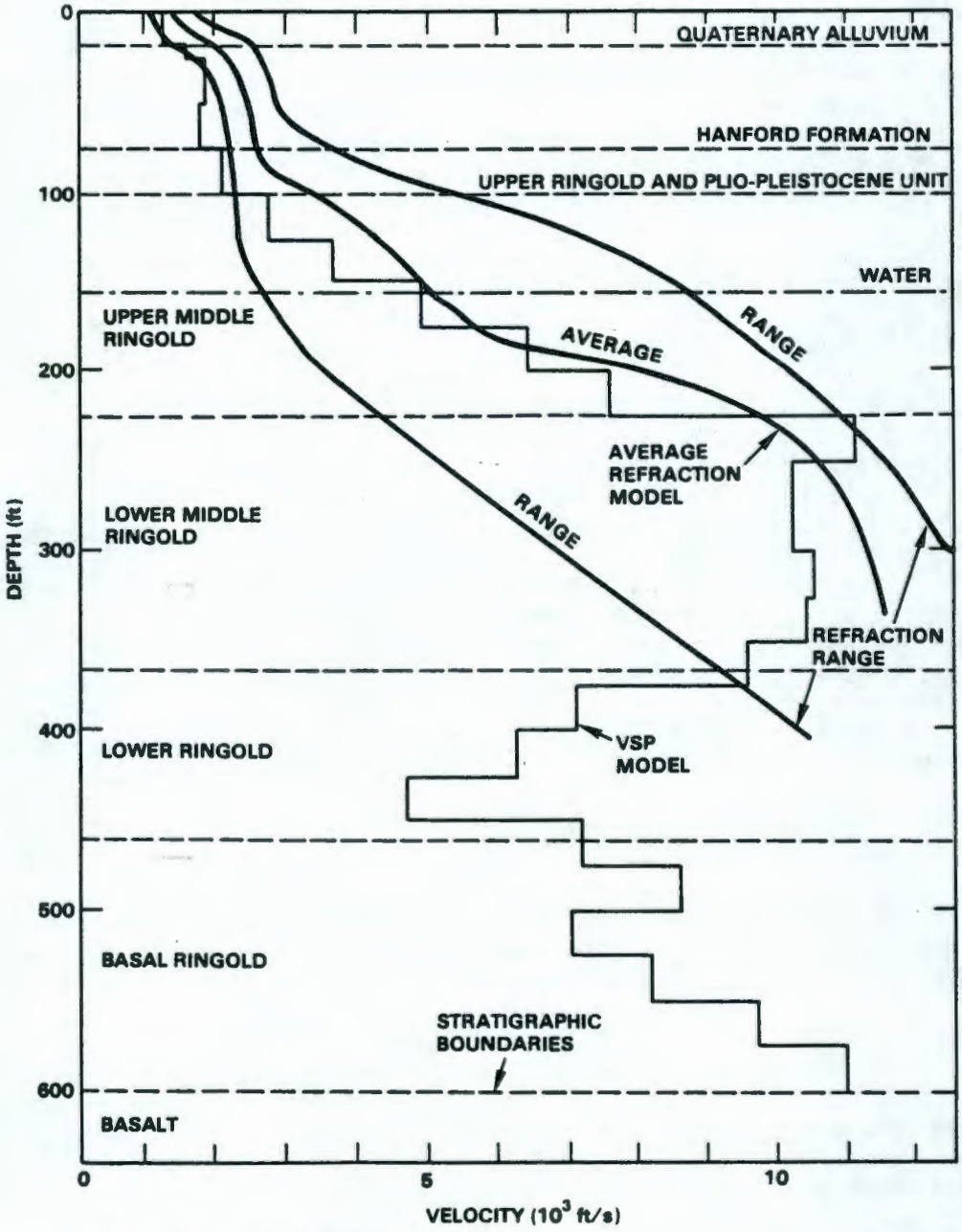

Figure 1.3-52. Average refraction and vertical seismic profiling velocity models associated with the stratigraphic section at borehole RRL-2 (from Odegard and Mitchell, 1987).

9 2 1 2 5 0 2 0 6 4 9

unavailable to direct geologic investigation. Several of these investigations involve the use of top-of-basalt determinations for structural problem resolution.

The high-velocity layer associated with the middle Ringold sedimentary unit is a distinctive feature of the sediments in the area of the reference repository location. It appears to be found throughout much of the Hanford Site. Based on refraction and reflection surveys, the high-velocity layer does not appear to exist north of the Umtanum Ridge-Gable Mountain structure and its extension, probably due to erosion in that area. The layer also has been eroded, partially or completely, in certain areas south of the Umtanum Ridge-Gable Mountain structure. These erosional features result in statics problems in seismic processing. These statics shifts may, in some cases, result in the interpretation of the resultant discontinuities in seismic sections as faults or disturbed areas. These problems will be investigated further during site characterization.

Sediments with velocities as high as those in the middle Ringold Formation are usually found only at much greater depths. Because these high-velocity sediments overlay sediments with lower velocities, the sediment structure and stratigraphy in the low-velocity zone cannot be determined with the seismic refraction method. In fact, the exact location of the top of basalt may be difficult to determine. This is because the actual top of basalt may be severely weathered and brecciated, as mentioned in the borehole analysis discussed in the Preliminary Safety Analysis Report for the Skagit/Hanford Nuclear Project (PSPL, 1982). That is why many of the reports mention the depth to high-velocity basalt, and why some of the borehole determinations differ from those of the refraction survey.

1.3.2.2.3.5 Seismic reflection surveys

The purpose of the seismic reflection surveys conducted by the BWIP has been to delineate the stratigraphy of sediment and basalt layers within the Hanford Site and to determine the presence and extent of anomalous features with potential structural significance.

Seismic reflection data are typically used to interpolate or extrapolate lithology and stratigraphy among borehole and outcrop data. This requires careful integration of geology and borehole data with the seismic reflection data. The integration of the seismic reflection data with borehole data, other geophysical survey data, and geologic data will be a primary objective during site characterization (Sections 8.3.1.2.3.3.1 and 8.3.1.2.3.3.4).

Several seismic surveys have been conducted on the Hanford Site since 1963. Until 1979 these surveys consisted of testing the method. The 1963 survey was a developmental test of seismic reflection and refraction methods to determine the depth to basalt beneath the Hanford Site. The tests and results are discussed in Donaldson (1963). Seismic reflection was not successful because of the limited processing capabilities available at that time, coupled with the difficult seismic characteristics of the area.

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Surveys conducted from 1978 through 1980

Testing of seismic reflection techniques was conducted by the BWIP in 1978 to determine the ability of the method to penetrate the basalt to the Umtanum flow of the Grande Ronde Basalt. A report of the test results is given in Seismograph Service Corporation (SSC, 1978) and Heineck and Beggs (1978). The data, as shown in Figure 1.3-53, showed good penetration with reasonably coherent energy down to approximately 0.5 s. Below this, there appears to be energy at scattered locations penetrating to at least 1.0 s. Also apparent are problems due to statics and off-line scattering. A section located just to the northeast of Gable Mountain shows the basalt layers ramping up as the line approaches the mountain.

Because the results of the 1978 test were encouraging, 140 line kilometers (87 line miles) of seismic reflection surveys were conducted by the BWIP in 1979 and 55 line kilometers (34 line miles) in 1980. The locations of the lines are shown in Figure 1.3-54. These lines were located to provide general coverage of the Hanford Site, but were concentrated in the Cold Creek syncline. Results of the surveys are reported in Seismograph Service Corporation (SSC, 1979, 1980), Myers/Price et al. (1979), and Holmes and Mitchell (1981). In addition to the record sections, Seismograph Service Corporation provided interpretations of the data to locate the top of basalt and anomalous features in the basalt. These anomalies, which ascribe to a variety of geologic structures or problems in processing, are compiled in Figure 1.3-55.

The top-of-basalt maps produced by Seismograph Service Corporation were based on an assumption of a velocity-depth function from the stacking velocities. As discussed by Odegard and Mitchell (1987), this assumption was in error along line 5 and probably in much of the Hanford Site south of the Umtanum Ridge-Gable Mountain structure. These errors result from a lack of velocity data from the sediments in the form of acoustic velocity logs or vertical seismic profile data. In addition, the interpretation appears to have been done without the constraint of top-of-basalt data from boreholes, although these data would be of limited use without velocity data. A reinterpretation of these data, constrained by available geological and geophysical data, will be a primary task during site characterization (Section 8.3.1.2.3.3.4); to be effective, this reinterpretation will require adequate velocity data from boreholes.

Holmes and Mitchell (1981) evaluated the seismic reflection data from the 1979 and 1980 surveys in conjunction with other geophysical data. They concluded that some of the anomalous seismic features correlated with anomalies identified in magnetic and gravity data.

During 1983, sections of lines 3, 5, and 8 were reprocessed for the BWIP. The results of this reprocessing were reported by Berkman (1984). The reprocessing was aimed at using better statics correction and stacking procedures based on velocity data from seismic reflection surveys. Careful attention also was paid to other parts of the processing sequence. This reprocessing resulted in somewhat better record sections.

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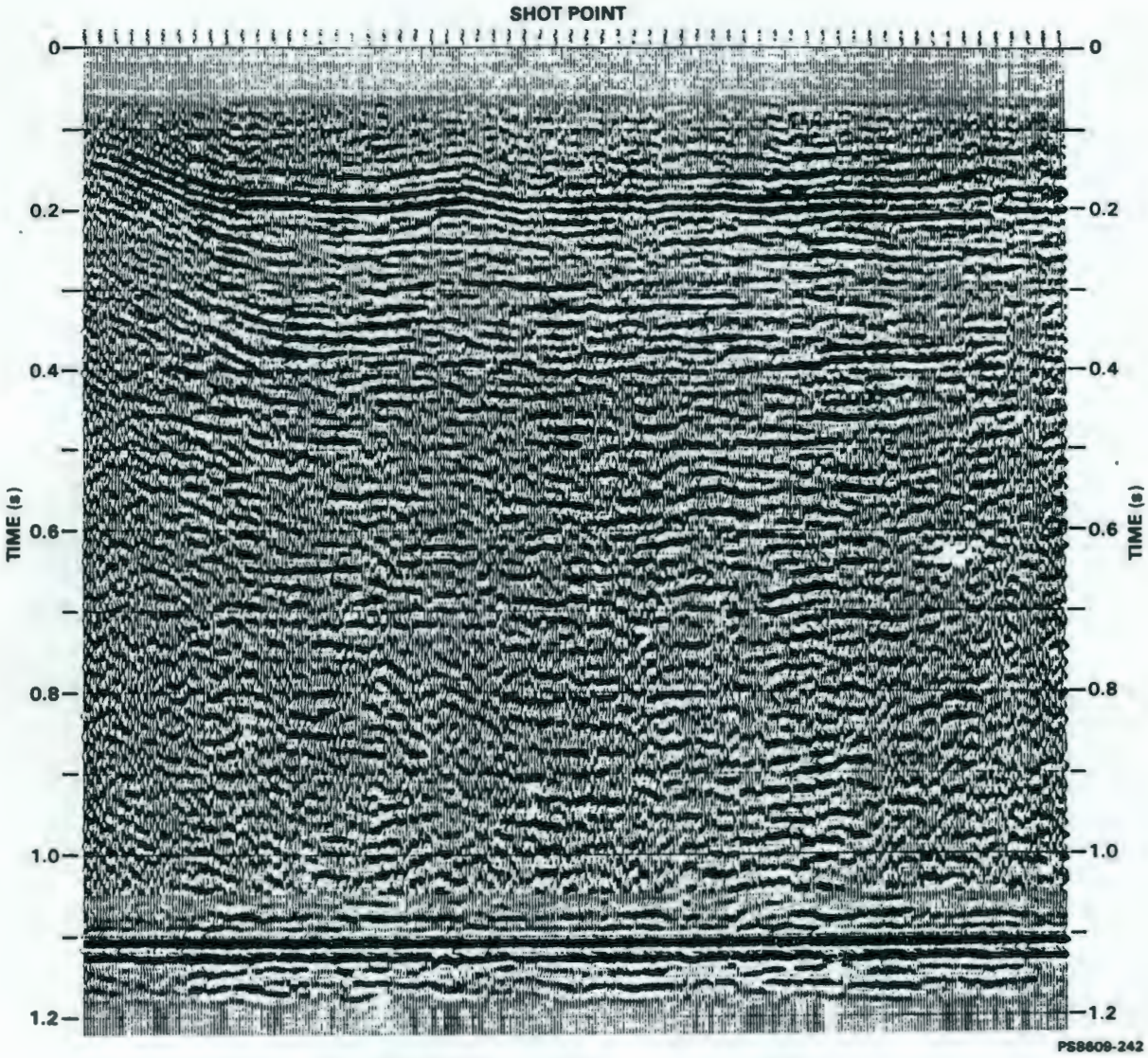

Figure 1.3-53. Wavelet processed seismic reflection line from the Basalt Waste Isolation Project test survey over DC-6 well (Heineck and Beggs, 1978). The wavelet used is shown at the bottom of the section.

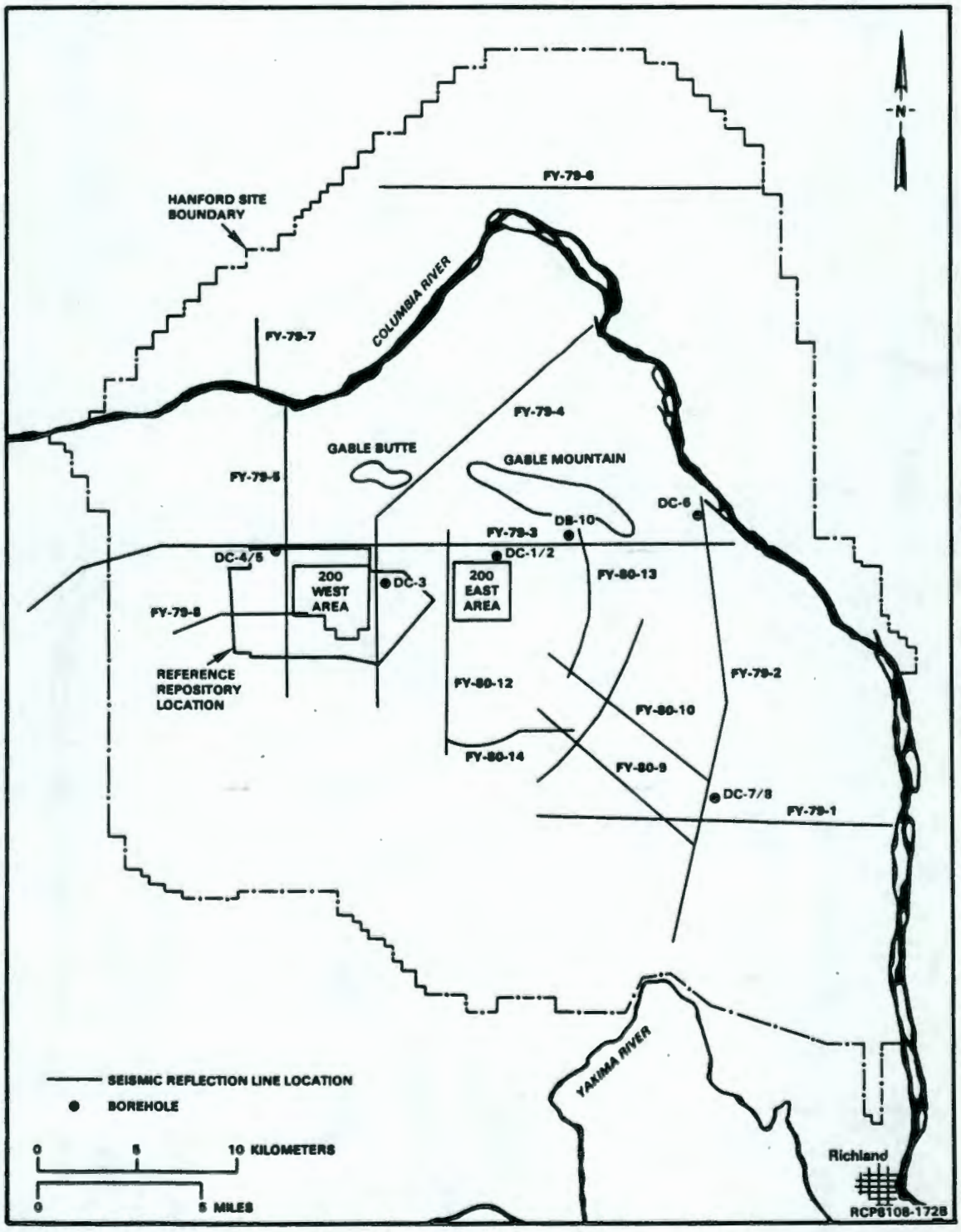

Figure 1.3-54. Seismic reflection line locations from surveys conducted for the Basalt Waste Isolation Project (SSC, 1979; 1980).

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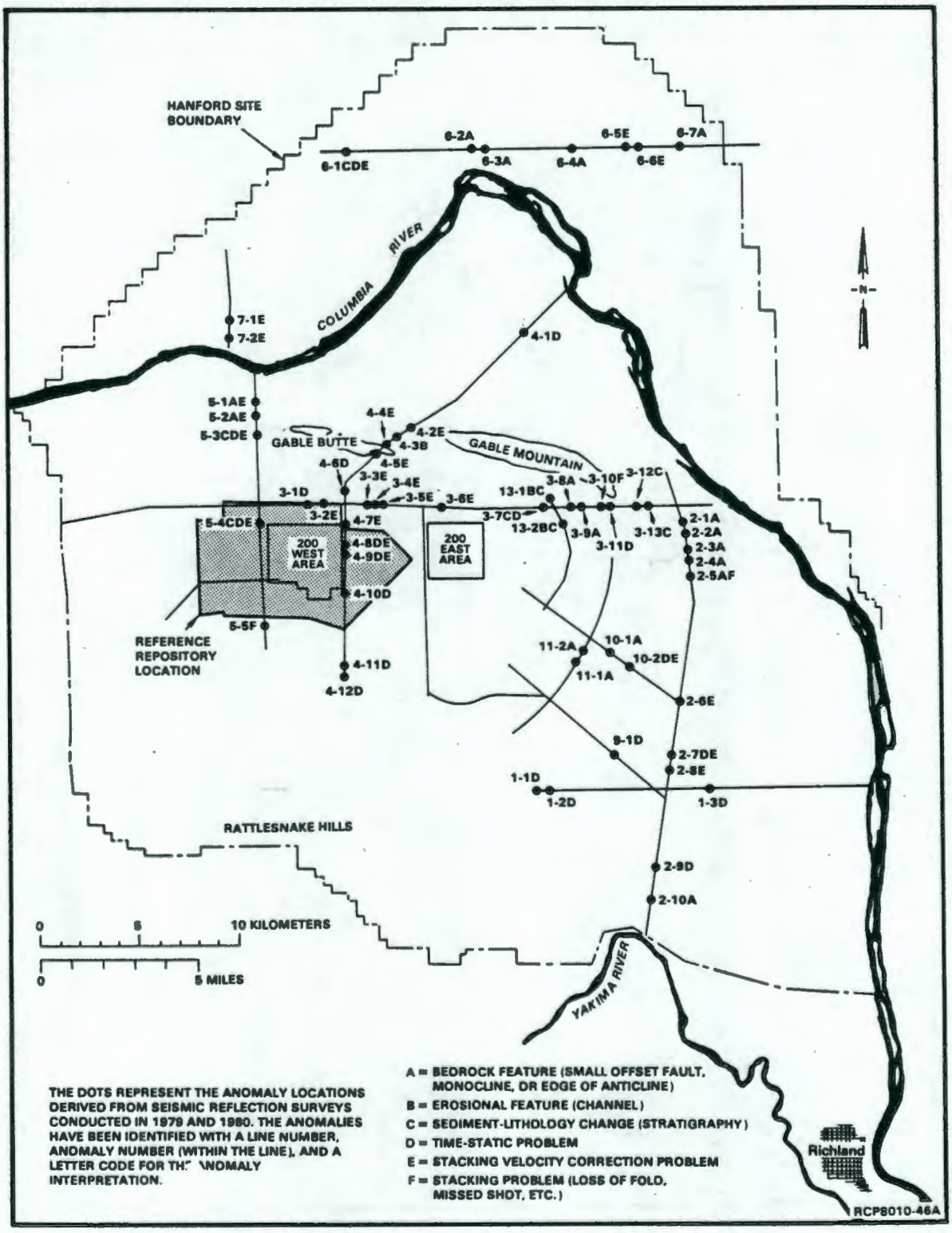

Figure 1.3-55. Seismic reflection anomaly location map (from Holmes and Mitchell, 1981).

The major result of the reprocessing was the realization that there are severe statics problems in the western part of the Cold Creek syncline. It also was recognized that data acquisition should be conducted to give a higher fold coverage at near offsets to better image the top of basalt. The statics problems and the need for higher fold data were not recognized initially, because the 1978 tests were conducted in an area that on the surface appeared to be similar, but in the subsurface was significantly different from the rest of the Hanford Site. Specifically, the thicknesses of the Hanford Formation and middle Ringold layers are significantly different, thus affecting the seismic response.

Surveys conducted during 1985

In 1985, additional seismic reflection was conducted in the area of the reference repository location to determine the best acquisition and processing parameters in the reference repository location. This survey was conducted along a 3.2-km (2-mi) test line shown in Figure 1.3-56; this is just to the west of a segment of line 5 of the Seismograph Service Corporation survey. Borehole RRL-2 is near shot point 120 in the following seismic sections. The survey included a series of tests to determine the best technique to acquire high-resolution seismic data.

The acquisition of these data was aimed at determining the depth to top of basalt. The acquisition used short geophone spreads, 1-ms sample rates, and relatively small energy sources. Three energy sources were tested, including a land air gun. Dynamite and primacord were tested to determine the optimum shot pattern, charge depth, and number of shots or shot size. After the initial tests, a shot point and group spacing of 7.6 m (25 ft) with a 15.44-m (50-ft) group length was chosen for production work. The spread geometry was asymmetric with a maximum offset of 350 m (1,150 ft).

The resultant data were processed by the contractor (Kunk, 1986). It was determined that the best energy sources were the air gun and dynamite. The results from these two sources were quite similar, so detailed processing was conducted only on the air gun section, which is the easiest to acquire. An example of the initial processing results are shown in Figure 1.3-57. This was processed by Walker Geophysical, using standard seismic processing techniques. The principal coherent arrival seen at a reflection time of just over 0.1 s can be correlated with the base of the Plio-Pleistocene layer. The apparent reflection is a result of the large velocity gradient at this point, which acts as an interface. Coherent reflectors can be seen at times down to slightly over 0.3 s, although they do not correlate well across the section. The top of basalt is at a depth of 0.27 s near shot point 120 but does not correlate well across the section.

This same line also was processed through Emerald Exploration Consultants, Inc. (Berkman, 1986). The results of this processing are shown in Figure 1.3-58. These data were processed using a similar processing sequence to that of Kunk (1986), except that an iterative, surface-consistent, statics and velocity-analysis procedure was used. In addition, a

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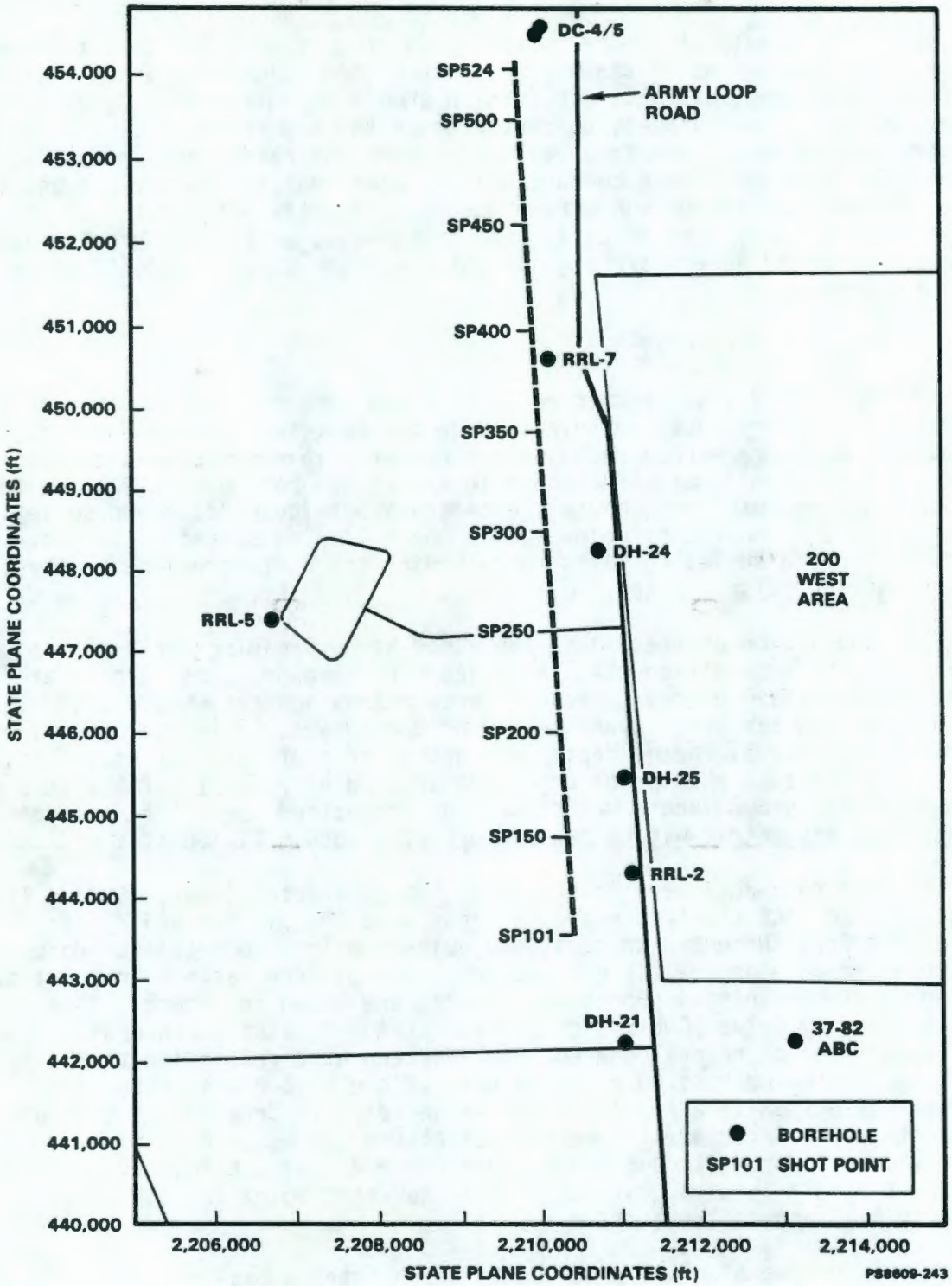

Figure 1.3-56. Location of seismic reflection test line acquired for the Basalt Waste Isolation Project (Kunk, 1985).

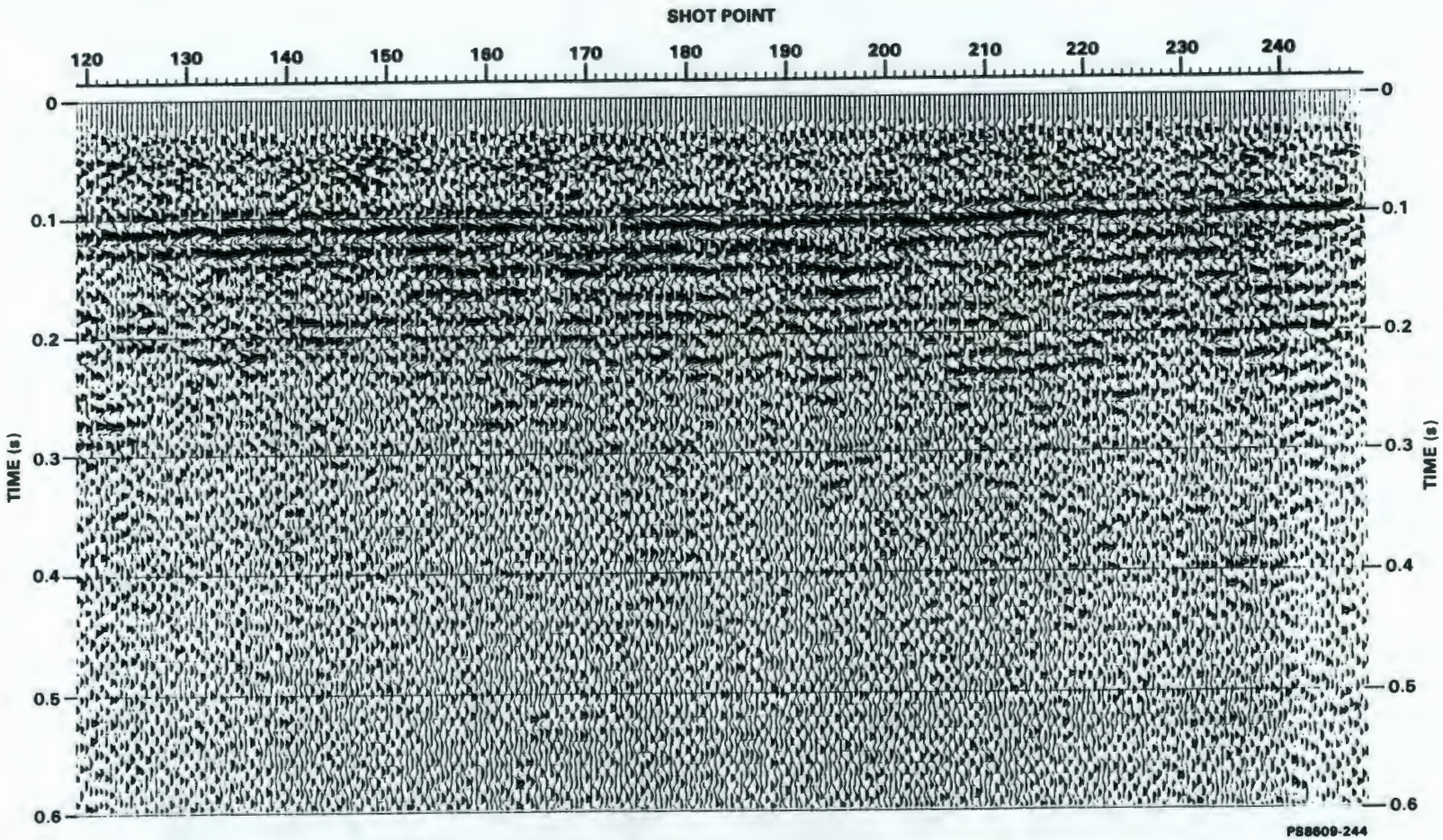

Figure 1.3-57. Initial processing of seismic reflection test line in Figure 1.3-56 (Kunk, 1985).

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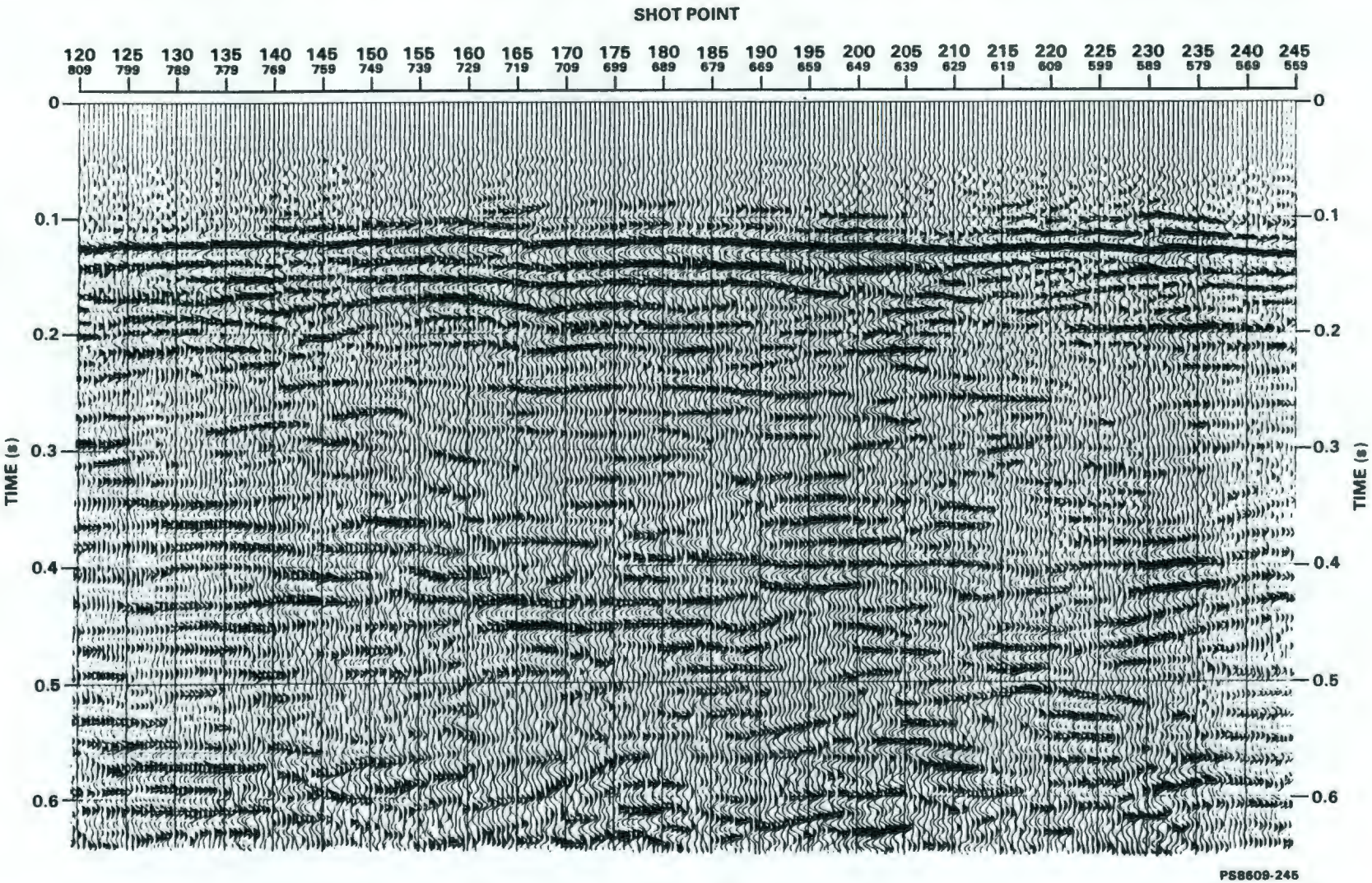

Figure 1.3-58. Processed section of test line in Figure 1.3-56 using repetitive statics corrections and a post stack dip correlation filter (Berkman, 1986).

CONSULTATION DRAFT

poststack, dip-correlation filter was used. This section also shows the Plio-Pleistocene boundary quite well, as well as other reflectors at reflection times at least to 0.5 s. This is approximately the depth of the Cohassett flow in this area. The top of basalt is not an obvious arrival in this section. The abundance of the coherent reflectors in this section could, to some extent, be an artifact of the dip-correlation filter, and the interpreter must be careful in interpreting these reflectors.

Kunk (1986) also processed this same section using a muting technique, which surgically removes areas of noise from the prestack data. The resultant common depth point gathers can be stacked in the normal way. The section shown in Figure 1.3-59 was processed in this way. Coherent noise trains due to channel waves produced in the sediments by the upper-middle Ringold unit and top-of-basalt interfaces were removed from these data by muting data in a wedge near zero offset. The resultant reflectors used in the common depth point stack are primarily refracted. Thus, the resultant section is much like a high-resolution seismic refraction section. This section shows a coherent reflector near the expected top-of-basalt reflection time. Other reflectors are clearly seen in the sediments, although the Plio-Pleistocene reflector is absent. No reflectors are seen below a reflection time of approximately 0.3 s. Reflectors below this depth were surgically muted. The extent of the sedimentary reflectors may be related to the existence of the upper-middle Ringold unit.

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General seismic reflection results

From a comparison of the seismic sections shown in Figures 1.3-57 through 1.3-59, it is obvious that different seismic processing procedures can be applied to seismic reflection data to enhance different areas of the record. From a careful consideration of the data, the BWIP also has concluded that more attention must be paid to the coherent noise trains, statics problems in the sediments, and on- and off-line scattering from sedimentary and basaltic features. These problems can be attacked with available state-of-the-art processing techniques. Attention also will have to be paid to acquisition techniques to image deeper basaltic features in the units in which the repository may be located. Plans to address these problems are included in the stratigraphy and structural geology study plans.

A principal objective of the seismic reflection program is to determine the location, extent, and origin of anomalous features within the controlled area study zone. As discussed in Section 1.3.2.2.3.4, anomalous features may occur in the record sections due to a variety of causes. During site characterization these features will be analyzed in great detail as discussed in Section 8.3.1.2.3.3.4.

1.3.2.2.3.6 Borehole geophysical surveys

Borehole geophysical surveys and logs are used to gather data on rock densities, velocities, porosities, and other parameters. The following discussion outlines several applications of these techniques at the Hanford Site and their potential for generating data useful to site characterization.

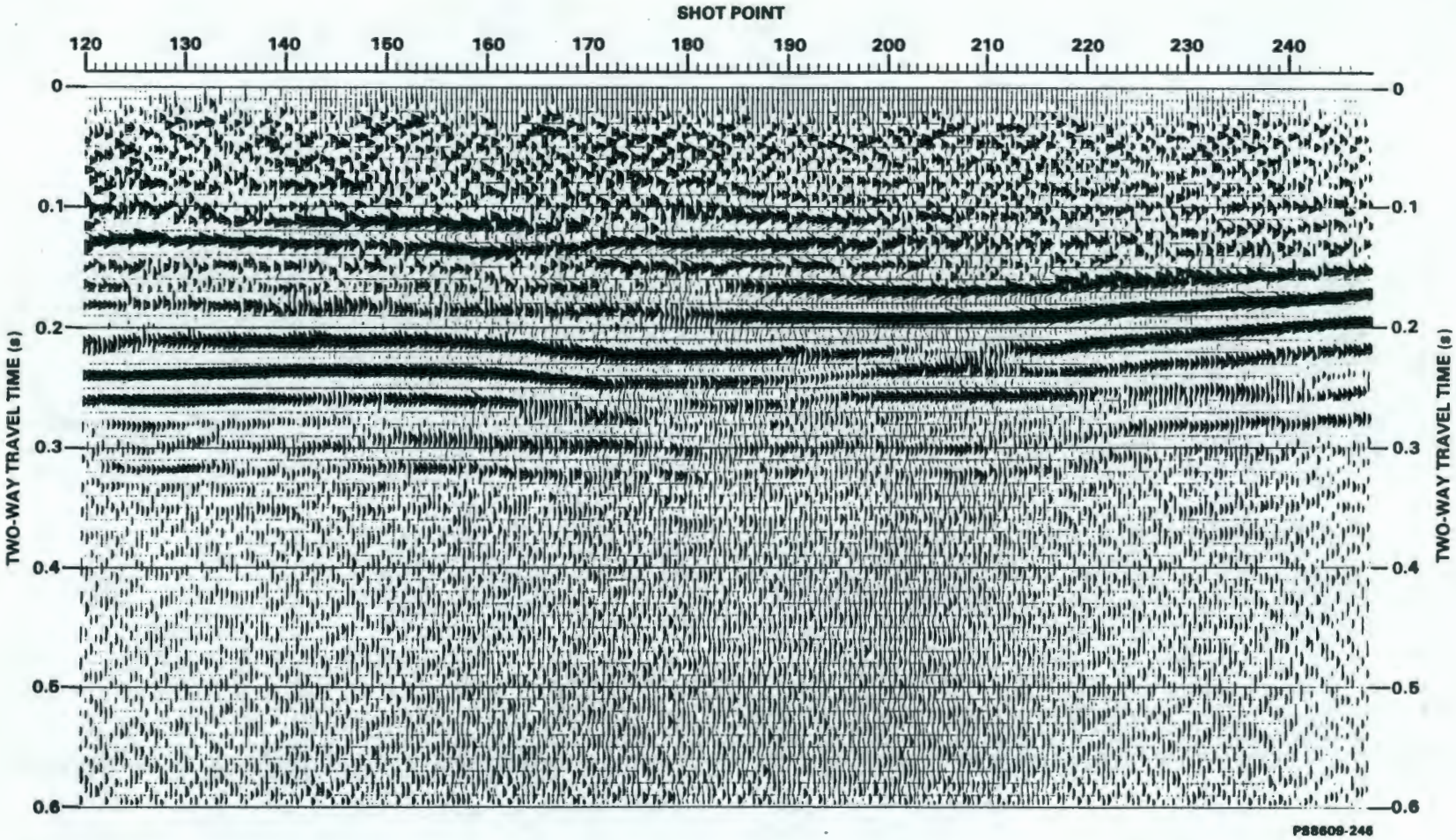

Figure 1.3-59. Processed section of test line in Figure 1.3-56 using a surgical mute of noise-contaminated sections of traces (Kunk, 1985).

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Sonic logs

Sonic logging data from the Shell Oil Company's Bissa 1-29 and Yakima Mineral Company's No. 1-33 wells (see Section 1.7.1.3) were used in a recent analysis of a model of the crustal structure of the Columbia Basin derived from large-scale seismic refraction surveys (Glover, 1985). Sonic logging data have been used to generate seismic impedance profiles used in synthetic seismogram modeling (Berkman, 1984). Seismic velocities in the basalt flows derived from sonic logging data have been used to aid contractor processing of seismic reflection data. However, lack of sonic data in the sediments overlying the basalt flows has severely hindered removal of static shifts in the seismic reflection data, resulting in less than optimally stacked seismic sections used for structural mapping.

Synthetic seismogram modeling will be used in wavelet analysis performed as part of seismic stratigraphic interpretations (Section 8.3.1.2.3.3.1). Compressional- and shear-wave velocities derived from full waveform sonic logging data will be required to assist future seismic reflection investigations. Full waveform sonic logging data have been used in conjunction with borehole televiewer data to characterize intraflow structures, fracturing, and borehole breakouts in a limited number of wells (Paillet, 1985). Further application of these techniques will be continued during characterization of the repository site (Section 8.3.1.2.3.3.1).

Density logs

The principal use of gamma-gamma density logging in geophysical investigations has been to provide a constraint on the rock density values for gravity modeling. Gamma-gamma density logging also has provided corroboration of density values derived from borehole gravity surveys. Potential future applications of these logging data are for accurate determination of seismic impedance profiles used in synthetic seismogram modeling, and quantitative logging analysis of intraflow structures and sedimentary interbeds.

Vertical seismic profiling

Vertical seismic profiling data have provided detailed velocity information about the suprabasalt sediments. This information is necessary to support seismic reflection processing. The difficult drilling of the suprabasalt sediments and interbeds has necessitated cased boreholes and frequent cementing in many boreholes. This, coupled with the shallow sediments, has made it difficult or impossible to acquire good sonic logs in many horizons above the basalts. Therefore, velocity/vertical seismic profile surveys have been conducted in several boreholes and have been used principally as high-resolution check shot surveys (Fig. 1.3-60). The surveys have provided insight into the velocity layering; however, more velocity information, specifically from more boreholes proximal to the reflection lines, will be required for site characterization seismic reflection surveys (Section 8.3.1.2.3.3.1).

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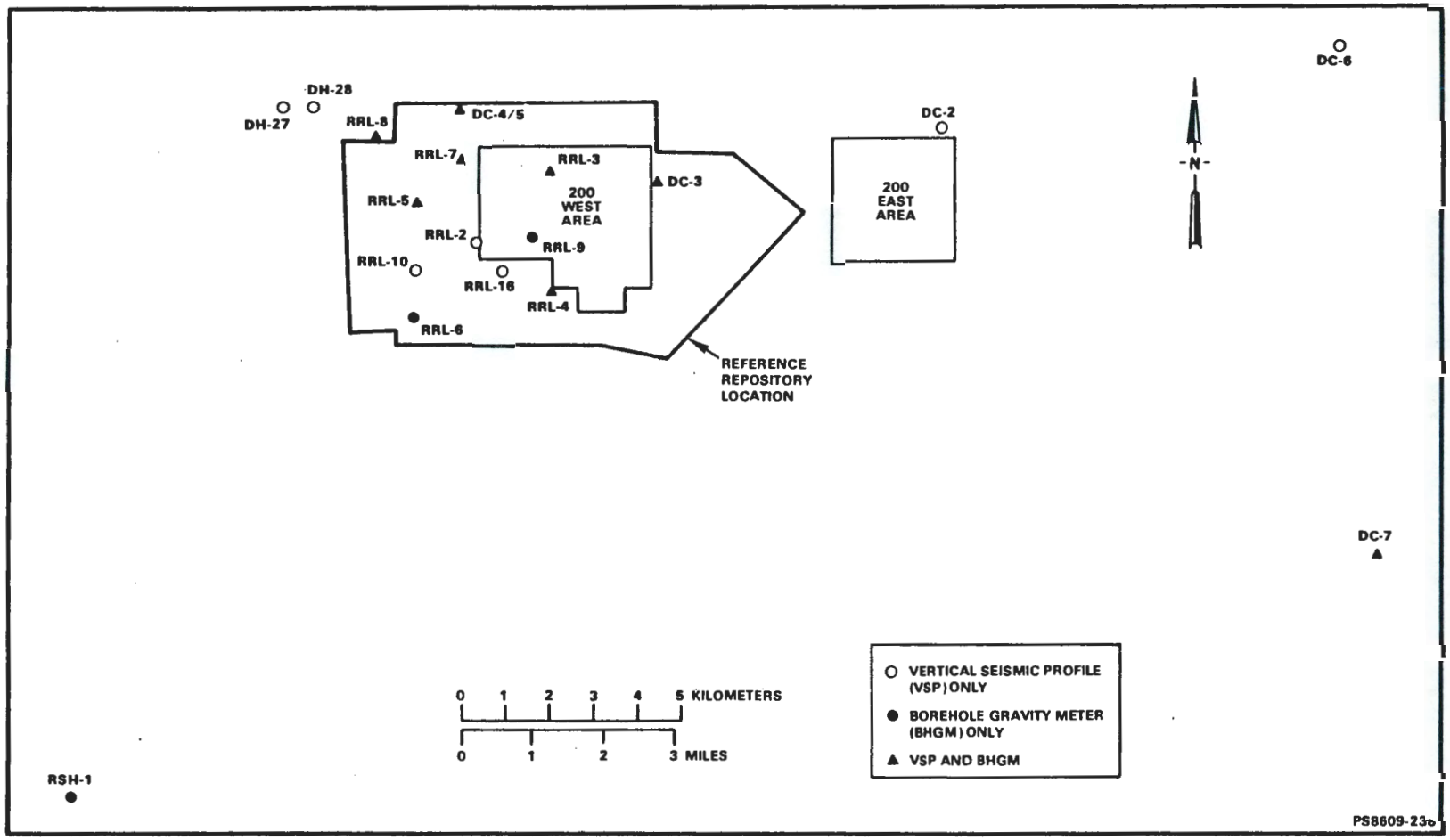

Figure 1.3-60. Location map for borehole gravity and vertical seismic profile surveys.

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The Birdwell Division of Seismograph Service Corporation conducted check shot and sonic log surveys in boreholes DC-2, DC-3, DC-4, DC-6, and DC-7 (Birdwell, 1979). Inversion of the check shot data is discussed by Odegard and Mitchell (1987). These surveys tested a maximum depth of 1,100 m (3,622 ft) in borehole DC-6. The surveys used a surface vibrator with a receiver placed at 8 to 11 different depth levels in each borehole. The velocity data are good, although incomplete, but more levels of recording in more boreholes are needed to understand the velocity layering. A typical velocity section is shown in Figure 1.3-61.

In 1981, Seismograph Service Corporation conducted vertical seismic profiling surveys in boreholes RRL-2, RRL-3, and RRL-4. Results of analyses of these data are discussed by Odegard and Mitchell (1987). These surveys used the Betsy Seisgun for the energy source, and the receiver was placed at each 7.6-m (25-ft) level from the surface down to the top of basalt. These surveys revealed large velocity variations and low-velocity zones in the suprabasalt sediments (Fig. 1.3-62). Of particular significance were the very high velocities, typical of more deeply buried sediments, encountered in the middle Ringold. These high velocities have led to misinterpretations of the lithologic boundary between the middle Ringold and the top of basalt on some of the seismic reflection lines. The vertical discontinuities, if not well defined, will certainly be a source of error in the processing and interpretation of seismic reflection data.

In 1984, Dresser Atlas conducted velocity/vertical seismic profiling surveys in boreholes RRL-5, RRL-7, RRL-8, RRL-10, and RRL-16 (Dresser, 1985). Explosives and the Betsy Seisgun were used as energy sources. These surveys, like the surveys conducted in 1981, were used to determine the velocity structure in the suprabasalt sediments, but sample levels were at 3-m (10-ft) intervals. A typical velocity profile from borehole RRL-10 is shown in Figure 1.3-63. The high-velocity layer in the middle Ringold is again evident, as well as additional variability throughout the section, which was not clearly evident on previous surveys. The 3-m (10-ft) sample interval of these surveys appears warranted because of the variability of the sediment velocities and variable borehole conditions that degrade the data quality in some zones.

Walker Geophysical Company conducted velocity/vertical seismic profiling surveys in boreholes DH-28 and DH-27 near the Yakima Barricade anomaly (see Section 1.3.2.2.3.7). These surveys sampled intervals at 3-m (10-ft) increments down to the top of basalt. These surveys, like the 1984 surveys, help define the suprabasalt velocity profile in the vicinity of the borehole but are lacking information from the basalts. During site characterization, vertical seismic profiling surveys in deeper boreholes will be conducted to aid the seismic reflection interpretations (Section 8.3.1.2.3.3.4).

Borehole gravity

Borehole gravity logs yield accurate, apparent bulk densities. Density information is necessary for gravity modeling and seismic reflection coefficient determinations. When layers are flat lying, and no structures are nearby, these apparent densities represent accurate, average bulk densities

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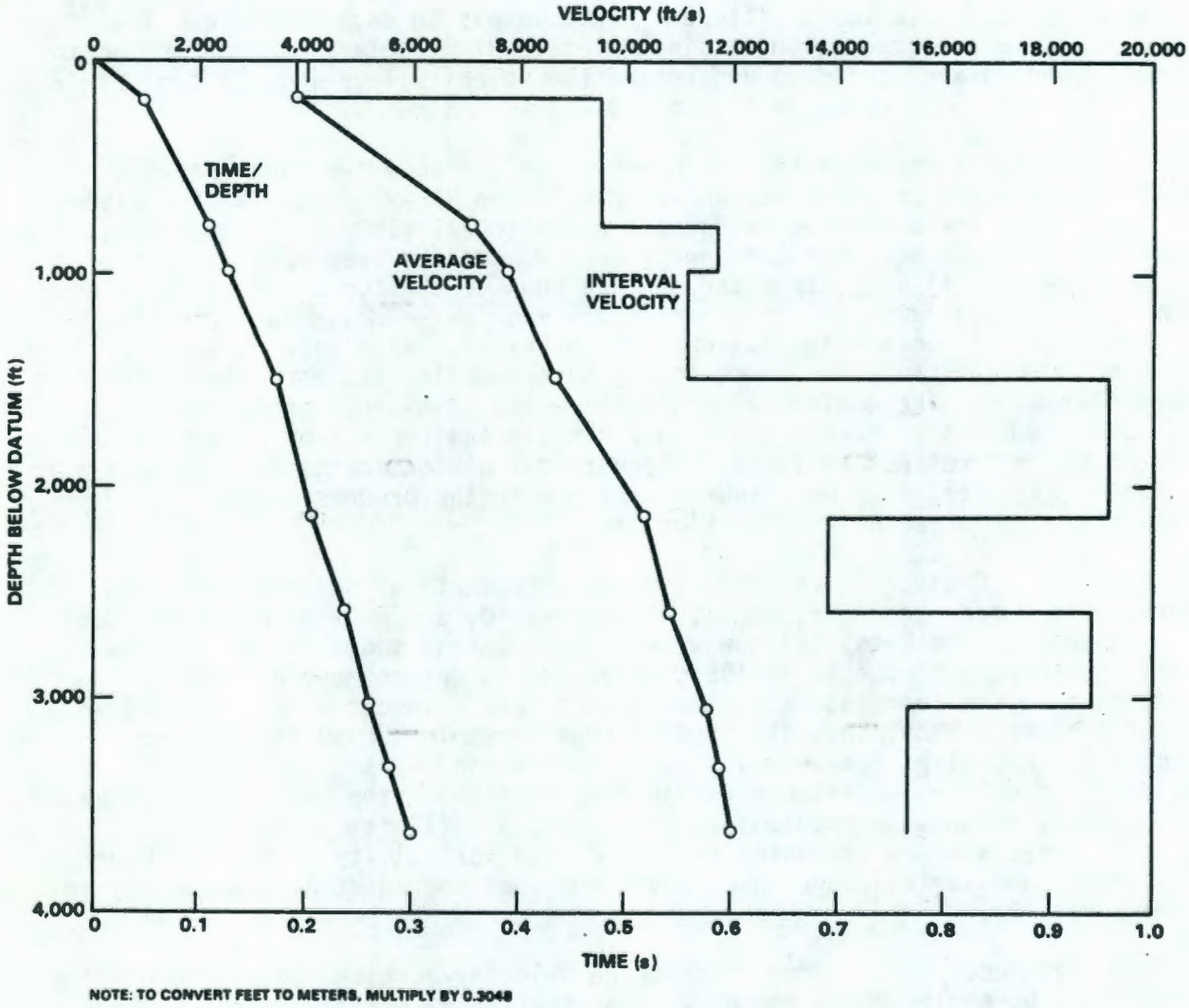

Figure 1.3-61. Time versus depth and velocity curves from borehole DC-6 (from Birdwell, 1979).

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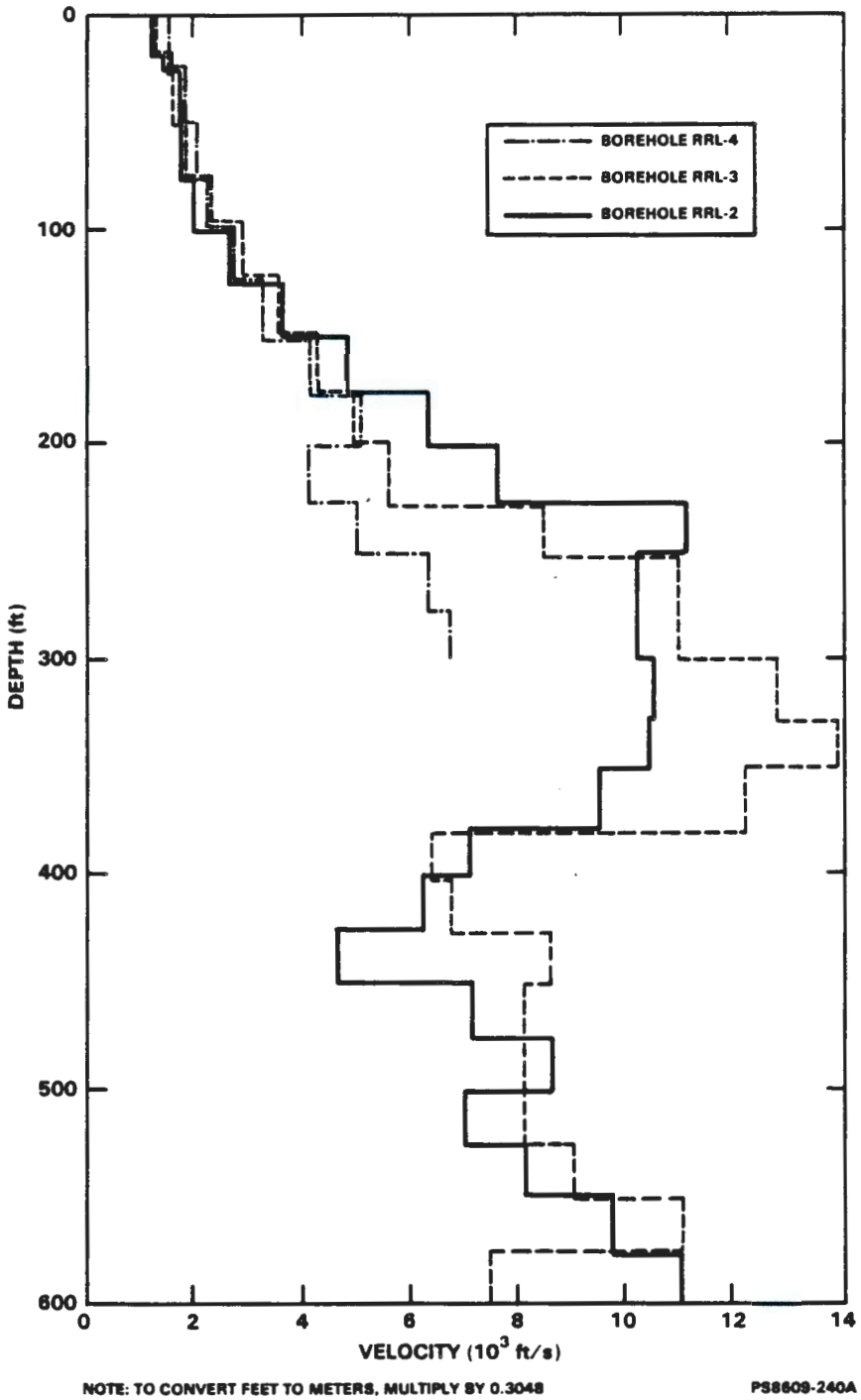

Figure 1.3-62. Results of vertical seismic profiling inversions from boreholes RRL-2, RRL-3, and RRL-4 (from Odegard and Mitchell, 1987).

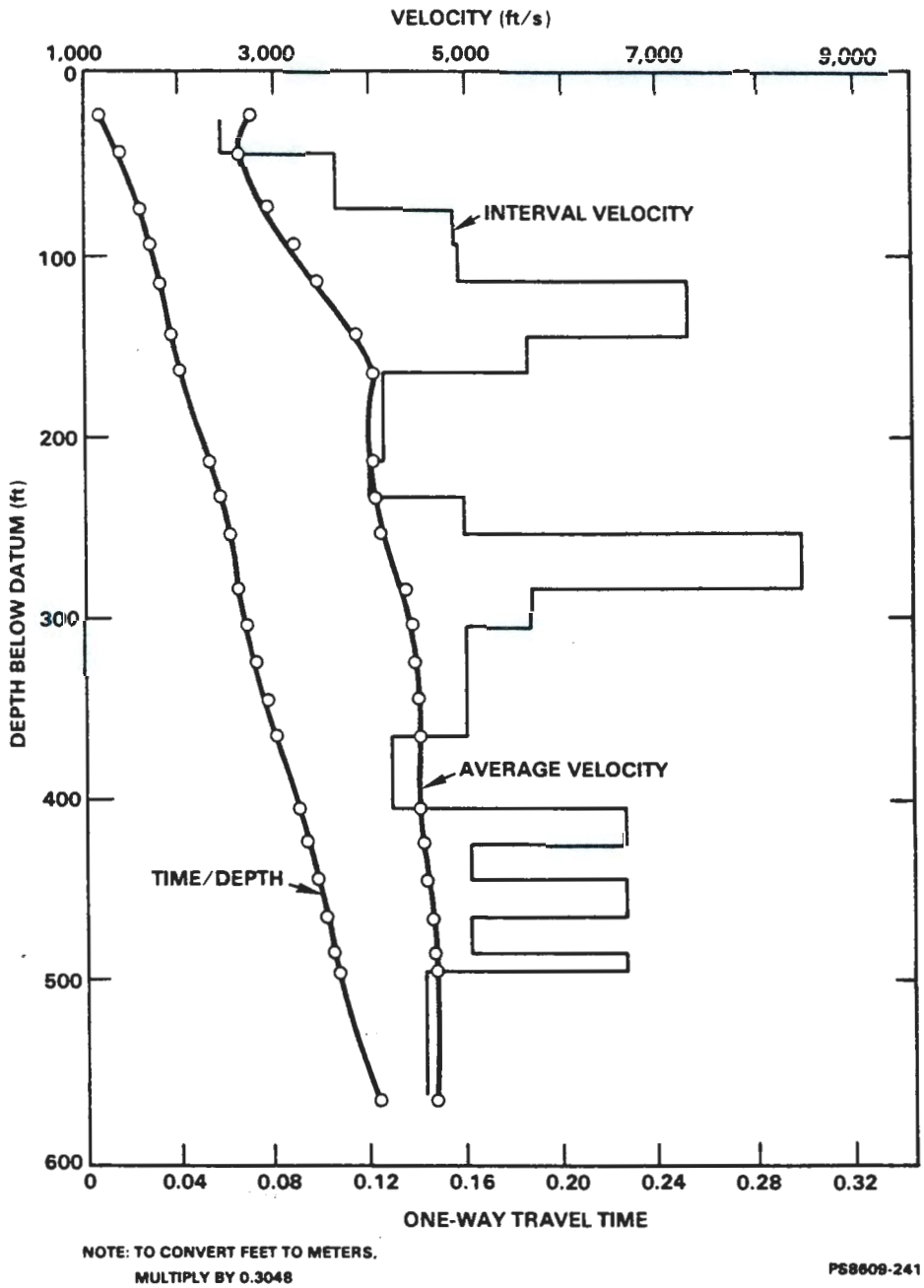

Figure 1.3-63. Velocity versus depth check shot plot from borehole RRL-10 (from Dresser, 1985).

for the strata between reading levels. Determinations of accurate, apparent bulk densities are possible with borehole gravity data due to the deep penetration of the measured field (Jageler, 1976, p. 714). Furthermore, borehole gravity logs are not generally influenced by rugosity and are unaffected by drilling mud and casing.

Borehole gravity surveys have been run in boreholes RRL-3, RRL-4, RRL-5, RRL-6, RRL-7, RRL-8, and RRL-9 (Robbins et al., 1983) to obtain density information on the suprabasalt sediments in the reference repository location. Surveys in boreholes DC-3, DC-5, DC-7, and RSH-1 (see Fig. 1.3-60) were run to acquire density information within the deep basalt horizons (Robbins et al., 1979). This information has significantly aided the surface gravity modeling, allowing more quantitative models. The densities derived from borehole gravity indicate that the gravity high located with surface gravity near borehole RRL-9 can be attributed to a high-density layer near the surface (Kunk and Ault, 1986).

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Other geophysical logs

Stratigraphic correlation of geologic horizons and delineation of intraflow structures have been the primary uses of well-logging data during the regional studies conducted by the BWIP. Uncalibrated neutron porosity and passive gamma-ray logs have been the most commonly used wireline data for these purposes (see Section 1.2.1.2.2.1). Electric resistivity logs have not been particularly useful in the stratigraphic determinations, because of the poor quality of the data that have been acquired to date. Poor electric log data quality and lack of well penetration into the sub-basalt sediments have resulted in limited use of these data as a constraint on magnetotelluric survey interpretation. Electric logging data from the Shell Oil Company BN1-9 Saddle Mountain well (see Section 1.7.1.3 for a location map for exploration boreholes) have been used to estimate appropriate resistivity values for the sub-basalt sediments. Geophysical logging of future wells drilled during site characterization must obtain high-quality, quantitative data for geological, geophysical, hydrological, and geomechanical applications.

1.3.2.2.3.7 Geophysical anomalies at the candidate site

The major structural and topographic features mapped in the Pasco Basin are depicted in the geophysical data. The magnetic and gravity fields exhibit characteristics that also indicate the rock layering in the reference repository location is not an evenly layered, homogeneous mass. However, there is less variability in the reference repository location than in known structures that are adjacent to the reference repository location, such as the buried extension of Yakima Ridge. This suggests that the reference repository location, although probably not free of structures, contains smaller structures than areas around the reference repository location, or that the greater thickness of suprabasalt sediments is masking any potential structures.

Examples of features known to exist in the reference repository location that could cause the geophysical anomalies include variable cementation of

sediments, gravel bars, thinning of basalt flows, erosional or depositional channeling, and variability in the elevation of the top of basalt. Faulting or folding, in addition to structures already interpreted from borehole data, also must be considered in the data analysis.

Figures 1.3-64 through 1.3-66 show the geophysical anomalies that have been identified in the proximity of the reference repository location. Table 1.3-8 summarizes the significance or source of these anomalies. Features in Figures 1.3-65 and 1.3-66 represent anomalies shown to be geologic structure, and unexplained anomalies. Features plotted on the north, west, and south represent mapped geologic structures of the Umtanum Ridge-Gable Mountain anticline, Yakima Barricade geophysical anomaly and Yakima Ridge, and the buried extension of Yakima Ridge, respectively. Although mapped on the surface, these structures have not been fully characterized in the subsurface. The features in the central and eastern limits of these figures do not have surface exposures and will be investigated further using geologic and geophysical methods. A review of the current qualitative integration of the geophysical data for these anomalies can be found in the Environmental Assessment (DOE, 1986, pp. C.5-135 to C.5-145).

Complete analyses and integration of data from all of the geophysical methods, along with geologic and hydrologic data, will be carried out during site characterization to address specifically the structural and tectonic regime of the reference repository location and the region in general (Sections 8.3.1.2.3 and 8.3.1.2.4). As part of this effort, the significant features and anomalies of the various geophysical data sets will be examined and resolved to the detail appropriate to the methods involved.

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1.3.2.3 Existing stress regime

The following is a description of the contemporary stress regime in the central Columbia Plateau. The description is limited to the local structural features and seismic activity that provide some evidence for the orientation and magnitude of stress within the basalts. The interpretations presented should be reviewed in light of models that have been proposed for the tectonic setting of the Pacific Northwest (see Sections 1.5 and 2.6).

Several types of information are available to infer the contemporary stress regime for the basalts. Data that have been used thus far come from the following sources:

- Geologic mapping and geophysical surveys. The location, geometry, and age relationships of geologic structures are indicators of past stress regimes and may be indicators of the present regime.

- Geodetic surveys. Leveling and trilateration surveys measure vertical and horizontal movements of the Earth's surface over an interval of time.

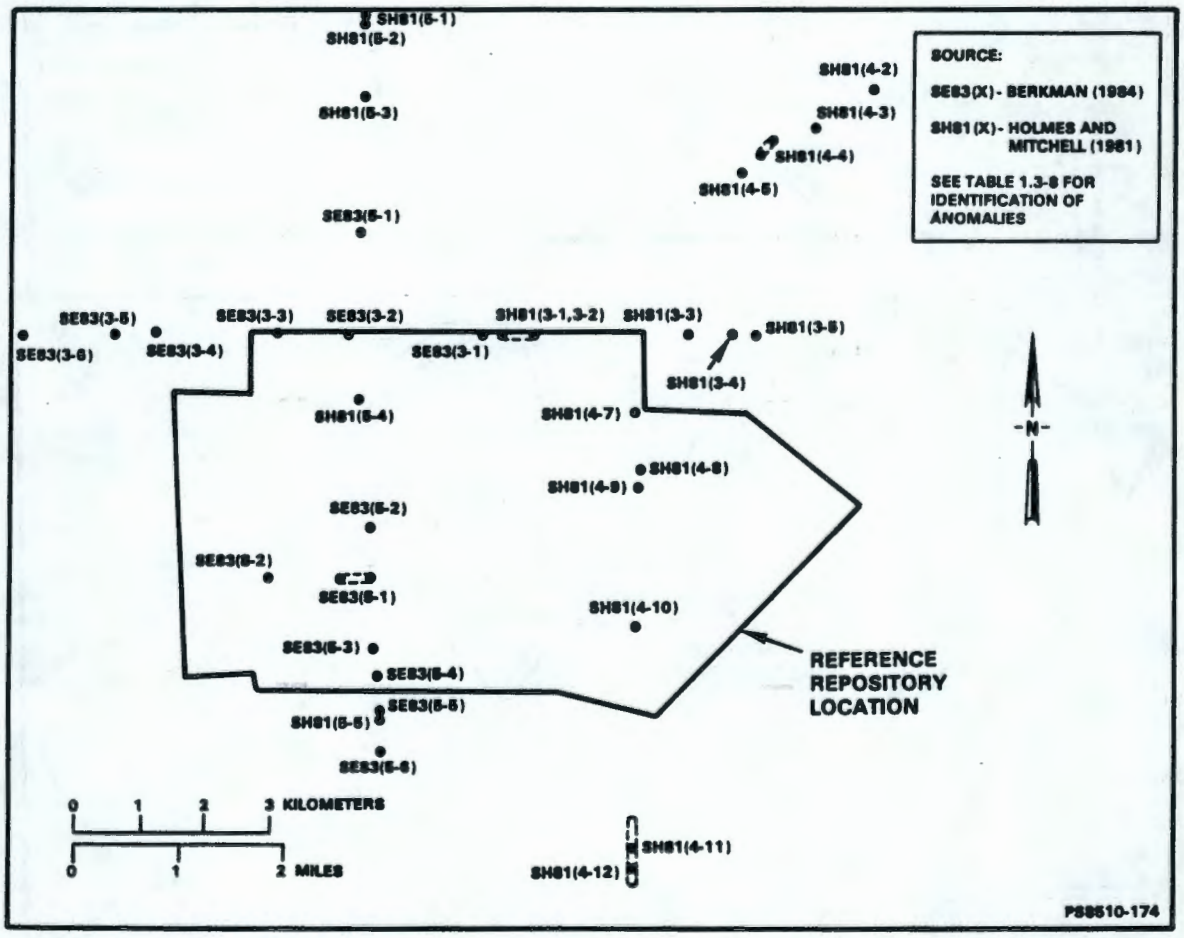

Figure 1.3-64. Location map of seismic reflection features in the vicinity of the reference repository location (from DOE, 1987c).

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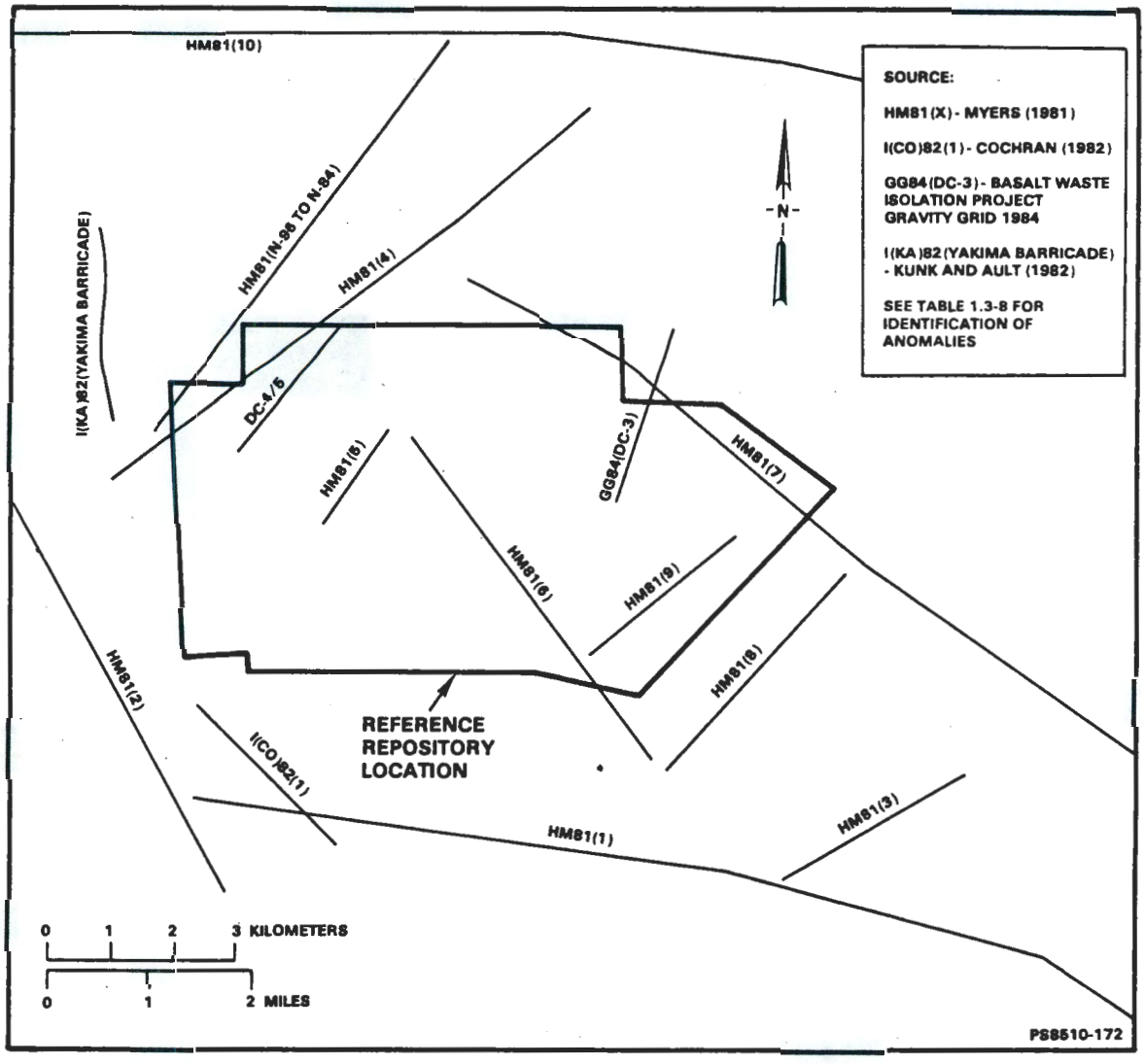

Figure 1.3-65. Potential-field geophysical features in the vicinity of the reference repository location.

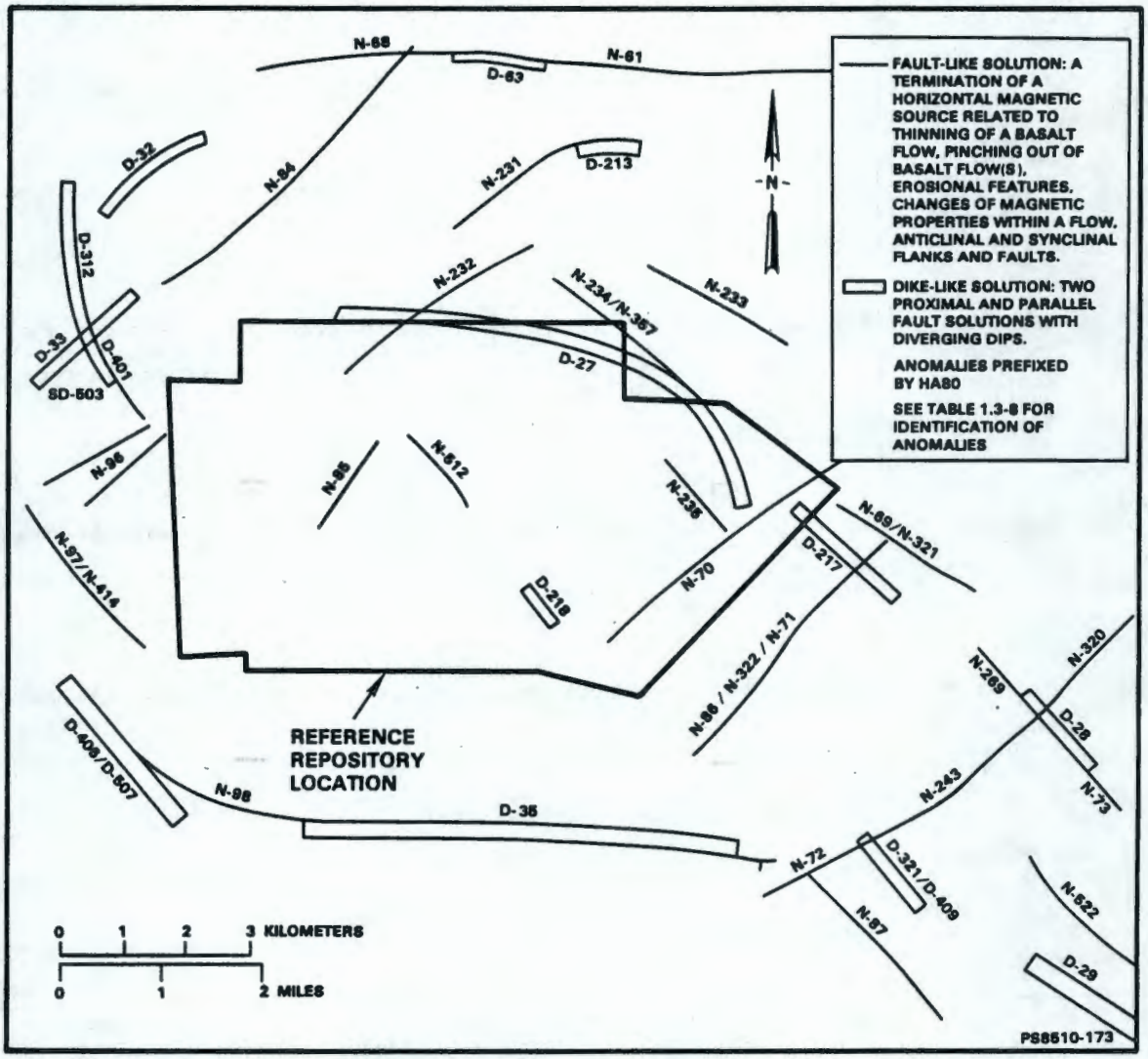

Figure 1.3-66. Werner deconvolution solutions for aeromagnetic survey data collected in the vicinity of the reference repository location (AERO, 1980; DOE, 1986).

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Table 1.3-8. Geophysical features in and around the reference repository location (sheet 1 of 4)

Geophysical features*	Source	Comments
HM 81 (1)	Myers (1981)	Bounding feature during initial reference repository location siting process.
Coincident Werner solutions		
HA80 (D-321) HA80 (D-409) HA80 (N-98) HA80 (D-35) HA80 (N-72) HA80 (N-87) HA80 (D-29) HA80 (N-522)	Holmes and Mitchell (1981)	Werner deconvolution solutions corresponding to buried eastern extension of Yakima Ridge structure. Associated faults are expected but not verified.
Coincident seismic features		
SE83 (5-4) SE83 (5-5) SE83 (5-6) SH81 (5-5) SH81 (4-11) SH81 (4-12)	Berkman (1984) Holmes and Mitchell (1981)	Anomalous zones identified and interpreted by Berkman (1984) could be related to faulting on the buried extension of Yakima Ridge but data quality is poor. The seismic anomalies are affected by static velocity-static correction errors.
Other		
I (CO) 82 (1)	Cochran (1982)	Reinterpreted to be a north-south tear fault on buried portion of Yakima Ridge.
HM 81 (2)	Myers (1981)	Topographic termination of Yakima Ridge structure.
Coincident Werner solutions		
HA80 (D-406) HA80 (D-507) HA80 (N-414) HA80 (N-97) HA80 (N-98)	Holmes and Mitchell (1981)	Werner solutions responding primarily to the topography of the Yakima Ridge structure.
HM 81 (3)	Myers (1981)	Defined by Werner solutions.
Coincident Werner solutions		
HA80 (N-243) HA80 (N-320) HA80 (N-72) HA80 (D-321)	Holmes and Mitchell (1981)	May be related to the buried extension of Yakima Ridge.
HM 81 (4)	Myers (1981)	Used to help define the northern boundary of the reference repository location during the siting process based on Werner solutions. The extreme northern and southern ends are possibly related to minor structure such as buried erosional channels in the Hanford and (or) Ringold Formations. The central portion does not appear to be related to any geologic features.
Coincident Werner solutions		
HA80 (N-96) HA80 (N-231) HA80 (D-213)	Holmes and Mitchell (1981)	
Coincident seismic features		
SE83 (3-2)	Berkman (1984)	Probably due to erosional features in the Hanford and (or) Ringold Formations.

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Table 1.3-8. Geophysical features in and around the reference repository location (sheet 2 of 4)

Geophysical features*	Source	Comments
HM 81 (5)	Myers (1981)	Defined by single Werner solution.
Werner solution		
HA80 (N-85)	Holmes and Mitchell (1981)	Interpreted to be responding to the west-striking magnetic gradient reflecting, in part, the southern dip of the northern limb of the Cold Creek syncline. The northeast strike of HA80 (N-85) may be due to flight-line orientation or to a change in direction of the gradient to the east of the plotted solution.
HM 81 (6)	Myers (1981)	Defined by Werner solutions.
Coincident Werner solutions		
HA80 (N-512) HA80 (D-218)	Holmes and Mitchell (1981)	The southern end is interpreted to coincide with a low-amplitude anticline, but the size of the anticline is smaller than the error of the borehole accuracy. The northern end corresponds with the dipping basalt of the northern limb of the Cold Creek syncline.
HM 81 (7)	Myers (1981)	Defined by Werner solutions and consists of three magnetically unique segments. A boundary feature in the reference repository location siting process.
Northern segment		
Coincident Werner solutions		
HA80 (D-27) HA80 (N-234) HA80 (N-357)	Holmes and Mitchell (1981)	Werner solutions responding to a 30-gamma low with highs to the east and west.
Coincident seismic features		
SH81 (3-1) SH81 (3-2)	Holmes and Mitchell (1981)	Probably a function of shallow sediment velocity variations causing stacking velocity correction errors.
Middle segment		
Coincident Werner solutions		
HA80 (N-69) HA80 (N-321) HA80 (D-217)	Holmes and Mitchell (1981)	Magnetic field relatively flat. Werner solutions are interpreted to be caused by minor perturbations in the magnetic field that are not clearly related to either the northern or southern segments of HM81 (7).
Southern segment		
Coincident Werner solutions		
HA80 (N-269) HA80 (D-28) HA80 (N-73)	Holmes and Mitchell (1981)	Werner solutions are not consistent with the magnetic total field contour maps.
HM 81 (8)	Myers (1981)	Inferred "deep structure" based on Werner solutions.
Coincident Werner solutions		
HA80 (N-71) HA80 (N-86) HA80 (N-322)	Holmes and Mitchell (1981)	Interpreted to be a response to a northeast-trending structural high across the axis of the Cold Creek syncline. Depths calculated by the Werner method are doubtful.

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Table 1.3-8. Geophysical features in and around the reference repository location (sheet 3 of 4)

Geophysical features*	Source	Comments
HM 81 (9)	Myers (1981)	Inferred "deep structure" based on Werner solutions.
Coincident Werner solution		
HA80 (N-70)	Holmes and Mitchell (1981)	Werner depths are likely in error because the Werner profiles are not perpendicular to a more westerly striking gradient that is interpreted to be responding to a south-dipping basalt on the northern limb of the Cold Creek syncline.
Coincident seismic features		
SH81 (4-10)	Holmes and Mitchell (1981)	Interpreted to be associated with time-static processing problems.
HA 81 (10)	Myers (1981)	Bounding feature during initial siting process.
Coincident Werner solutions		
HA80 (N-68) HA80 (D-63) HA80 (N-61)	Holmes and Mitchell (1981)	Werner deconvolution solutions corresponding to Umtanum Ridge-Gable Mountain structure.
Coincident seismic features		
SH81 (5-1) SH81 (5-2)	Holmes and Mitchell (1981)	Related to the faulting and (or) folding of the Umtanum Ridge-Gable Mountain structure.
HM 81 (N-96 to N-84)	Myers (1981)	Bounding feature in the reference repository location siting process.
Coincident Werner solutions		
HA80 (N-84) HA80 (N-96)	Holmes and Mitchell (1981)	These magnetic features are responding to an 80- to 100-gamma magnetic gradient that is coincident to a segment of the Nancy Linear (Weston, 1978c).
I(KA) 82 Yakima Barricade	Kunk and Ault (1982)	North-south Cold Creek barrier. Magnetic and gravity data indicate a north-south linear. Hydrologic head differences, particularly in the Wanapum Basalts. Termination of the Elephant Mountain Member. Elevation difference of 122 m (400 ft) between correlatable Pomona Member over a half mile east-west distance.
Coincident Werner solutions		
HA80 (N-84) HA80 (D-33) HA80 (D-312) HA80 (D-401) HA80 (SD-503)	Holmes and Mitchell (1981)	Several Werner solutions responding to a variety of magnetic gradients, highs, and lows.
Coincident seism ic features		
SE83 (3-4) SE83 (3-5) SE83 (3-6) SE83 (3-7)	Berkman (1984)	Poor data quality probably due to thick deposits of the Hanford Formation. Indications of faulting or other reflection discontinuities.

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Table 1.3-8. Geophysical features in and around the reference repository location (sheet 4 of 4)

Geophysical features*	Source	Comments
GG84 (DC-3)	Kunk (1984)	A north-northeast-trending gravity anomaly that is interpreted to be responding to Hanford Formation infilling of an erosional scarp in the middle Ringold Formation.
Coincident seismic features		
SH81 (4-8) SH81 (4-9) SH81 (3-3)	Holmes and Mitchell (1981)	These seismic anomalies are probably related to stacking velocity-static correction errors that could in part be related to variable sediment velocities.
Miscellaneous Werner solutions		
HA80 (N-235)	Holmes and Mitchell (1981)	Interpreted to be a shallow feature.
HA80 (N-232)		May be related to an interpreted broad-open anticline (Myers, 1981).
HA80 (N-233)		Small northwest-striking gradient of approximately 20 gammas.
Miscellaneous seismic features		
SE83 (5-3) SE83 (8-2)	Berkman (1984)	Small, broad depression in the upper basalt seismic reflectors, making the absolute location of the Cold Creek syncline axis difficult. The total magnetic field (Holmes and Mitchell, 1981) exhibits a spatially coincident magnetic low with about the same orientation.
SE83 (5-2) SE83 (8-1)	Berkman (1984)	The seismic reflectors are flat lying and have no significant time offset on the two sides of a seismic character change. Nearby boreholes and borehole gravity indicate intermittent high-density layers in the middle Ringold Formation. The seismic anomaly appears to be due to variable properties in the middle Ringold Formation.
SH81 (3-4) SH81 (3-5) SH81 (4-2) SH81 (4-3) SH81 (4-4) SH81 (4-5) SH81 (4-7) SH81 (5-3) SH81 (5-4)	Holmes and Mitchell (1981)	These seismic anomalies are not spatially related but are grouped together because they are all interpreted to be a result of stacking-velocity correction problems. Variable suprabasalt sediment velocities contribute to these processing problems.
SE83 (3-2) SE83 (3-3)	Berkman (1984)	These anomalies appear to be responding to velocity variations in the sediments, probably due to cut-fill features in the Hanford and Ringold Formations.
SE83 (3-1) SE83 (5-1)	Berkman (1984)	Possibly a low-amplitude anticline with minor associated faulting.

Source: DOE, 1986a, C.5-135 to C.5-145.

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*Coincident, as used in this table, is defined as describing different geophysical anomalies that are spatially close together.

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- Seismic surveillance. Focal mechanism solutions for earthquakes indicate the type and orientation of faulting. Recurrence relationships reveal the rate of stress release.

- Borehole observations. Core disking and borehole spalling provide data on stresses at depth in the basalt.

- In situ stress measurements. Hydraulic fracturing techniques in boreholes are used to determine the orientation and magnitude of stress.

1.3.2.3.1 Geologic mapping and geophysical surveys

In the Yakima Fold Belt adjacent to the Pasco Basin, geologic structures are interpreted to have developed under a stress regime whose principal compressive stress direction is oriented nearly north-south and is horizontal (see Section 1.3.2.2.1). The presence of east-west-trending folds and east-west-striking thrust and reverse faults, along with northwest-trending strike-slip faults to the west of the Pasco Basin, supports this interpretation of horizontal, north-south compression. The occurrence of folds and thrust faults suggests that the axis of least compressive stress is vertical.

1.3.2.3.2 Geodetic surveys

Geodetic surveys across the Pasco Basin have been conducted by the U.S. Geological Survey between 1972 and 1983 (Savage et al., 1981; Prescott and Savage, 1984, pp. 1-28). Eight surveys of a trilateration network containing 19 monuments and 29 lines have been conducted during this period using a single-color laser geodolite. The rate of horizontal change in monument position is very low and is within the range of instrument error and the range of daily Earth tides.

1.3.2.3.3 Seismic surveillance

Focal mechanism solutions for shallow and deep earthquakes in the Pasco Basin area are compatible with nearly east-west-trending reverse faults, and have an approximately horizontal, north-south axis of maximum compression and nearly vertical axis of least compression (Section 1.4.1.2.3). Focal mechanisms are consistent with geologic data, which suggest that the current stress regime has probably existed for at least 16 m.y. and has been responsible for the development of folds and faults in the Columbia River basalt, as well as for the earthquake activity that is currently observed. Further description of focal mechanism solutions for earthquakes of the central Columbia Plateau can be found in Rohay and Davis (1983) and Section 1.4.

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1.3.2.3.4 Borehole observations

Relatively high in situ stress is indicated by borehole spalling and core disking, phenomena observed in boreholes drilled within the Hanford Site (Section 2.6). Borehole spalling and core disking allow interpretation of stress orientation (Kim et al., 1986, pp. 7-17).

Spalling in deep boreholes on the Hanford Site has been observed in downhole television surveys, impression-packer tests, and acoustic-televiewer techniques. Paillet (1985) obtained acoustic-televiewer logs for intervals of approximately 400 m (1,300 ft) each in boreholes DC-4, DC-7, DC-12, RRL-2, and RRL-6 and concluded that borehole spalling or borehole wall breakouts have a consistent east-west orientation. This orientation of borehole spalling indicates that the maximum horizontal stress is approximately north-south (Section 2.6.2.1).

The possibility of relatively high in situ stress in the basalt beneath the Hanford Site was first indicated by the occurrence of core disking. Core disking is the phenomenon by which the core fractures into thin disks during the drilling process. Core disks have been described by Moak (1981) and Long and Woodward-Clyde Consultants (Long and WCC, 1984, p. I-230). The presence of saddle-shaped disks in the basalt core is indicative of anisotropic horizontal stresses. Study of oriented cores that experienced disking indicates that the maximum horizontal stress is generally north-south (Lehnhoff et al., 1982).

Core disking and borehole spalling could occur where the in situ stress is high or where the rock is weak (Kim et al., 1986, pp. 7-62). Paillet (1985, p. 47) studied the occurrence of spalling and disking with depth in three boreholes and concluded that spalling and disking are confined primarily to the interiors of individual flows. The frequency of core disking and borehole spalling supports the interpretation that the distribution of in situ stresses at the Hanford Site is not lithostatic and that tectonic stresses are present.

1.3.2.3.5 In situ stress measurements

The hydraulic fracturing method allows direct determination of in situ stress magnitudes at depth. In situ stress measurements by the hydraulic fracturing (hydrofracture) technique have been conducted at depths of from approximately 900 to 1,200 m (3,000 to 3,300 ft) in boreholes DC-12, -4, RRL-2, and -6 (Kim et al., 1986, Table 6). Hydraulic fracturing test data, data analysis procedures, and calculated in situ stresses for the Cohassett flow, Grande Ronde flow 7, Umtanum, and McCoy Canyon flows are presented in Section 2.6.

Hydraulic fracturing test results indicate that the maximum, intermediate, and minimum principal compressive stresses are oriented approximately north-south, east-west, and vertical, respectively. This is consistent with

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geologic interpretation data (Sections 1.3.2.2 and 1.4.1.2). Because the hydraulic fracturing method assumes that the principal stress directions are parallel or perpendicular to the borehole axis, the actual stress orientation may differ from the test results. Hydraulic fracturing tests further indicate that horizontal in situ stresses do not vary significantly within the Cohassett, Grande Ronde 7, McCoy Canyon, and Umtanum flows at the reference repository location (Kim et al., 1986, Fig. 17, p. 61).

Hydraulic fracturing tests in selected boreholes have provided numerical estimates for the magnitudes of the horizontal stresses. Vertical stresses are estimated from the thickness and density of the overlying strata. Within the Cohassett flow, the mean maximum and minimum horizontal stresses are 61.5 and 32.8 MPa (8,920 and 4,760 lbf/in^2), respectively; the mean vertical stress is 24.2 MPa (3,510 lbf/in^2) (see Tables 2.6-4, 2.6-5; Section 2.6.2.2.5). These mean values result in ratios of mean maximum horizontal stress to vertical stress of approximately 2.5:1. These data are important in the engineering design of the underground works of a repository (Chapter 2).

The in situ stress data can be used to predict the tectonic stability or instability of fractures in the Cohassett flow. For example, the shear stress computed from the measured principal stresses can be compared to the shear stress required by Byerlee's friction law to initiate sliding, for a given normal stress, on a preexisting surface (Byerlee, 1978). Such comparisons indicate that the existing stress state is insufficient to cause shear failure, based on Byerlee's criterion (Kim et al., 1986, p. 58; Section 2.6.2.2.5).

1.3.2.4 Vertical and lateral crustal movement

Information on vertical and lateral crustal movement is derived from two primary sources: interpretation of geologic data and geodetic survey results. Geologic data, which includes the spatial and temporal relationship of strata to geologic structures such as folds and faults, document the amount and rate of crustal deformation over geologic time. Because the stratigraphic record is incomplete and there are uncertainties in dating specific horizons, estimates for amounts and rates of deformation that are based on available data are only approximate. Geodetic survey results provide information on contemporary crustal movement. They record crustal deformation that has occurred in historic time following the development of precise surveying instruments and techniques. Geodetic surveys record changes in elevation and horizontal distance over time by repeated surveys of monuments in established networks.

1.3.2.4.1 Geologic studies of crustal deformation

Geologic studies of the amount and rates of crustal deformation have focused on the Yakima Fold Belt of the Columbia Plateau, particularly within and surrounding the Pasco Basin and at the reference repository location (Reidel et al., 1983). The investigations have emphasized the study of variations in thickness and of paleosurface structures of flows of the Columbia River Basalt Group, interbedded Ellensburg Formation, and the suprabasalt Ringold Formation. The variations in thickness record paleostructural relief and provide a method of calculating the amount and rate of growth of the anticlines of the Yakima Fold Belt. Preliminary estimates for the amount and rate of crustal shortening across the fold structures of the Yakima Fold Belt have been derived from an analysis of geologic cross sections (Reidel, 1984, pp. 966-973). Information on lateral movement of the crust also has been interpreted from analysis of paleomagnetic data for Columbia River basalt flows. Such analysis provides information on possible horizontal rotation, about a vertical axis, of parts of the Earth's crust (Reidel et al., 1984).

From analyses of the variations in thickness and the lateral extent of basalt flows and intercalated sedimentary units, it has been argued that the Pasco Basin was evolving structurally during Grande Ronde, Wanapum, and Saddle Mountains times, approximately 16.5 to 6 m.y.B.P. (Reidel et al., 1980, 1982, 1983, pp. 5-1 to 5-19; Reidel and Fecht, 1981, pp. 3-41; Reidel, 1984). Although the great volume and rapid rate of eruption of the Grande Ronde Basalt, combined with limited surface exposures, have masked evidence for the development of structural features, the evolution of several broad features is discernible. Examples include the growth of the Hog Ranch-Naneum Ridge anticline (Reidel and Fecht, 1981, pp. 3-41; Landon et al., 1982; Campbell, 1985) and the structural subsidence of the Pasco Basin (Reidel et al., 1982; Landon et al., 1982).

The growth of several Yakima folds during Grande Ronde time (approximately 17.0 to 15.5 m.y.B.P.) also can be demonstrated using other lines of evidence (Beeson and Moran, 1979a, pp. 5-77; Reidel, 1984, pp. 955-958). The Saddle Mountains were evolving structurally in late Grande Ronde time, as evidenced by the thinning and the absence of flows of the high-magnesium chemical type near Sentinel Gap. Price (1982, p. 39) documented evidence for thinning of the Umtanum flow near Priest Rapids Dam, but was uncertain as to whether thinning was related to growth of the Umtanum Ridge anticline or of the Hog Ranch-Naneum Ridge anticline. The absence of the Vantage interbed along parts of the Saddle Mountains, Umtanum Ridge, and other Yakima folds (Reidel and Fecht, 1981) suggests that most Yakima folds were developing topographically, hence structurally, during Grande Ronde time.

Variations in thickness and in the lateral extent of all Wanapum and Saddle Mountains flows, and some Grande Ronde flows, indicate that the present Yakima folds were actively developing throughout much of the Miocene (Reidel et al., 1980, pp. 1-43; Reidel, 1984, pp. 955-975; Reidel and Fecht, 1981, pp. 3-41). Deformation was concentrated along first-order folds, as shown by areas of maximum thinning that consistently correspond to anticlines

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and areas of maximum thickening that correspond to synclines. On the basis of thicknesses and distributions of basalt flows across the Saddle Mountains, the average rate of uplift is interpreted to be greatest during Grande Ronde time, at an average of approximately 250 m/m.y. (825 ft/m.y.) (Reidel, 1984, Fig. 13). The average uplift rate decreased to approximately 40 to 80 m/m.y. (130 to 260 ft/m.y.) by late Miocene (Reidel et al., 1980, 1983; Reidel, 1984, Fig. 13).

Evidence for the continuation of deformation--whether uninterrupted or episodic--from the Miocene to the present time is summarized by Reidel et al. (1983, pp. 5-1 to 5-19) and Reidel (1984, pp. 966-973) for the Pasco Basin and by Bjornstad (1985) for the area within and adjacent to the reference repository location. The evidence is (1) thinning or nondeposition on ridges and continued deposition and accumulation of sediments in synclines; (2) cumulative deformation in the suprabasalt sedimentary deposits, and (3) average rates of uplift and subsidence, extrapolated from the Miocene to the present, that can account for the present structural relief.

After emplacement of the basalts, thick sequences of sediment continued to be deposited in the basins (Tallman et al., 1981, pp. 2-1 to 2-28). Because deformation continued during deposition, the older suprabasalt sedimentary deposits (i.e., the lower and basal Ringold units) have increasingly greater dip with increasing age in the flanks of synclines (PSPL, 1982, p. 2R-3). This is demonstrated by decreasing structural relief on top of Ringold units. The history of deformation since the end of Ringold time at approximately 3 m.y.B.P. is less clear because of erosion. The upper surface of the Ringold Formation, for example, is less the result of structures than the result of erosion; a paleovalley is incised into the Ringold Formation. The top of the Plio-Pleistocene unit represents partial filling of this paleovalley with locally derived alluvium (Bjornstad, 1985).

The rate of uplift in Ringold time is estimated to be the same as that calculated for late Saddle Mountains time, approximately 40 m/m.y. (130 ft/m.y.) (Reidel, 1984, Fig. 13). However, preliminary age estimates and stratigraphic relationships along the margins of the central Cold Creek syncline suggest that the rate of subsidence in the reference repository location may have accelerated temporarily during middle Ringold time (Bjornstad, 1985). Extrapolation of the 40-m/m.y. (130-ft/m.y.) rate of uplift to the present is supported by the work of Rohay and Davis (1983), who analyzed microearthquake swarms at the Saddle Mountains and modeled the seismicity on an assumed planar fault that dips 45°. They estimated the seismic deformation to be approximately 0.02 to 0.04 mm/yr (0.0008 to 0.0016 in/yr), which is in reasonable agreement with the rate of uplift extrapolated from geologic data (i.e., 0.04 to 0.08 mm/yr or 40 to 80 m/m.y. (0.0016 to 0.003 in/yr or 130 to 260 ft/m.y.))

Estimates for the amount and rate of crustal shortening appear to be of the same order of magnitude as that of uplift (Reidel, 1984, pp. 972-973). Because the Yakima Fold Belt consists of a series of generally east-west-trending folds, crustal shortening as derived from geologic data is in a north-south direction, perpendicular to this trend. Bentley (1980b) developed

north-south cross sections across the western part of the Columbia Plateau and, from them, calculated minimum amounts of crustal shortening. For the areas west of 120° W. longitude, along the 120° W. longitude, and east of 120° W. longitude, the total minimum amounts of shortening are 15, 9, and 4 km (9, 5.5, and 2.5 mi), respectively. Reidel (1984, pp. 972-973) estimated a minimum amount (3 km (1.8 mi)) of shortening at Sentinel Gap, due to folding and faulting of the Saddle Mountains anticline, with at least 2.5 km (1.5 mi) of shortening due to fault displacement alone.

Beck (1976, 1980) and Reidel et al. (1984) noted that varying amounts of clockwise rotation are consistently identified in paleomagnetic studies of rocks from eastern and western Washington and Oregon. Within the Pasco Basin, clockwise rotation of up to 30° in the Pomona flow (12 m.y.B.P.) has predominated, although counterclockwise rotation of as much as 6° has occurred locally (Reidel et al., 1984, Fig. 7). The clockwise rotation reaches its maximum in the crest and hinge areas of the anticlines of the Pasco Basin and decreases toward the synclinal troughs. The amount of rotation appears to be controlled by segments of the anticlines. It has probably occurred along a closely spaced, northwest-trending, right-lateral shear system that developed in the anticlines as they evolved structurally under the presence of north-south compression. Because of the apparently close relationship between the anticline and the rotation, rotation probably began with folding and continued as the folds evolved structurally (Reidel et al., 1984).

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1.3.2.4.2 Contemporary crustal movement

Indications of contemporary crustal movement come from geodetic surveys and earthquake seismicity. Studies of contemporary vertical and lateral crustal movement in the Columbia Plateau have focused on the site and have relied primarily on the analysis of geodetic data. The data from these surveys provide information on contemporary crustal deformation through repeated measurements of changes in relative elevation and distance that occur with time. Vertical control data are obtained through leveling surveys, and horizontal control data through trilateration surveys.

The analysis of leveling data for the Columbia Plateau is based on the review and evaluation of survey data and results reported by Tillson (1970). Tillson (1970) used first-order leveling data obtained during the 1904 through 1959 period from surveys along four regional survey lines: (1) Seattle, Washington, to Pasco, Washington; (2) Pasco, Washington, to Spokane, Washington; (3) Pasco, Washington, to Ontario, Oregon; and (4) Pasco, Washington, to Portland, Oregon. Because elevation data for the four survey lines were collected at different times and along numerous line segments, no single point was considered constant for the purpose of calculating absolute uplift or subsidence. Tillson's results are, therefore, relative vertical velocities calculated for the remaining survey lines relative to the Seattle, Washington, to Pasco, Washington, line. From these relative vertical velocities, Tillson constructed a velocity contour map of the Columbia Plateau that was used in the analysis of crustal changes.

Tillson's (1970) analysis of the regional leveling data suggests that the Pasco Basin is gradually subsiding at an average rate of approximately 1 mm/yr (0.04 in/yr). Only data from first-order leveling surveys were used to calculate the rates. The most consistent and accurate data come from the Pasco, Washington, to Portland, Oregon, line and show a maximum of 33 mm (1.3 in.) of subsidence at Umatilla, Oregon, in 22 yr. The average rate of subsidence is less than 1 mm/yr (0.04 in/yr) along The Dalles, Oregon, to Pasco, Washington, line. The Seattle, Washington, to Pasco, Washington, and Pasco, Washington, to Spokane, Washington, lines also show an average rate of subsidence of 1 to 2 mm/yr (0.04 to 0.08 in/yr), with a maximum rate of approximately 3 mm/yr (0.12 in/yr) at Selah, Washington. The leveling surveys do not indicate any significant movements where the lines cross known tectonic structures. In particular, the leveling data do not indicate vertical displacement at Wallula Gap, where the Pasco, Washington, to Ontario, Oregon, level line crosses the Olympic-Wallula lineament. This line showed 1 mm/yr (0.04 in/yr) of subsidence as far south as Pendleton, Oregon. Tillson (1970) considered the 1-mm/yr (0.04-in/yr) rate of subsidence observed in the Pasco Basin to be comparable with other surveyed areas where crustal movement is minor or negligible.

Tillson's (1970) analysis of triangulation data for the Columbia Plateau provides no evidence for horizontal crustal movement. All position changes were less than the magnitude of the errors associated with the measurement techniques or were attributable to the instability of surveying monuments.

The analysis of leveling data for the site is based on data from a 20-km (12-mi) first-order level line that traverses the reference repository location in a north-south direction from Gable Mountain to Rattlesnake Mountain (Prescott and Savage, 1984, pp. 22-28; Fig. 1.3-67). This survey line was established to investigate possible contemporary vertical crustal movements in proximity to the reference repository location. The line consists of 15 monuments that were emplaced in 1982 and 5 preexisting benchmarks. The line was surveyed initially in 1982 for baseline elevation data and again in 1983 to assess monument stability. It is not possible to compare directly the elevations observed for this 1-yr interval for several reasons: not all first-order surveying specifications were adhered to in the two surveys, different sets of intermediate monuments were used during the two surveys, and some monuments were reset without being tied to the original location (Prescott and Savage, 1984, pp. 23-24). However, Prescott and Savage believe that a baseline now exists to which the data from future surveys can be compared.

Horizontal control data come from a trilateration network established by the U.S. Geological Survey in 1972 to measure horizontal strain accumulation in the Pasco Basin (Savage et al., 1981). This network consists of 19 monuments and their corresponding trilateration observation lines (see Fig. 1.3-67). Nearly all these lines have been surveyed eight times: twice in 1972 and once each in 1973, 1975, 1978, 1979, 1981, and 1983. During 1981, nine additional monuments were established for the BWIP to expand the previously established network in the reference repository location. The purpose of this expansion was to measure any horizontal strain that might be accumulating along the Rattlesnake-Wallula alignment.

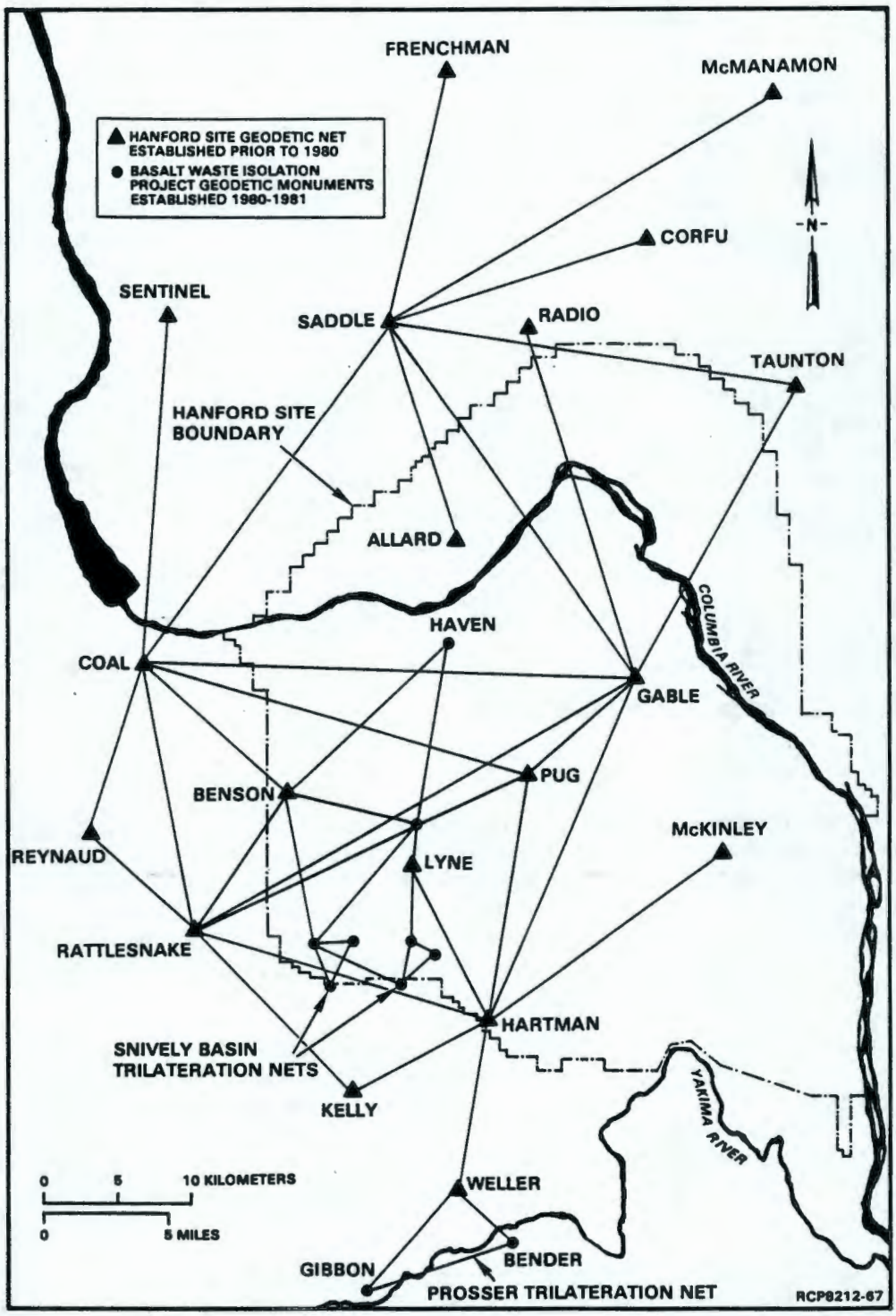

Figure 1.3-67. Locations of geodetic trilateration survey lines within and immediately adjacent to the Hanford Site, Washington (Prescott and Savage, 1984).

A survey of the 29 lines of the Hanford trilateration network was last conducted in 1983 (Prescott and Savage, 1984, pp. 4-20). The results of this survey indicate only minor horizontal changes since the 1981 survey. The horizontal changes for the 1982 to 1983 period could represent uniform strain accumulation, with principal strain rates of -0.016 ±0.013 microstrain per year oriented N. 3° W. ±34° and -0.024 ±0.013 microstrain per year oriented N. 87° E. ±34° (Prescott and Savage, 1984). The horizontal changes from 1981 to 1983 observed across the Cold Creek syncline suggest north-south shortening at a rate of -0.27 ±0.22 microstrain per year (Prescott and Savage, 1984, p. 6).

However, these measured changes are not statistically significant at the 95% confidence level and are within the error limits for the recording equipment. Thus, it is not evident that deformation is being measured. To verify that shortening is being recorded, surveying of the network will be necessary for several more years (see Section 8.3.1.2.4.3.1 for geodetic survey plans). However, the present data, which show very low rates of horizontal changes in the surveys, are consistent with the long-term, low-average rates derived from geologic information.

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1.3.2.5 Geothermal regime

1.3.2.5.1 Geothermal characteristics

1.3.2.5.1.1 Temperature

Temperature data provide a direct measure of subsurface heat energy, which is the primary target of geothermal assessment. Numerous temperature surveys and geothermal resource assessments have been made through the Washington State Department of Natural Resources and through DOE-funded contracts (Schuster, 1974; Blackwell, 1974; Korosec and Schuster, 1980; Biggane, 1982; Korosec et al., 1983; Widness, 1983; Stoffell and Widness, 1983; Blackwell et al., 1985; and Barnett, 1986).

A temperature gradient contour map of Washington (Fig. 1.3-68) was published by the Washington State Department of Natural Resources (Korosek et al., 1983). This map demonstrates the general configuration of temperatures in southeastern Washington and includes the Hanford Site. Based on the temperature data selected and analyzed in the above-mentioned report, the geothermal gradient in the Hanford Site ranges from 35 to 55 °C/km (152 to 210 °F/mi).

The ambient temperature for the Cohassett flow at the approximate proposed repository depth of 1 km (3,280 ft) can be determined from borehole temperature surveys. The temperature data available that are closest to the proposed repository location are from borehole RRL-2A (Wintczak, 1984, pp. 30-37). Two BWIP contractors ran temperature surveys in the borehole. Birdwell ran an open-hole temperature log that indicates 36 °C (97 °F) at 826 m (2,710 ft). Extrapolating the temperature gradient to the center of the

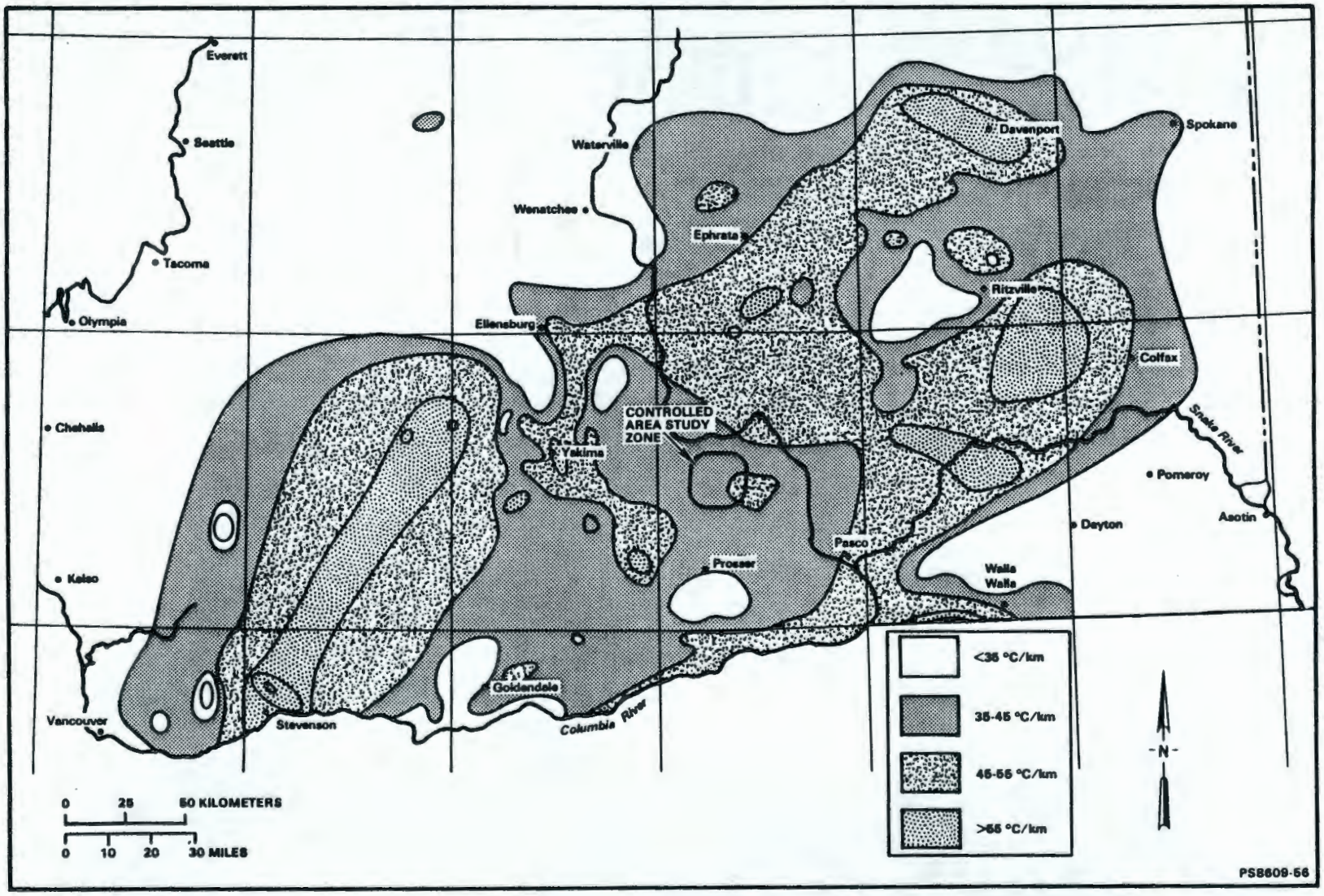

Figure 1.3-68. Temperature gradient contour map of Washington State (from Korosek et al., 1983).

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Cohassett flow (a depth of 976 m (3,200 ft)), a temperature of approximately 57 °C (135 °F) would be predicted. Pacific Northwest Laboratory ran a temperature log through the 100-m- (300-ft-) thick Cohassett flow that recorded 45 °C (113 °F) at 926 m (3,036 ft) and 47 °C (117 °F) at 1,017 m (3,336 ft). Therefore, the range of predicted temperatures for the Cohassett flow at the proposed repository location is from 45 to 57 °C (113 to 135 °F).

The differences in the temperature surveys run by the two contractors has to be resolved before a narrower range of expected ambient temperaures can be determined. The differences may be due to the time when the temperature survey was run relative to the time when drilling stopped. Typically, borehole fluids circulated through the formation during drilling reduces the formation temperature by approximately 10%. A sufficient time interval between ceasing drilling and running a temperature survey needs to take place, so that the formation can reach thermal equilibrium. Instrument calibration prior to the temperature survey was done by both of the contractors mentioned above.

An assessment of geothermal resource potential for the Pasco Basin and vicinity was prepared for the BWIP by Murphy and Johnpeer (1981). These authors selected data from Korosec and Schuster (1980) and from the BWIP, using only what they considered to be the most reliable data. The thermal gradients that they determined were within the range of 35 to 45 °C/km (152 to 210 °F/mi) and are considered normal. However, within the Hanford Site, several exceptions were listed, with three boreholes having geothermal gradients of 45 to 50 °C/km (181 to 196 °F/mi). In addition, a group of five wells northeast of the Hanford Site had measured and calculated gradients above normal (40 to 90 °C/km (167 to 312 °F/mi). Although the authors indicated that further investigation of the causes for these elevated gradients is warranted, they judged the potential for high- and intermediate-temperature geothermal systems in the Pasco Basin to be insignificant. However, they believe there is the potential for low-temperature hydrothermal convection systems within the Pasco Basin.

Inherent problems existing within any temperature survey can include (1) the methods used for selecting the temperature data, (2) the methods used for determining the geothermal gradients, and (3) the quality control of thermal tool calibration. The least reliable temperature measurements are from shallow, uncased, or poorly cased water wells, where temperature logs are often run from water table to the top of the aquifer. The most reliable temperature measurements are made in deeper holes, using high-resolution temperature probes. Therefore, understanding how and where the temperature data were collected in the borehole is important to describe accurately the geothermal regime of this area.

The inherent problems associated with temperature surveys and resulting assessments for geothermal regimes are demonstrated by the two contractors discussed above. The uncertainties of the data selected and the different methods used for determining the geothermal gradient suggest that a thorough review and assessment of the temperature surveys available in the Hanford Site should be performed. Plans for additional geothermal work are discussed in Section 8.3.1.6.

1.3.2.5.1.2 Thermal properties

Thermal properties of the Grande Ronde Basalt and Umtanum and Pomona flows on the Hanford Site have been compiled and analyzed in reports by Schmidt et al. (1980), FSI (1980), and Sublette (1983), and are discussed in Section 2.4 (Tables 2.4-5 through 2.4-8).

1.3.2.5.1.3 Heat flux

Heat flow measured at the Earth's surface is the effect of crustal and mantle radioactivity, heat sources, regional hydrology, and thermal refraction (related to structurally or depositionally created thermal conductivity contrasts). Mechanisms for heat transfer in the Earth are through conduction, convection, and advection. Heat transfer by radiation is considered insignificant at crustal depths.

The thermal effects of conduction are mathematically expressed using a diffusion equation. The diffusion equation can be simplified to a one-dimensional, steady-state equation and used to determine a heat flow value:

$$Q = K\, dT/dz$$

where

Q = Heat flow

K = Thermal conductivity

dT/dz = Geothermal gradient.

Transmission of heat by convection is through vertical movement of the heat-transporting medium (water) as a result of density differences. Advection is the horizontal movement of water as a result of hydraulic pressure gradients. Convection and advection in a groundwater system will disturb the geothermal gradient and introduce errors into heat flow, which is estimated using a purely conductive heat flow model.

The interpretation of the geothermal gradient must take into account the influences of local geology and hydrology on the temperature-depth curve. If conductive heat flow dominates, a uniform temperature-depth curve is observed. Sharp perturbations in the temperature-depth profile are indicative of hydrologic and (or) geologic (thermal refraction) effects on the geothermal gradient. Figure 1.3-69 demonstrates the effects of local hydrology and local geology on the temperature-depth curve in a borehole (DC-23GR) drilled at the Hanford Site. The fluctuations of the temperature-depth curve in Figure 1.3-69 occur at flow tops where permeability is high, compared to the the lower permeabilities of flow interiors. The temperature survey was run before any hydrologic testing. The cooling effect, or sharp temperature drops, can be interpreted to represent invasion of the drilling fluid into the formation. Deviations in temperature profiles from temperature surveys run soon after drilling and prior to hydrologic testing can be used to delineate

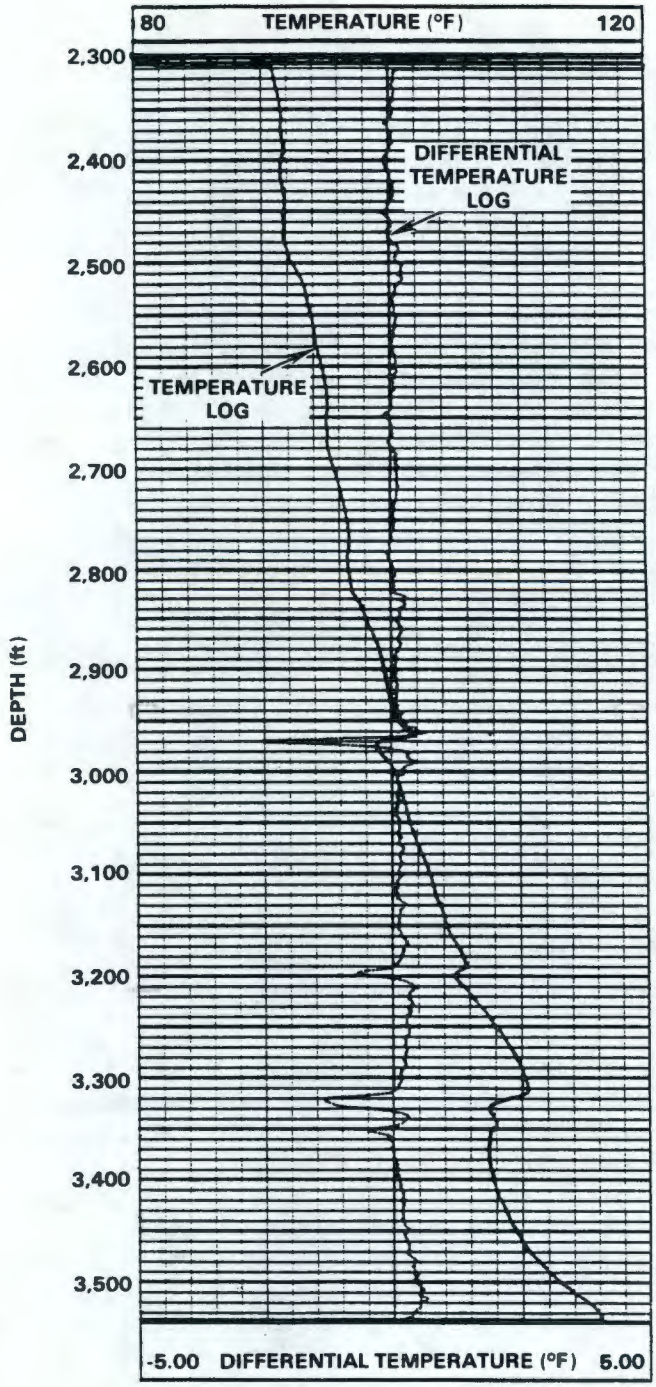

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Figure 1.3-69. Temperature and differential temperature logs at borehole DC-23. Logs were run by Gearhardt on May 1, 1986.

permeable zones, thus helping define hydrologic conditions in the vicinity of the borehole.

The complexity in interpreting the thermal pattern in the Columbia Plateau is discussed by Blackwell et al. (1985) with respect to changing water flow conditions in a hole through time. Three temperature surveys, shown in Figure 1.3-70, were run on a deep hydrocarbon exploration well (Development Associates Basalt Explorer No. 1) over a 20-yr period. Blackwell et al. (1985) have interpreted the water flow conditions of the well from the three temperature curves. The conditions appear to be simplest in 1961, with the water table at 40 m (131 ft); water flowed downhole to between 700 to 800 m (2,297 to 2,625 ft) and discharged into the formation. Between 800 and 1,200 m (2,625 to 3,937 ft), the temperature gradient appears constant, except at the bottom where an isothermal section suggests either intrahole water flow or possible hangup of the cable in the hole. In 1972, the water flow pattern had changed. Water entered at the 500-m (1,640-ft) depth with upward flow between 300 to 500 m (984 to 1,640 ft) and downward flow between 500 to 800 m (1,640 to 2,625 ft). In 1981, the flow pattern had changed again; water was entering at the water table and discharging at depths of 210 to 300 m (689 to 984 ft) and approximately 450 m (1,476 ft). Figures 1.3-69 and 1.3-70 clearly demonstrate the effect that water flow can have on temperature-depth curves and that water flow patterns change through time.

In determining heat flow, it is important to ascertain the dominant mechanism for heat transfer. In the Columbia Plateau, heat transfer by convection and advection associated with hydrologic systems is an important parameter in the overall regional heat flow. Errors in estimating heat flow can be introduced if heat transfer is affected by advective/convective mechanisms in a region, and a purely conductive heat flow model is assumed in the numerical analyses. Proper treatment of the heat flow data would include advective, convective, and conductive mechanisms in the derivation of the governing equations.

Four data points for heat flow have been reported by Blackwell (1980) for the Pasco Basin. The locations of these data points relative to the Hanford Site are indicated on Figure 1.3-71. Available temperature surveys, coupled with thermal conductivity data, could be used to determine additional heat flow values in the Pasco Basin.

1.3.2.5.2 Geothermal implications

1.3.2.5.2.1 Tectonics

Several authors (Baksi and Watkins, 1973; Swanson et al., 1975) have attempted to identify the tectonic regime that produced the Columbia River basalts. The authors compare the estimated rate of accumulation of Columbia River basalts to different tectonic regimes where similar volumes and types of basalts are being produced. The tectonic regimes include ocean island (hot spots) and ocean (spreading) ridges. Baksi and Watkins (1973) calculated the

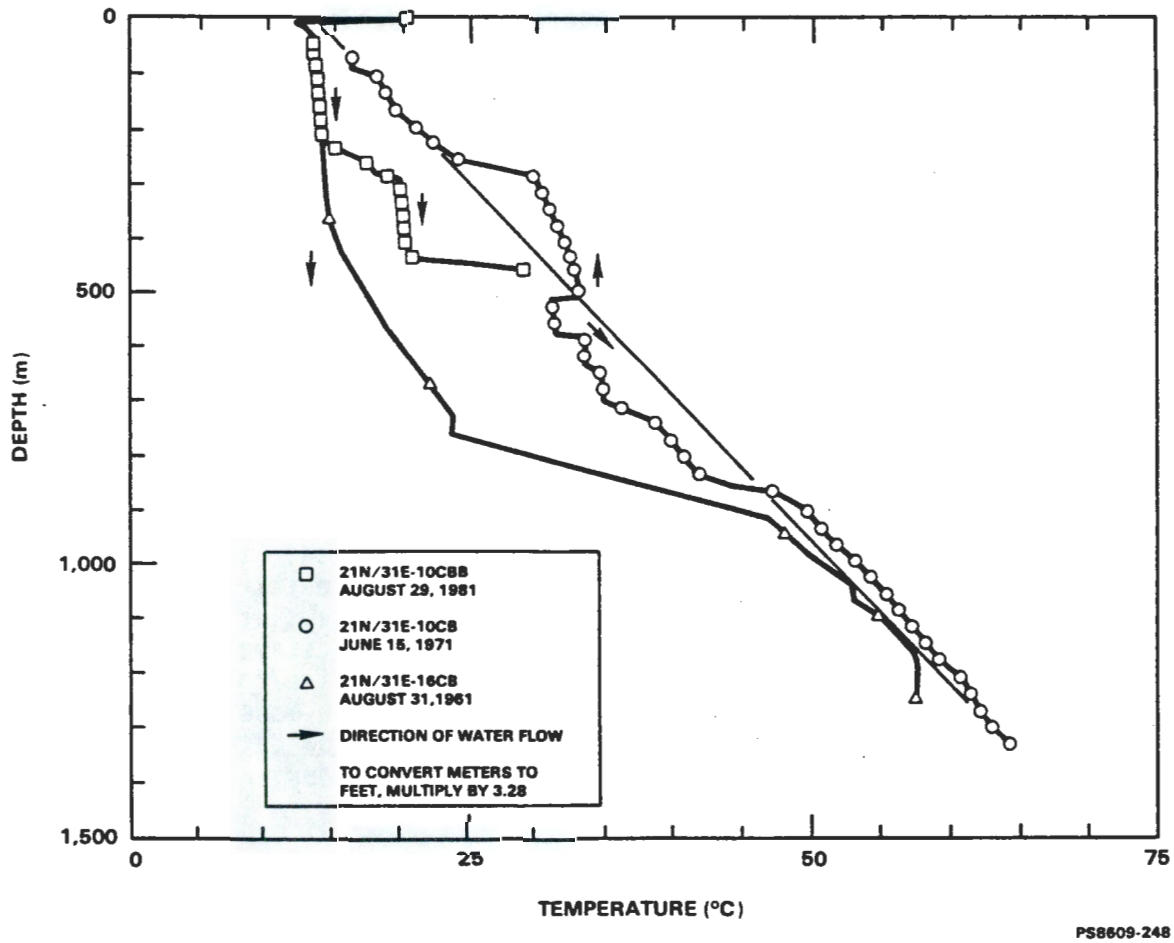

Figure 1.3-70. Temperature-depth curves for Development Associates Basalt Explorer No. 1. Three logs measured over a 20-yr period are illustrated for this hole. Every fifth point on each log is plotted by a symbol (direction of water flow interpreted by Blackwell et al., 1985).

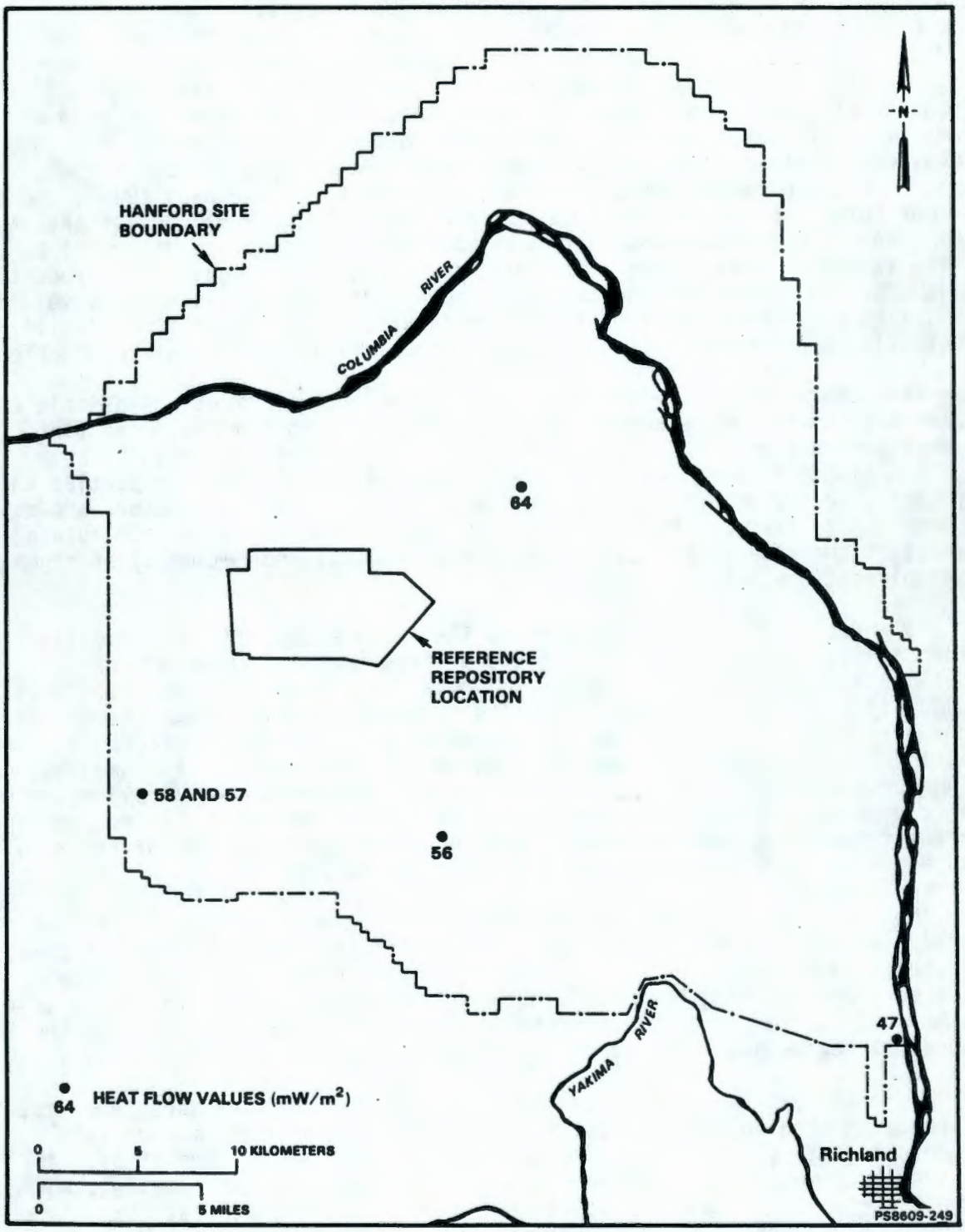

Figure 1.3-71. Heat flow in the Pasco Basin (from Blackwell, 1980).

accumulation rate of the Columbia River basalts to be 1.1 x 10^{-1} km^3/yr (0.028 x 10^{-1} mi^3/yr). They consider this to be two to three times the production rate of oceanic islands and four to six times the production rate of spreading ocean ridges. Swanson et al. (1975) indicate that rates of discharge of some Yakima Basalt Subgroup flows were comparable to those of older flows of Mauna Loa and Kilauea; while other flows, including the Roza flows, were erupted at rates of three to four orders of magnitude higher. Hawaiian rates of magma production have varied with time (Shaw, 1973), and the current rate is considered a maximum. Swanson et al. (1975) suggest that the Yakima Basalt Subgroup production rate appears to be comparable to, but more likely several times greater than, the rate along most ridges. The production rates described above for the two tectonic regimes that produce large volumes of basalts similar to those of the Columbia River basalts are inconclusive in identifying the precise tectonic regime for Columbia River basalt production.

Parameters to consider in discerning geothermal implications associated with the tectonic regime are those that contributed to the development of magma supply and eruption and subsequent accumulation of Columbia River basalts. These parameters are based on chemical and physical properties that may control magma production and eruption. Some of these parameters are magma reservoir size (large, small, or equal to approximate volume of accumulated basalt), magma reservoir location (mantle or crust), and number(s) of magma reservoir(s) (one large or many small).

Tolan et al. (1987) has determined the areal extent and volume of the Columbia River Basalt Group. Table 1.3-9 lists the time interval for eruptions and volumes for the major Columbia River basalts. The rates of accumulation for the sequence of basalts decrease through time. The Grande Ronde Basalt represents the largest volume of basalt erupted over the shortest time interval, whereas the Saddle Mountains Basalt represents the smallest volume erupted over the longest time interval. The geothermal implication that can be drawn from the waning volcanism is that the mechanism responsible for the magma production, eruption, and subsequent accumulation of the Columbia River basalts has not been active for the past 6 m.y.

The implications of various possible tectonic regimes that led to the eruption of the Columbia River Basalt Group affected the possible magnitude, duration, and dissipation of heat flux within the crust and at the Earth's surface. The resulting heat residing within the rocks due to the tectonic regime that led to the eruption of the Columbia River basalts affected the geothermal regime and, consequently, the geothermal resource potential.

Regional heat flow maps have been developed for western North America, and patterns of high and low heat flow have been associated with certain tectonic regimes (Blackwell, 1969, 1978; Roy et al., 1968; Sass et al., 1971). The tectonic implications of heat flow patterns and gravity anomalies, with respect to subduction and arc volcanism in the Pacific Northwest, have been discussed by several authors. They include studies in the Idaho Snake River Plain (Brott et al., 1978), northern Oregon (Blackwell et al., 1982), and southwestern British Columbia (Hyndman, 1976). Heat flow patterns observed in the western part of the Pacific Northwest are considered to be related to the

Table 1.3-9. Age, duration, volume, percent of total volume, and rate of accumulation of major Columbia River Basalts

Formation	Age, m.y. (duration)	Volume (km^3)	Total volume (%)	Rate of accumulation, (km^3/m.y.)
Saddle Mountains Basalt	6.0 - 14.5 (8.5)	2,393	<1	282
Wanapum Basalt	14.5 - 15.6 (1.1)	10,673	6	9,703
Grande Ronde Basalt	15.6 - 16.5 (1.3)	149,244	87	93,616
Picture Gorge/Imnaha Basalt	>16.5	8,164	5	--

NOTE: The rate of accumulation decreases with younger age of the formations

subduction zone of Oregon and Washington (Blackwell et al., 1982). The high heat flow inland in southern British Columbia is considered by Berry et al. (1971) to be the northern extension of the Cordilleran thermal zone of Blackwell (1969), which includes the Columbia Plateau, northern Rocky Mountains, and the Basin and Range geologic provinces.

Present knowledge of heat flow and its association with tectonics relative to long-term stability are not well understood for the Columbia Plateau (Section 1.5).

1.3.2.5.2.2 Repository design

The geothermal implications for repository design are addressed in Section 2.9.3.6 and Section 6.2.6.3.1.

1.3.2.5.2.3 Repository performance

The geothermal implications for repository performance are addressed in Section 8.3.5.

1.3.2.5.2.4 Energy resource extraction

Murphy and Johnpeer (1981) published a study that discusses the potential for low-temperature hydrothermal convection systems within the Pasco Basin. Comparing the Pasco Basin to areas of high geothermal resource potential (average greater than 100 mW/m^2), such as the Oregon Cascades, southern Idaho, Imperial Valley, and Rio Grande Rift, the authors state that there is no indication that a localized heat source is present within the Pasco Basin, or that the region is characterized by anomalously high heat flow.

The Washington State Energy Office conducted a study for the Bonneville Power Administration in 1985 that evaluated geothermal and economic data, and ranked 1,265 potential geothermal resource sites in Washington, Oregon, Idaho, and Montana. Several potential sites ranked for direct low temperature geothermal utilization are in close proximity (less than 72 km (less than 45 mi)) to the repository site (Bloomquist, 1985, Table 10.2). Some of these sites and their ranks include Yakima (3rd), Richland (18th), Pasco (20th), and Othello (53rd).

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1.4 SEISMOLOGY OF CANDIDATE AREA AND SITE

1.4.1 SEISMOLOGY OF THE CANDIDATE AREA

1.4.1.1 Seismicity of candidate area

1.4.1.1.1 Regional setting

An analysis of earthquake activity in areas beyond the Columbia Plateau is necessary to provide an understanding of the tectonic setting and for subsequent determination of earthquake risk to a repository. The regional setting to be considered in the following description is the area generally referred to as the Pacific Northwest, which includes Washington State and parts of Oregon, Idaho, and British Columbia. The historic record of earthquake activity in this region dates from about 1840. The early part of the record is based on felt reports and is probably incomplete, since the region was sparsely populated and seismograph networks did not start providing reasonably complete coverage of eastern Washington State until approximately 1969. Hence, the early history is qualitative and provides only general information about regional seismicity.

Numerous earthquakes of modified Mercalli (MM) intensity V or greater have occurred in the Pacific Northwest (Fig. 1.4-1; Coffman and von Hake, 1982), most of which are concentrated west of the Cascade Range. The strongest and most numerous shocks have occurred in the vicinity of Puget Sound. One of the largest known events occurred in the Strait of Georgia on June 23, 1946, and produced an MM intensity of VIII and magnitude of 7.3. Another large event occurred near Olympia, Washington, on April 13, 1949, of magnitude 7.1 and an MM intensity VIII. A large event of uncertain location and size occurred in north-central Washington on December 14, 1872. Current NRC consensus for this event assigns a maximum MM intensity ranging from VIII to IX and a surface-wave magnitude of approximately 7, and places it somewhere within a broad region of the Northern Cascades-Okanogan Tectonic Province extending from near Lake Chelan, Washington, to southern British Columbia (NRC, 1982, pp. 2-31 to 2-32, and Appendix G). Analyses of isoseismal data suggest that a location in the northern part of this broad region is most appropriate (Malone and Bor, 1979). The largest earthquakes east of the Cascades were the 1959 Hebgen Lake, Montana, earthquake, which had a surface-wave magnitude of 7.5 (Doser, 1985), and the Borah Peak, Idaho, event, which had a surface-wave magnitude of 7.3 (Doser and Smith, 1985).

The distribution of instrumentally located events for the period 1965 through 1979 is shown in Figures 1.4-2 and 1.4-3. Most of the activity in Washington State occurs in the Puget Sound area; this is especially true for events with focal depths greater than approximately 10 km (6 mi). Reviews of

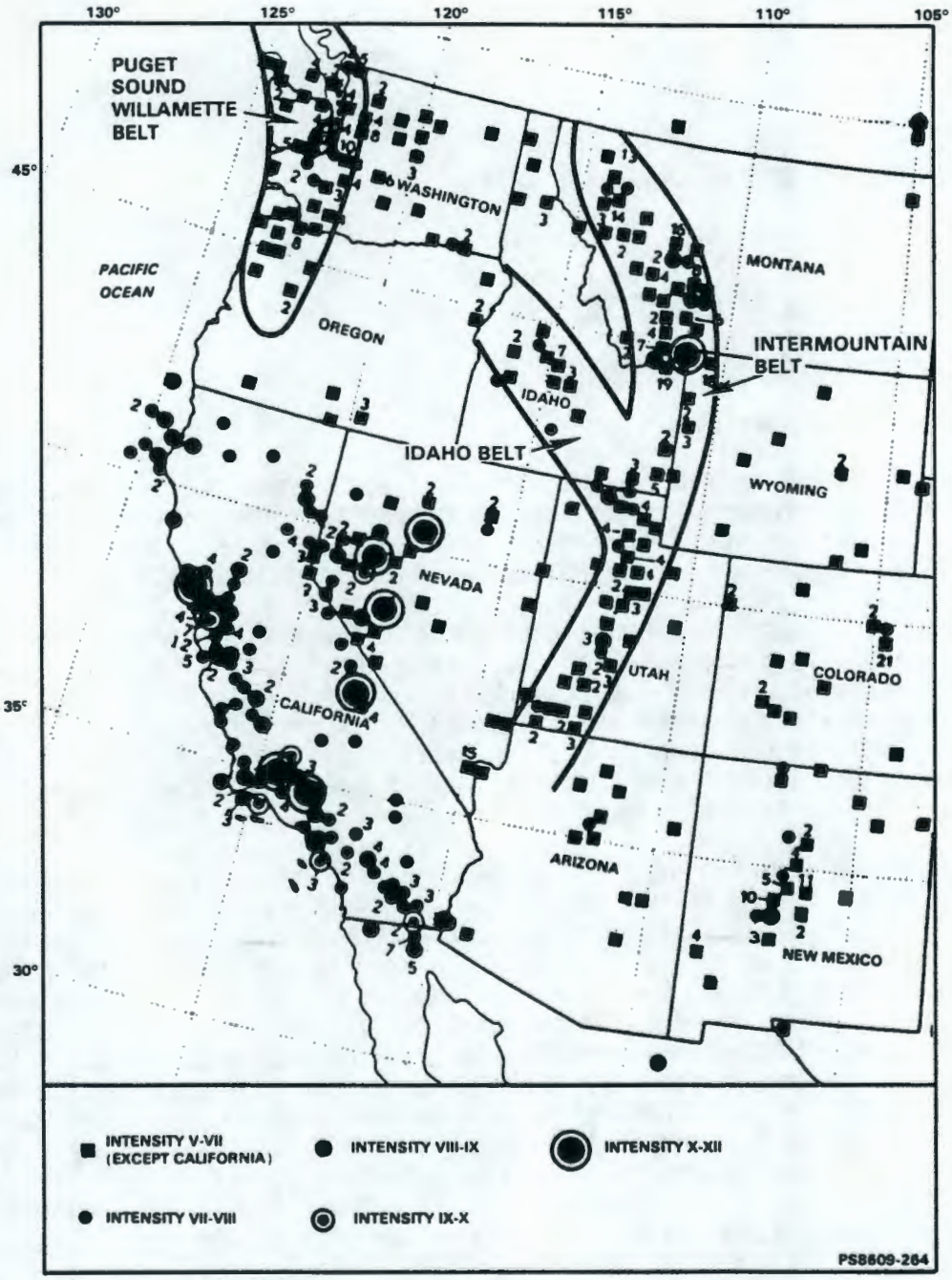

Figure 1.4-1. Earthquakes of modified Mercalli intensity V and greater for the western United States through 1980 (modified from Coffman and von Hake, 1982, p. iv; the 1872 earthquake was classified as only intensity VI and was plotted as having occurred in the Puget Sound region in this publication). The numerals in this figure denote the total number of events where several occurred in the same general area. Also shown are the boundaries of seismic provinces discussed in the text.

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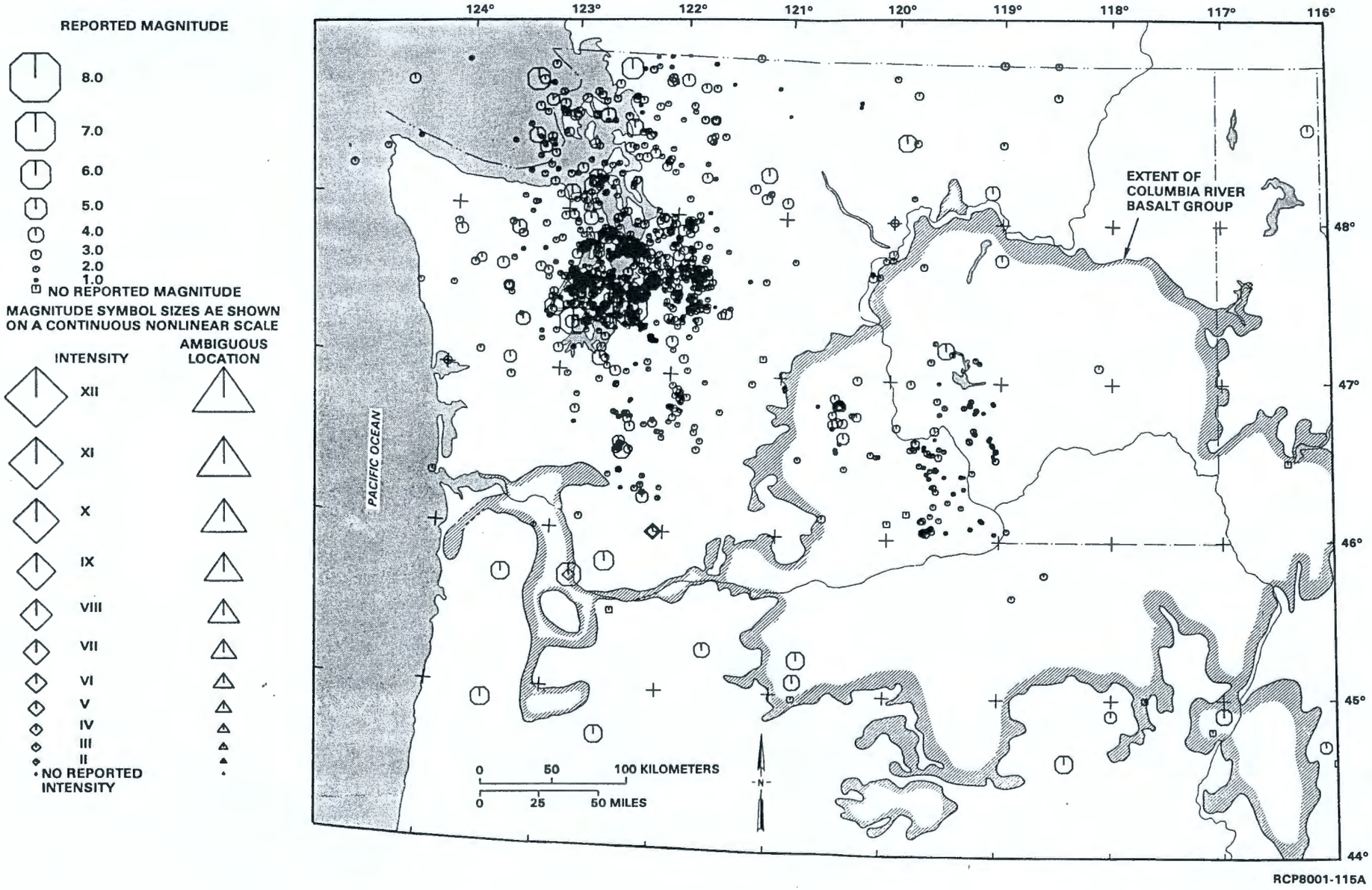

Figure 1.4-2. Instrumentally located events in Washington, northern Oregon, and western Idaho in the Pacific Northwest, 1965 to 1979 (Caggiano, 1983, pp. 2-12 to 2-13). Events with focal depths greater than 10 km (6.2 mi).

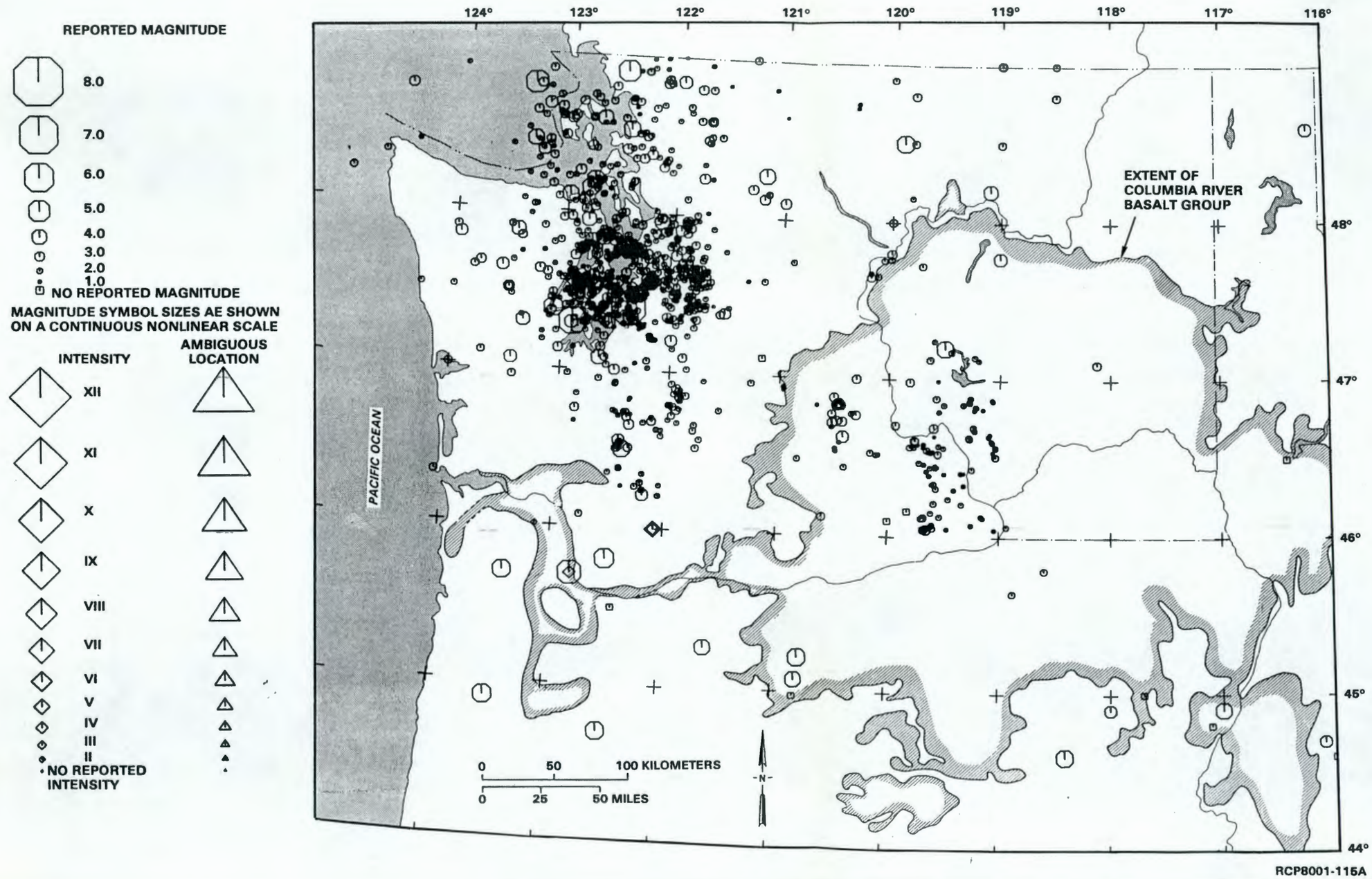

Figure 1.4-2. Instrumentally located events in Washington, northern Oregon, and western Idaho in the Pacific Northwest, 1965 to 1979 (Caggiano, 1983, pp. 2-12 to 2-13). Events with focal depths greater than 10 km (6.2 mi).

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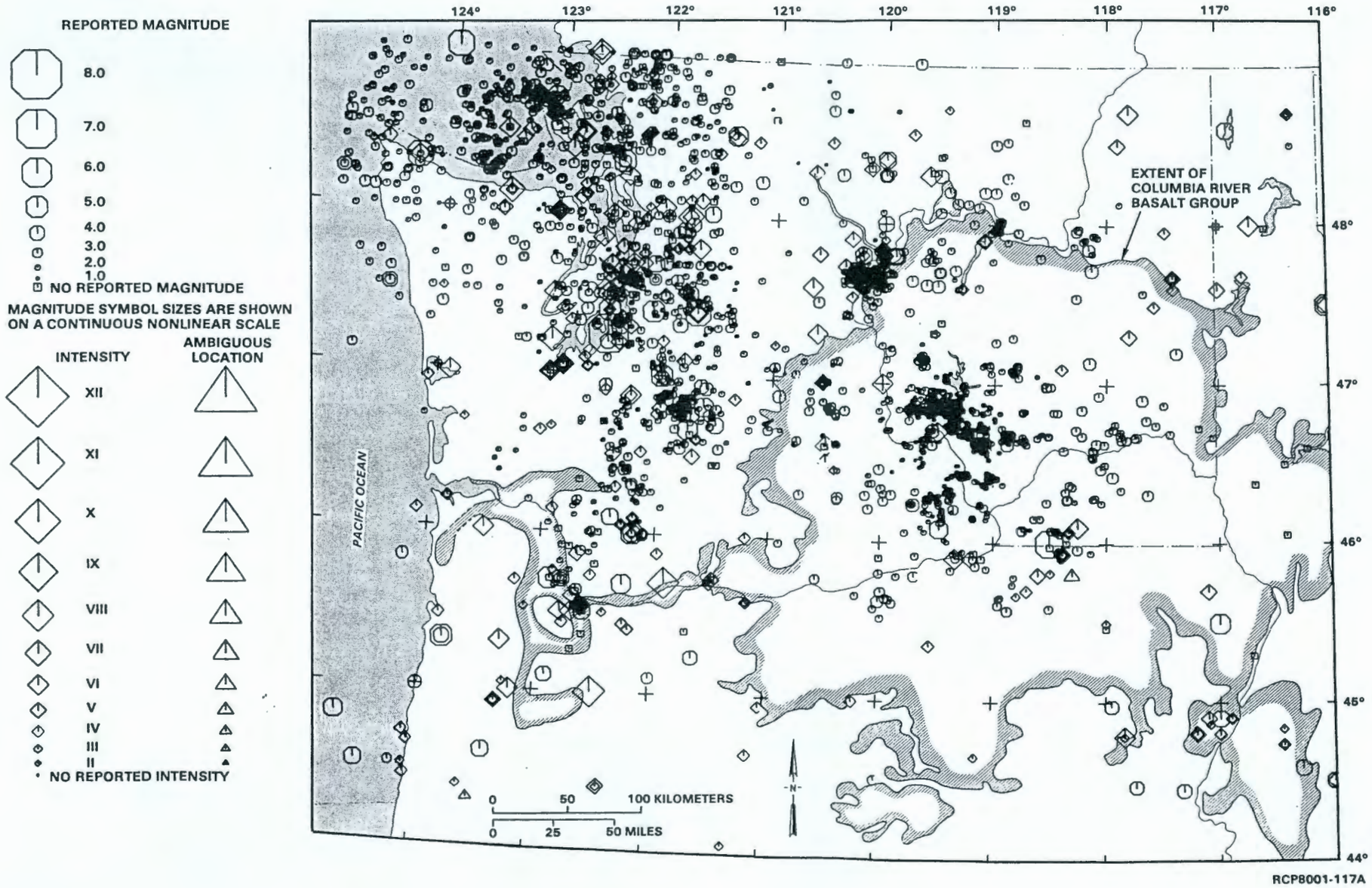

Figure 1.4-3. Instrumentally located events in Washington, northern Oregon, and western Idaho in the Pacific Northwest, 1965 to 1979 (Caggiano, 1983, pp. 2-12 to 2-13). Events with focal depths less than 10 km (6.2 mi).

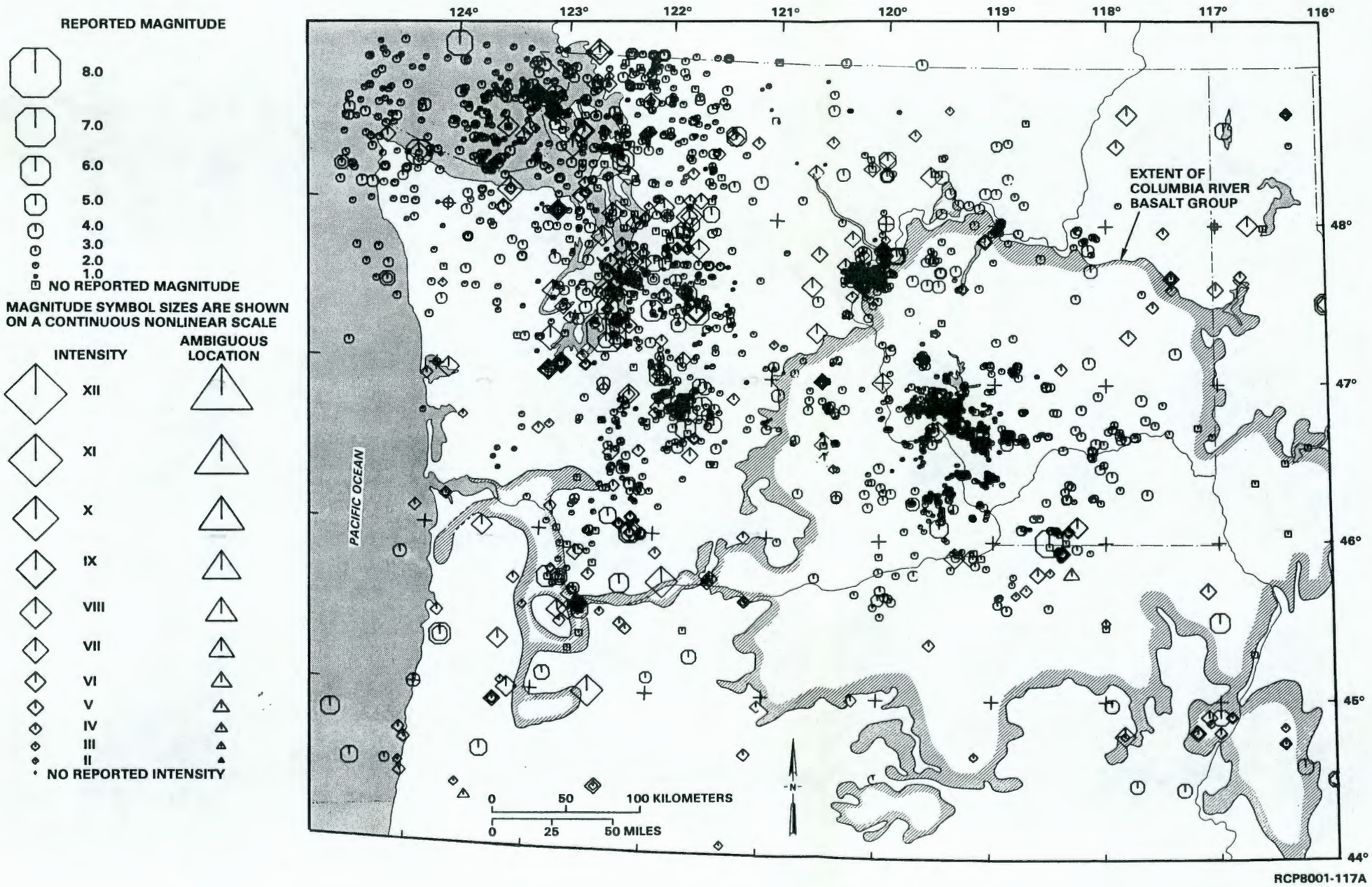

Figure 1.4-3. Instrumentally located events in Washington, northern Oregon, and western Idaho in the Pacific Northwest, 1965 to 1979 (Caggiano, 1983, pp. 2-12 to 2-13). Events with focal depths less than 10 km (6.2 mi).

The velocity model used by the University of Washington for locating

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seismicity in the Puget Sound lowland can be found in Rasmussen (1967), Crosson (1972), and Stepp (1973). This zone of relatively high seismic activity extends northwestward into British Columbia across Vancouver Island, the Strait of Juan de Fuca, and the Strait of Georgia. Near the center of Vancouver Island, the trend turns westward and joins a zone of high earthquake activity that is associated with an active sea-floor spreading center and transform faults (Chandra, 1974; Milne et al., 1978). Relatively high activity continues southward through the Willamette Valley in Oregon, where it diminishes south of Eugene, Oregon (Couch and Lowell, 1971; Crosson, 1972).

Within the Puget Sound area, earthquakes as large as magnitude 7.1, with focal depths as deep as 90 km (56 mi), have occurred. Most earthquakes and, in particular, most of the larger events have occurred at focal depths greater than 10 km (6 mi), which is in distinct contrast to the magnitudes and focal depths of events east of the Cascade Range (See Fig. 1.4-2 and 1.4-3).

Focal mechanism solutions for earthquakes in the Puget Sound area are reviewed by Weaver and Smith (1983, p. 10,380-10,383). Crustal earthquakes show northeast- to north-directed maximum compressive axes, with a mixture of strike-slip and reverse faulting. The northeast-directed maximum compression, found predominantly in southwest Washington, roughly parallels the inferred relative plate convergence direction. The deeper earthquakes, including the 1965 Seattle earthquake (body-wave magnitude 6.5), have focal mechanisms that indicate normal faulting with tensional axes dipping 25° to the northeast. The deeper earthquakes are believed to be occurring in the subducted plate, and the tension axes tend to parallel the inferred dip of the subducting plate. Baker and Langston (1987) suggest that the tension axis of the 1949 South Puget Sound earthquake (magnitude 7.1) also parallels the dip direction of the subducting plate. Heaton and Kanamori (1984) review the evidence for present day subduction, and compare the Pacific Northwest subduction zone and its earthquake potential to other regions of active subduction.

In the Pacific Northwest, east of the Cascade Range and west of the Rocky Mountain Crest, earthquake activity is relatively low, with the largest events limited to magnitudes that rarely exceed 7. The 1959 Hebgen Lake, Montana, and the 1983 Borah Peak, Idaho, events are the exceptions in the historical record, with surface-wave magnitudes of 7.5 (Doser, 1985) and 7.3 (Doser and Smith, 1985), respectively. The most seismic activity occurs in a zone that extends in a northwesterly direction across central Idaho and appears to branch off from a larger north-trending zone in Utah referred to as the Intermountain Seismic Belt (see Fig. 1.4-1). The former zone, known as the Idaho Seismic Belt, is an area of shallow earthquake activity that extends across the Idaho Batholith province (Smith and Sbar, 1974; Vincent and Applegate, 1978). Earthquakes in the Idaho Seismic Belt typically have focal depths less than 15 km (9 mi), magnitudes less than approximately 6, and occur as swarms of events. They can frequently be correlated with post-Miocene faulting where geologic maps are available (Vincent and Applegate, 1978). To the south of this belt, the Snake River Plain appears as an area of low earthquake activity, as indicated by historical reports of felt events and by the instrumental record (Smith and Sbar, 1974; Pennington et al., 1974).

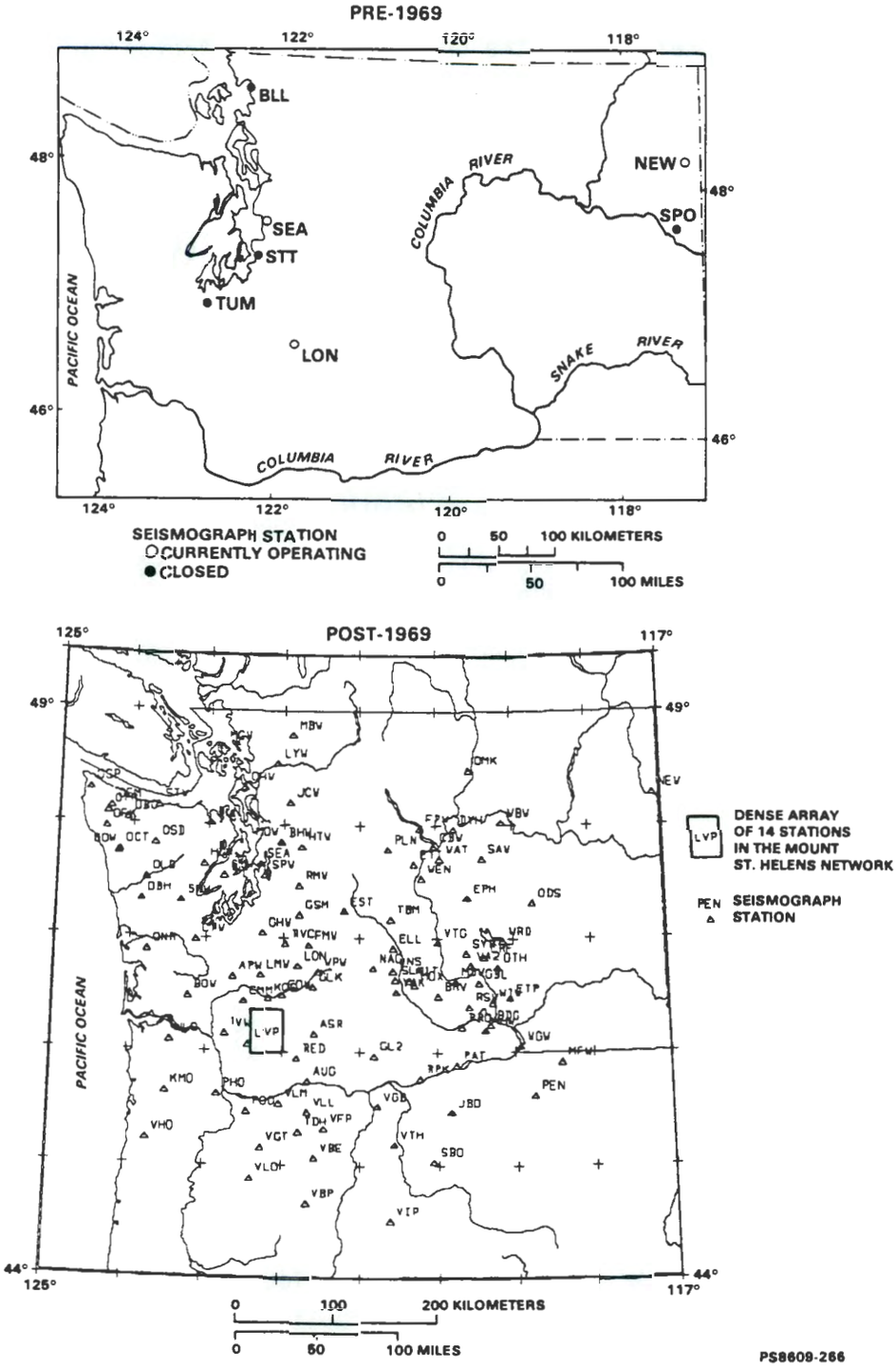

Figure 1.4-4. The distribution of seismograph stations in the Pacific Northwest before 1969 (upper figure) and as of 1984 (lower figure) (UWGP, 1984).

The velocity model used by the University of Washington for locating hypocenters of all events that occurred from 1969 to present is discussed in the University of Washington Geophysics Program Annual Technical Report (UWGP, 1977, pp. 27-34). The current procedure employed by BWIP for locating hypocenters using the program HYPO71 is detailed in Lee and Lahr (1975, pp. 1-116). The University of Washington routinely used the same program prior to 1980, but has subsequently used a modification of program FASTHYPO (Herrmann, 1979, pp. 25-37). A new velocity model for the Pasco Basin has been developed from recent seismic refraction surveys conducted to interpret the crustal structure underlying the Columbia Plateau (Rohay et al., 1985, pp. 1-19; Glover, 1985). This new velocity model will be used in an attempt to improve previous earthquake locations (Section 8.3.1.2.4.3.3.2).

The development of the University of Washington network, station locations, and thresholds of earthquake detection have previously been described by Woodward-Clyde Consultants (WCC, 1981a, pp. 7-8). Earthquake magnitudes are determined using a coda-length magnitude relationship that was developed for this region (UWGP, 1979, pp. 38-45). Prior to 1972, earthquake magnitudes were determined from amplitudes of the seismograph trace (Pitt, 1971, p. 19). The relationship between these two magnitude determination methods is being studied UWGP (1986, pp. 27-28), since it is important for relating earthquake data acquired before 1972 to that acquired after 1972 (Section 8.3.1.2.4.3.3.4).

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1.4.1.1.3 Historical record for the Columbia Plateau

1.4.1.1.3.1 Earthquake catalogs

Prior to 1969, the instrumental detection of earthquakes in eastern Washington State, northeastern Oregon, and northern Idaho was limited to a few events that were sufficiently large to have been recorded by the sparse network of stations that existed. This restricted the instrumental record to events that were generally larger than Richter magnitude 4. Smaller events were located from felt reports, resulting in records that have greater uncertainty in determining the epicenter location and no means of determining focal depth. Since the installation of additional networks in 1969 by the U.S. Geological Survey and the University of Washington, the instrumental record has become far more complete and accurate. Figure 1.4-4 contrasts seismograph station coverage for the period prior to 1969 with that for the period following 1969.

Numerous catalogs for events within the geologic setting have been assembled for a variety of studies. Rasmussen (1967) assembled a catalog of events for Washington State between 1851 and 1965. The University of Washington Geophysics Program maintains an archive for all data collected by the U.S. Geological Survey from 1969 through 1974 and by the University of Washington since 1975. These data are published in annual reports (UWGP, 1975, 1977, 1978, 1979, 1980, 1981, 1982, 1983, 1984, 1985; Malone, 1976).

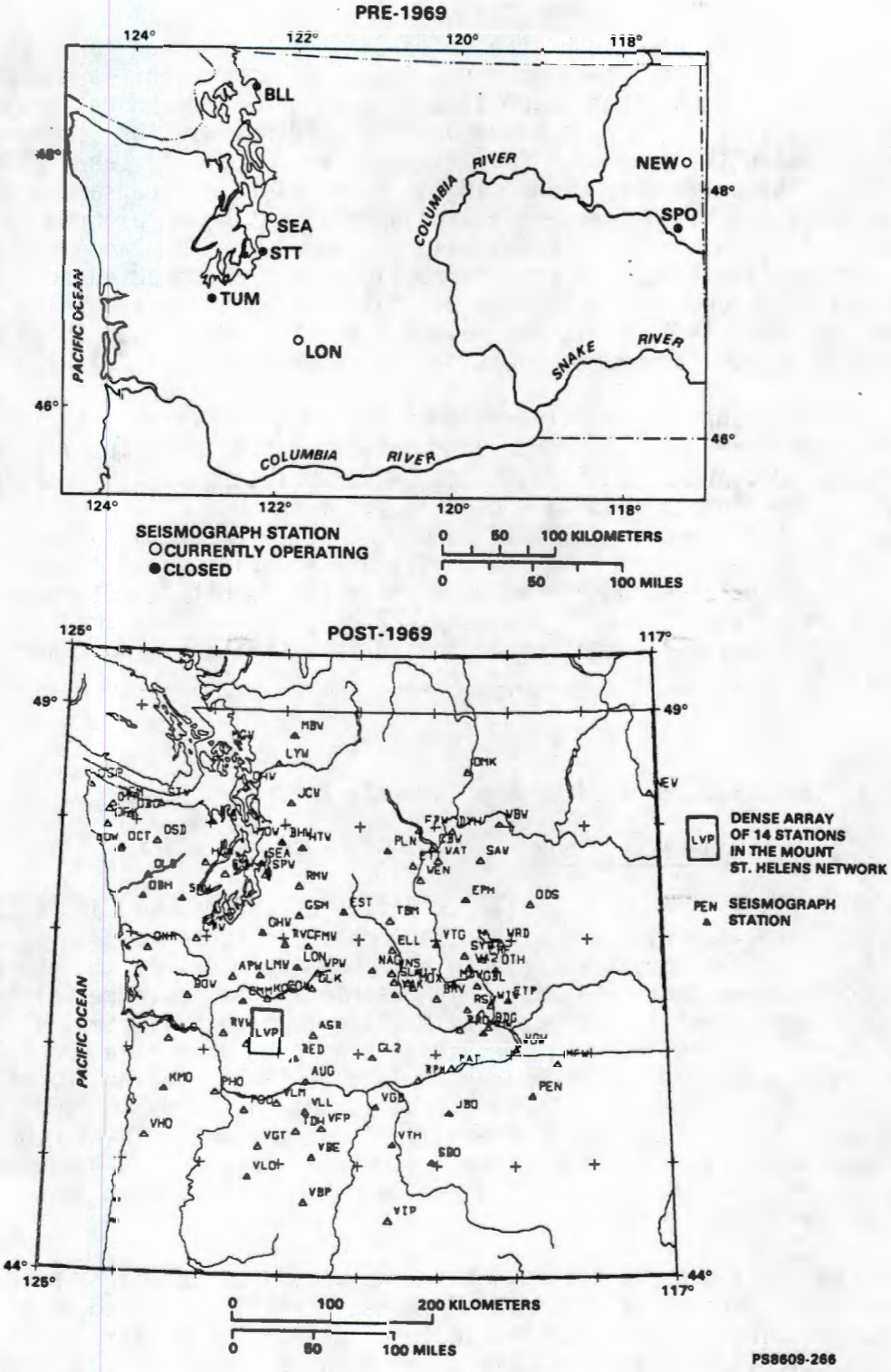

Figure 1.4-4. The distribution of seismograph stations in the Pacific Northwest before 1969 (upper figure) and as of 1984 (lower figure) (UWGP, 1984).

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A comprehensive catalog of historical earthquakes was assembled as part of the nuclear powerplant siting investigations conducted during the late 1970s, which included a listing of all events of MM intensity III, or magnitudes 3.0 and larger, for the Pacific Northwest through December 1979 (WPPSS, 1981, pp. 2.5-221 to 2.5-393). A summary of larger events can also be found in Coffman and von Hake (1982), and more detailed accounts are included in annual reports of the Environmental Data and Information Service of the National Oceanic and Atmospheric Administration.

Using the above sources, Table 1.4-2 has been compiled to list all earthquakes known to have occurred in the Columbia Plateau that have MM intensities greater than IV or magnitudes of 4.0 or greater. The record for events having an MM intensity of less than IV or a magnitude less than 4.0 is incomplete for the area; therefore, these smaller events are not included in Table 1.4-2. The Washington Public Power Supply System (WPPSS, 1981, Table 2.5-5, pp. 2.5-220 to 2.5-385) lists the magnitude 3.0 and MM intensity III events felt and (or) located in the Pacific Northwest.

1.4.1.1.3.2 Description of selected earthquakes

On December 4, 1872 a major earthquake occurred somewhere in the vicinity of north-central Washington State. Because of the sparse population and lack of recording instruments at that time, the location and size of this earthquake are uncertain. The earthquake was studied during siting investigations for nuclear powerplants in both western and eastern Washington State. A review by the Washington Public Power Supply System indicated the 1872 earthquake had a maximum MM intensity of VIII to IX and a surface-wave magnitude of 7 to 7-1/4 (WPPSS, 1981, pp. 2.5-115 through 2.5-118), in general agreement with the findings of the NRC and the U.S. Geological Survey (NRC, 1982, pp. 2-31 to 2-31, and Appendix G). The Washington Public Power Supply System study also concluded that the earthquake occurred within the Northern Cascades tectonic province in a broad meizoseismal zone extending northward from the vicinity of Lake Chelan to southern British Columbia. The NRC concluded (NRC, 1982) that the boundary between the North Cascades tectonic province and the Columbia Plateau is about 140 km (88 mi) north of the Hanford Site at its closest approach.

On March 5, 1893, an earthquake occurred near Umatilla, Oregon, which is about 70 km (44 mi) south of the reference repository location. Early estimates suggested that this earthquake had a maximum MM intensity of VII, but this was subsequently reduced to MM intensity VI (WPPSS, 1981, p. 123). The earthquake appears to have affected only a limited area, as no felt reports could be found during a search of old newspapers from Pendleton and Milton-Freewater, Oregon, and Yakima, Walla Walla, and Spokane, Washington (WPPSS, 1981, p. 123).

An earthquake occurred in the vicinity of the Saddle Mountains and Frenchman Hills on November 1, 1918, which was followed by several, smaller events over subsequent weeks. The original report of this event (BSSA, 1918; also, WPPSS, 1981, p. 2.5-120) estimated a Rossi-Forel epicentral intensity of IV, which is equivalent to an MM intensity IV to V (Richter, 1958,

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Table 1.4-2. Earthquake listing for the Columbia Plateau and surrounding area (sheet 1 of 7)

Date	Universal time	Intensity[a]/ magnitude	Coordinates	Remarks
Earthquakes with magnitude ≥3 or intensity ≥IV, 1866 to 1969 (source: WPPSS, 1981, pp. 2.5-299 to 385)				
November 24, 1866	18:10:00.0	IV	45.595°N. 121.173°W.	The Dalles, Oregon
December 15, 1872	05:40:00.0	IX	49.000°N. 121.000°W.	Lake Chelan, Washington
September 2, 1891	10:30:LT	IV	47.100°N. 118.400°W.	Ritzville, Washington
September 17, 1891	04:30:00.0	IV	44.940°N. 121.033°W.	Salem, Oregon
February 29, 1892	10:45:00.0	IV	45.595°N. 121.173°W.	The Dalles, Oregon
March 5, 1892	LT	VI	46.600°N. 120.500°W.	North Yakima, Washington
March 5, 1893	LT	VI	45.900°N. 119.333°W.	Umatilla, Oregon
December 15, 1897	LT	V	47.800°N. 120.000°W.	Lakeside, Washington
October 18, 1905	23: LT	V	47.800°N. 120.000°W.	Chelan, Washington
January 2, 1906	LT	VI	48.700°N. 117.800°W.	Stevens County, Washington
November 2, 1906	01:49:00.0	V	48.500°N. 117.900°W.	Reported felt information
February 18, 1907	12:20:LT	V	47.842°N. 120.023°W.	Chelan, Washington
January 21, 1909	05: LT	IV	47.800°N. 120.000°W.	Chelan, Washington
May 24, 1909	22: LT	V	47.730°N. 120.360°W.	Chelan-Leavenworth, Washington
July 5, 1911	08:00:00.0	V	46.998°N. 120.540°W.	Ellensburg, Washington
October 14, 1913	23:00:00.0	V	45.700°N. 117.100°W.	Reported felt information
March 5, 1915	05:10:00.0	IV	47.830°N. 120.020°W.	Lakeside, Washington
March 5, 1915	05:30:00.0	IV	47.830°N. 120.020°W.	Lakeside, Washington
July 18, 1915	20:54:00.0	IV	47.830°N. 120.020°W.	Lakeside, Washington
August 18, 1915	14:05:00.0	V	48.500°N. 121.400°W.	Felt over 78,000 km² (30,000 mi²)
December 10, 1915	20:45:00.0	IV	47.672°N. 117.405°W.	Spokane, Washington
February 21, 1918	LT	IV	46.867°N. 121.333°W.	Bumping Lake, Washington
February 28, 1918	23:15:00.0	V	46.500°N. 120.500°W.	Near Yakima, Washington
March 12, 1918	03:26:00.0	V	47.600°N. 117.000°W.	Reported felt information
April 18, 1918	21:13:00.0	IV	47.600°N. 117.400°W.	White Bluffs Prairie, Washington
November 1, 1918	17:20:00.0	VI	46.858°N. 119.375°W.	Corfu, Washington
October 7, 1920	02: LT	V	47.633°N. 120.067°W.	Waterville, Washington
November 28, 1920	11:30:00.0	IV	45.700°N. 121.500°W.	Hood River, Oregon
September 14, 1921	11:00:00.0	VI	46.100°N. 118.250°W.	Dixie-Walla Walla, Washington
June 1, 1922	23:30:00.0	IV	47.672°N. 117.405°W.	Spokane, Washington
January 6, 1924	13:09:00.0	IV	46.070°N. 118.328°W.	Walla Walla, Washington
January 6, 1924	23:10:00.0	V	45.800°N. 118.300°W.	Milton and Weston, Oregon

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Table 1.4-2. Earthquake listing for the Columbia Plateau and surrounding area (sheet 2 of 7)

Date	Universal time	Intensity[a]/ magnitude	Coordinates	Remarks
Earthquakes with magnitude ≥3 or intensity ≥IV, 1866 to 1969 (source: WPPSS, 1981, pp. 2.5-299 to 385)				
May 27, 1924	00:19:00.0	IV	46.070°N. 118.328°W.	Walla Walla, Washington
November 28, 1925	01:25:00.0	4.30 ML	47.500°N. 116.000°W.	--
April 23, 1926	13:56:00.0	IV	46.070°N. 118.328°W.	Walla Walla, Washington
October 17, 1926	02:45:00.0	V	45.730°N. 121.483°W.	White Salmon, Washington
November 27, 1926	18:25:LT	V	47.500°N. 116.000°W.	Near Rathdrum, Idaho
December 30, 1926	17:57:00.0	VI	47.700°N. 120.200°W.	Chelan-East Central Washington
January 3, 1927	04:58:00.0	VI	47.593°N. 120.658°W.	Leavenworth, Washington
September 3, 1930	13:00:00.0	V	47.300°N. 117.800°W.	Near Lamont, Washington
December 8, 1931	14:25:00.0	IV	47.830°N. 120.020°W.	Lakeside-Chelan Falls, Washington
May 31, 1933	20:20:00.0	IV	47.842°N. 120.013°W.	Chelan, Washington
May 31, 1933	20:30:00.0	IV	47.842°N. 120.013°W.	Chelan, Washington
March 9, 1934	16:00:00.0	IV	47.830°N. 120.020°W.	Lakeside, Washington
September 18, 1934	24: LT	V	46.998°N. 120.540°W.	Ellensburg, Washington
September 22, 1934	11:30:LT	IV	46.998°N. 120.540°W.	Ellensburg, Washington
September 22, 1934	17:37:LT	IV	46.998°N. 120.540°W.	Ellensburg, Washington
September 26, 1934	16:15:LT	V	46.998°N. 120.540°W.	Ellensburg, Washington
September 26, 1934	16:45:LT	V	46.998°N. 120.540°W.	Ellensburg, Washington
September 26, 1934	21:15:LT	V	46.998°N. 120.540°W.	Ellensburg, Washington
October 4, 1934	02:26:LT	IV	46.998°N. 120.540°W.	Ellensburg, Washington
October 11, 1934	21:19:LT	IV	46.998°N. 120.540°W.	Ellensburg, Washington
October 19, 1934	23:31:LT	V	46.998°N. 120.540°W.	Ellensburg, Washington
October 29, 1934	18:36:LT	IV	46.998°N. 120.540°W.	Ellensburg, Washington
November 1, 1934	07:28:LT	V	46.998°N. 120.540°W.	Ellensburg, Washington
November 2, 1934	15:17:LT	V	46.998°N. 120.540°W.	Ellensburg, Washington
July 9, 1935	22:45:00.0	V	47.700°N. 120.000°W.	Near Chelan Falls, Washington
October 12, 1935	01:03:00.0	V	47.662°N. 120.223°W.	Entiat, Washington
November 1, 1935	03:35:00.0	IV	47.472°N. 115.925°W.	Wallace, Idaho
July 16, 1936	07:07:49.0	VII 6.10 ML	46.208°N. 118.233°W.	Milton-Freewater, Oregon
July 18, 1936	16:30:00.0	V	45.933°N. 118.383°W.	Milton-Freewater, Oregon
July 30, 1936	11:20:00.0	IV	45.935°N. 118.388°W.	Freewater, Oregon
July 30, 1936	12:00:00.0	IV	45.935°N. 118.388°W.	Freewater, Oregon
July 30, 1936	12:20:00.0	IV	46.070°N. 118.328°W.	Walla Walla, Washington

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Table 1.4-2. Earthquake listing for the Columbia Plateau and surrounding area (sheet 3 of 7)

Date	Universal time	Intensity[a]/ magnitude	Coordinates	Remarks
Earthquakes with magnitude ≥3 or intensity ≥IV, 1866 to 1969 (source: WPPSS, 1981, pp. 2.5-299 to 385)				
August 4, 1936	09:19:00.0	V	45.800°N. 118.600°W.	Helix, Oregon
August 28, 1936	04:39:00.0	V	45.933°N. 118.383°W.	Milton-Freewater, Oregon
February 9, 1937	22:20:00.0	IV	46.070°N. 118.328°W.	Walla Walla, Washington
June 4, 1937	14:43:00.0	IV	46.070°N. 118.328°W.	Walla Walla, Washington
August 11, 1938	18:52:00.0	IV	45.935°N. 118.388°W.	Milton, Oregon
October 27, 1938	23:10:00.0	IV	45.935°N. 118.388°W.	Milton, Oregon
January 26, 1939	07:59:00.0	IV	45.700°N. 118.700°W.	Mission, Oregon
March 24, 1940	03:04:00.0	IV	46.000°N. 121.200°W.	Mt. Rainier, Washington
April 7, 1941	09:25:00.0	VI 4.50	48.300°N. 119.600°W.	Felt over 14,000 km² (5,500 mi²)
April 12, 1941	17:40:00.0	IV	47.648°N. 120.069°W.	Waterville, Washington
February 23, 1942	14:03:00.0	V	47.600°N. 120.200°W.	Wenatchee-Chelan, Washington
June 12, 1942	09:30:00.0	V	44.900°N. 117.100°W.	Halfway and Pine, Oregon
October 14, 1942	11:30:00.0	V	48.310°N. 120.652°W.	Stehekin, Washington
November 1, 1942	18:50:06.0	VI 5.50 ML	48.000°N. 116.700°W.	Sandpoint, Idaho
April 24, 1943	00:10:46.0	VI	47.300°N. 120.600°W.	Felt over 24,000 km² (10,000 mi²)
September 22, 1943	21:50:LT	IV	47.967°N. 119.000°W.	Grande Coulee, Washington
September 2, 1944	01:25:14.0	IV	46.070°N. 118.328°W.	Walla Walla, Washington
September 20, 1944	03:00:00.0	IV	44.900°N. 116.900°W.	Rockville, Oregon
October 31, 1944	11:34:28.7	V	47.800°N. 120.600°W.	--
December 25, 1944	13:12:08.8	IV	47.662°N. 120.223°W.	Entiat, Washington
January 4, 1945	02:34:48.7	V	47.662°N. 120.223°W.	Entiat, Washington
February 27, 1945	11:00:00.0	IV	48.480°N. 121.190°W.	Winthrop, Washington
March 2, 1945	07:54:59.3	IV	47.662°N. 120.223°W.	Entiat, Washington
September 23, 1945	02:40:00.0	IV	46.070°N. 118.328°W.	Walla Walla, Washington
February 5, 1946	16:12:42.0	IV	47.800°N. 120.200°W.	Chelan-Ardenvoir, Washington
February 6, 1946	03:20:00.0	IV	48.527°N. 121.430°W.	Marblemount, Washington
December 22, 1947	10:30:00.0	IV	47.662°N. 120.223°W.	Entiat, Washington
January 13, 1948	06:55:00.0	V	47.900°N. 120.300°W.	Lucerne-Waterville, Washington
August 28, 1948	22:25:00.0	IV	47.957°N. 117.475°W.	Deer Park, Washington
October 25, 1948	19:50:00.0	IV	47.842°N. 120.013°W.	Chelan, Washington
December 20, 1948	16:18:00.0	IV	44.996°N. 120.215°W.	Fossil, Oregon
March 15, 1949	20:53:11.0	4.80 ML	45.500°N. 117.000°W.	--

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Table 1.4-2. Earthquake listing for the Columbia Plateau and surrounding area (sheet 4 of 7)

Date	Universal time	Intensity[a]/ magnitude	Coordinates	Remarks
Earthquakes with magnitude ≥3 or intensity ≥IV, 1866 to 1969 (source: WPPSS, 1981, pp. 2.5-299 to 385)				
October 20, 1949	16:00:00.0	IV	48.500°N. 120.500°W.	Lost River, Washington
March 8, 1950	06:25:00.0	IV	47.662°N. 120.223°W.	Entiat, Washington
June 25, 1950	23:45:00.0	IV	47.491°N. 117.575°W.	Cheney, Washington
January 4, 1951	13:45:00.0	V	47.700°N. 120.000°W.	Chelan-Waterville, Washington
January 7, 1951	22:45:00.0	V	45.900°N. 119.200°W.	McNary, Oregon
March 4, 1952	19:42:00.0	V	47.672°N. 117 405°W.	Spokane, Washington
September 9, 1952	09:30:00.0	IV	48.698°N. 116.315°W.	Felt Bonners Ferry, Idaho
September 9, 1952	09:45:00.0	IV	48:698°N. 116.315°W.	Felt Bonners Ferry, Idaho
September 9, 1953	09:30:00.0	IV	48.698°N. 116.315°W.	Felt Bonners Ferry, Idaho
May 23, 1954	13:41:42.0	V	48.342°N. 120 137°W.	Twisp, Washington
June 8, 1954	00:16:13.0	V	47.500°N. 116.000°W.	Mortaern-Coeur D'Alene, Idaho
February 6, 1955	LT	IV	47.967°N. 119.000°W.	Grand Coulee, Washington
May 31, 1955	23:35:00.0	IV	47.680°N. 116.773°W.	Felt Coeur D'Alene, Idaho
February 24, 1956	22:00:00.0	V	47.900°N. 119.100°W.	Electric City, Washington
November 1, 1957	10:12:02.0	4.20 ML	46.700°N. 121.500°W.	--
December 18, 1957	25:25:00.0	5.00 ML	47.500°N. 116.000°W.	--
April 12, 1958	00:00:00.0	IV	47.900°N. 119.100°W.	Electric City, Washington
April 12, 1958	22:37:11.0	4.10 ML	48.000°N. 120.000°W.	--
January 21, 1959	07:15:00.0	IV	46.070°N. 118.328°W.	Walla Walla, Washington
July 11, 1959	15: LT	IV	47.600°N. 119.300°W.	Deep Lake, Washington
August 6, 1959	03:44:32.0	4.40 ML	47.800°N. 119.900°W.	--
November 9, 1959	21:10:00.0	IV	45.353°N. 119.550°W.	Heppner, Oregon
May 22, 1961	01:57:51.4	IV	47.600°N. 120.200°W.	--
June 28, 1961	10:22:52.9	IV	47.537°N. 120.293°W.	Rocky Reach Dam, Washington
October 31, 1961	02:35:00.0	4.30 ML	48.400°N. 120.000°W.	--
October 31, 1961	03:34:29.8	V	48.400°N. 120.000°W.	Felt over 3,000 km² (1,200 mi²)
January 15, 1962	05:29:00.0	4.30 ML	47.800°N. 120.200°W.	--
December 22, 1963	02:54:04.9	V 4.40 MB	48.590°N. 119.760°W.	Reported felt information
April 28, 1965	19:00:00.0	4.30 ML	48.600°N. 116.900°W.	--
November 7, 1965	16:41:47.4	4.30 MB	44.900°N. 117.000°W.	--
July 23, 1966	01:57:08.8	4.30 MB	47.200°N. 119.500°W.	--
December 30, 1966	03:51:40.3	4.20 MB	44.900°N. 117.000°W.	--

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Table 1.4-2. Earthquake listing for the Columbia Plateau and surrounding area (sheet 5 of 7)

Date	Universal time	Magnitude[b]	Coordinates	Depth (km)	Remarks
Earthquakes with magnitude ≥3 within the Columbia Plateau, 1969 to 1986 (source: University of Washington on-line earthquake catalog)					
April 19, 1969	05:46:03:20	3.1	45.889°N. 119.742°W.	3.00	--
April 20, 1969	02:19:16:04	3.2	48.250°N. 119.272°W.	5.72	--
May 11, 1969	05:50:11:92	3.1	48.194°N. 119.228°W.	3.00	--
August 2, 1969	03:04:16:35	3.4	47.198°N. 117.375°W.	15.22	--
August 31, 1969	16:27:35:05	3.1	46.286°N. 120 776°W.	1.50	--
January 1, 1970	06.44:28:24	3.0	46.324°N. 118.396°W.	0.68	--
July 11, 1970	10:24:31:17	3.0	48.180°N. 121.311°W.	34.20	--
July 29, 1970	20:42:31:56	3.0	48.176°N. 119.313°W	3.00	--
August 23, 1970	11:11:40:67	3.3	46.745°N. 119.345°W.	2.08	--
September 11, 1970	02:20:54:11	3.5	46.642°N. 120.386°W.	9.67	--
October 2, 1970	15:56:24:73	3.3	46.760°N. 119.371°W.	3.78	--
October 19, 1970	07:15:08:09	3.2	46.904°N. 117.684°W.	3.00	--
November 6, 1970	18:15:16:77	3.1	46.691°N. 118.884°W.	3.00	--
January 26, 1971	10:17:05:02	3.2	46.921°N. 119.554°W.	1.36	--
May 22, 1971	15:57:10:83	3.3	47.788°N. 118.964°W.	14.54	--
July 13, 1971	23:29:24:49	3.5	44.922°N. 117.946°W.	3.00	--
August 18, 1971	23:44:25:96	3.2	47.610°N. 120.083°W.	1.86	--
October 25, 1971	18:52:49:98	3.8	46.709°N. 119.548°W.	0.07	--
November 23, 1971	02:12:15:42	4.1	48.233°N. 121.248°W.	18.20	--
June 19, 1972	23:57:57:57	3.2	48.131°N. 121.186°W.	9.00	--
February 6, 1973	07:17:06:89	3.0	46.936°N. 120.896°W.	8.00	--
September 4, 1973	17:56:49:92	3.7	48.239°N. 121.165°W.	6.10	--
December 20, 1973	01:08:28:24	4.4	46.869°N. 119.354°W.	2.35	--
June 15, 1975	17:51:31:49	3.1	46.237°N. 119.104°W.	0.07	--
June 28, 1975	16:33:43:66	3.3	46.129°N. 119.702°W.	10.67	--
June 28, 1975	22:17:52:65	3.8	46.118°N. 119.697°W.	10.35	--
July 1, 1975	05:28:02:24	3.6	45.628°N. 120.002°W.	1.50	--
July 7, 1975	20:41:17:79	3.2	46.074°N. 118.449°W.	2.50	--
September 18, 1975	12:19:28:51	3.5	47.796°N. 118.231°W.	0.50	--
April 13, 1976	00:47:17.1	4.8 ML, 4.5MB	45.22°N. 120.77°W.	15	Depth constrained (NOAA)
April 17, 1976	02:11:44.1	4.2 ML	45.08°N. 120.79°W.	15	Depth constrained (NOAA)

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Table 1.4-2. Earthquake listing for the Columbia Plateau and surrounding area (sheet 6 of 7)

Date	Universal time	Magnitude[b]	Coordinates	Depth (km)	Remarks
Earthquakes with magnitude ≥3 within the Columbia Plateau, 1969 to 1986 (source: University of Washington on-line earthquake catalog)					
May 15, 1976	13:04:53:56	3.0	47.707°N. 120.033°W.	4.58	--
June 15, 1976	01:01:45:68	3.0	46.488°N. 117.683°W.	0.90	--
June 15, 1976	09:08:04:90	3.0	47.627°N. 120.296°W.	0.55	--
July 23, 1976	17:59:36:78	3 0	46.080°N. 118.745°W.	2.70	--
August 30, 1976	16:34:01:55	3.0	47.649°N. 120.177°W.	3.00	--
December 13, 1976	08:47:29:41	3.1	47.643°N. 120.129°W.	5.60	--
January 27, 1977	07:47:29:20	3.2	46.939°N. 119.593°W.	1.40	--
March 11, 1977	22:50:11:41	3.1	45.895°N. 119.675°W.	0.08	--
July 13, 1977	07:15:05:68	3.8	47.058°N. 121.046°W.	0.10	--
January 25, 1978	01:09:20:80	3.3	47.892°N. 120.108°W.	1.03	--
March 22, 1978	03:08:59:57	3.3	48.090°N. 119.492°W.	11.96	--
April 16, 1978	19:45:16:90	3.3	47.752°N. 120.234°W.	0.71	--
June 11, 1978	2:43:55:05	3.1	46.841°N. 120.955°W.	0.10	--
June 27, 1978	02:19:00:26	3.4	46.938°N. 121.137°W.	3.10	--
October 10, 1978	12:04:27:93	3.1	47.901°N. 119.682°W.	2.43	--
January 19, 1979	14:55:16:97	3.9	47.896°N. 119.686°W.	6.69	--
January 21, 1979	20:40:06:14	3.0	47.895°N. 119.682°W.	3.19	--
January 30, 1979	16:06:45:71	3.0	47.662°N. 120.120°W.	5.06	--
February 17, 1979	08:36:21:41	3.6	46.169°N. 119.935°W.	9.10	--
April 7, 1979	03:47:23:62	3.0	46.956°N. 120.412°W.	9.83	--
April 8, 1979	07:29:37:81	4.2	45.995°N. 118.447°W.	4.70	--
July 28, 1979	02:19:06:94	3.7	46.670°N. 120.591°W.	0.10	--
November 10, 1979	04:53:29:82	3.2	47.720°N. 120.057°W.	0.09	--
November 18, 1979	02:08:45:53	3.1	46.887°N. 119.567°W.	1.10	--
November 24, 1979	11:51:14:98	3.4	46.931°N. 119.566°W.	0.45	--
December 10, 1979	05:40:07:46	3.4	46.657°N. 120.575°W.	5.10	--
November 19, 1980	21:35:24:07	3.3	46.950°N. 119.469°W.	0.86	--
February 2, 1981	01:23:18:30	4.0	46.263°N. 120.989°W.	1.98	Depth fixed
February 18, 1981	06:09:38:71	4.2	47.197°N. 120.892°W.	3.37	--
March 15, 1981	07:23:66:85	3.6	47.987°N. 121.493°W.	5.35	--
May 28, 1981	08:55:62:54	4.6	46.530°N. 121.398°W.	2.98	--
May 28, 1981	09:10:45:90	5.0	46.525°N. 121.394°W.	3.22	--

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Table 1.4-2. Earthquake listing for the Columbia Plateau and surrounding area (sheet 7 of 7)

Date	Universal time	Magnitude[b]	Coordinates	Depth (km)	Remarks
Earthquakes with magnitude ≥3 within the Columbia Plateau, 1969 to 1986 (source: University of Washington on-line earthquake catalog)					
June 14, 1981	13:12:56:81	3.2	45.962°N. 120.507°W.	13.58	--
July 22, 1981	06:05:50:38	3.0	47.777°N. 120.288°W.	9.53	--
October 25, 1981	03:20:63:67	3.2	47.758°N. 120.196°W.	7.58	--
January 23, 1982	15:31:37:16	3.2	46.546°N. 121.378°W.	3.33	--
September 26, 1982	10:09:23:58	3.4	46.867°N. 121.048°W.	3.25	--
March 22, 1983	12:47:02:37	3.8	45.992°N. 118.403°W.	7.53	--
April 25, 1983	15:48:20:43	3.0	48.630°N. 119.567°W.	8.03	Depth fixed
October 20, 1983	09:44:58:46	3.4	46.717°N. 119.584°W.	1.86	--
November 14, 1983	11:18:60:40	3.8	46.655°N. 120.600°W.	7.87	--
December 5, 1983	07:24:18:61	3.8	46.915°N. 120.713°W.	7.76	Depth and location fixed
January 31, 1984	05:29:17:96	4.0	45.496°N. 116.673°W.	5.65	Depth and location fixed
April 11, 1984	03:07:42:05	4.3	47.535°N. 120.185°W.	8.02	--
June 18, 1984	19:34:08:93	3.1	45.486°N. 118.840°W.	5.96	--
August 24, 1984	04:42:67:21	3.0	47.649°N. 120.955°W.	0.75	Depth and location fixed
October 10, 1984	03:24:18:24	3.0	47.904°N. 119.079°W.	15.39	--
January 9, 1985	05:46:13:26	3.3	47.064°N. 120.094°W.	0.34	--
January 25, 1985	07:28:54:49	3.1	46.500°N. 120.632°W.	16.63	--
January 31, 1985	03:02:35:09	3.3	47.059°N. 120.084°W.	0.29	--
February 10, 1985	20:29:31:72	3.9	45.704°N. 119.634°W.	18.41	--
March 9, 1985	01:31:24:44	3.3	46.984°N. 118.590°W.	3.41	--
April 19, 1985	10:52:44:29	3.2	46.897°N. 120.284°W.	5.35	--
June 9, 1985	01:24:51:45	3.2	46.675°N. 118.977°W.	3.21	--
June 17, 1985	07:00:17:26	3.0	47.058°N. 120.077°W.	0.28	--
July 16, 1985	21:13:16:33	3.2	46.189°N. 121.009°W.	0.02	Depth fixed
October 1, 1985	05:21:60	3.0	46.796°N. 120.048°W.	1.09	--
October 1, 1985	06:53:11:58	3.0	46.789°N. 120.047°W.	1.71	--
October 10, 1985	10:06:40:72	3.2	47.749°N. 120.265°W.	7.04	--
November 22, 1986	18:09:56:76	3.2	47.263°N. 119.351°W.	20.82	--
February 4, 1986	01:58:67:17	3.2	46.044°N. 118.810°W.	7.80	--
April 8, 1986	10:57:37:58	3.3	47.770°N. 120.230°W.	13.76	--
September 1, 1986	21:32:44:96	3.4	46.718°N. 119.285°W.	14.09	--

NOTE: LT = Local time.
MB = Body-wave magnitude.
ML = Local (Richter) magnitude.
NOAA = National Oceanic and Atmospheric Administration.
[a]All intensities are modified Mercalli.
[b]Unless otherwise noted, all magnitudes are coda-length magnitudes.

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Appendix III). Contemporary catalogs (Rasmussen, 1967; Coffman and von Hake, 1982) assign an MM intensity V to VI and place this event near White Bluffs, Washington although a reevaluation of felt reports of the event (Fifer, 1966) suggests that the epicenter was approximately 15 km (8 mi) to the northeast near Corfu, Washington. Recently, the instrumental location and magnitude of this event have been estimated from the lone seismogram recorded at Spokane or station SPO (WPPSS, 1981, pp. 2.5J-36 to -37). The travel time differences between the S and P waves indicate a location in the vicinity of the east end of the Saddle Mountains and the Frenchman Hills (WPPSS, 1981, pp. 2.5J-36 to -37, and Fig. 2.5J-31). A surface-wave magnitude of 4.4 is estimated on the basis of the recorded waveform and an empirical moment-magnitude relationship (WPPSS, 1981, p. 2.5J-36).

The largest earthquake known to have occurred within the Columbia Plateau was the July 16, 1936, Milton-Freewater, Oregon, earthquake. This earthquake was felt over much of eastern Washington State and northeastern Oregon and was accompanied by a number of foreshocks and aftershocks (Rasmussen, 1967, p. 468; WCC, 1980c, p. 28). The maximum epicentral intensity was estimated to be MM VII, and the surface-wave magnitude was originally estimated to be 5-3/4 (Gutenberg and Richter, 1965, p. 164). An evaluation of Gutenberg's original seismographic data suggested that the Richter magnitude could be as high as 6.1 (WCC, 1980c, p. 12). A reevaluation using station corrections (WCC, 1982) yielded a surface wave magnitude of 5.7 to 5.8 (NRC, 1982, G-17).

The location of the 1936 earthquake and, therefore, its association with a known geologic structure are uncertain. A summary of the various locations of the event is given in WCC (1980c). The epicenter was originally estimated as 45° 50' N, 118° 18' W, near Milton-Freewater, Oregon, on the basis of felt reports. The earliest determinations based on the instrumental data place the epicenter at 46.2° N, 118.2° W, northeast of Walla Walla and approximately 30 km (18 mi) north of the felt epicenter. Most recently, WCC (1980c) estimated a location at 46° 12.3' N, 118° 14.0' W from a reexamination of the instrumental data.

The spatial and temporal distributions of aftershocks of the 1936 Milton-Freewater, Oregon, earthquake, along with fault-plane solutions, indicate a north to northeast-trending fault plane, which is consistent with the trend of the Hite Fault System (NRC, 1982). However, this north-northeast trend lies to the west of the surface trace of the Hite Fault. Because of the uncertainty in associating this earthquake to a specific structure, the NRC concluded that it could have occurred along the Hite Fault System, the Rattlesnake-Wallula alignment, or some as-yet unmapped fault.

A coda-length magnitude 4.1 earthquake occurred near College Place, Washington, on April 8, 1979. This was a shallow event with a focal depth of between 3 and 6 km (1.9 to 3.7 mi) and a fault-plane solution that suggests east-west compression (see Section 1.4.1.2.3). This earthquake and the 1936 Milton-Freewater, Oregon, earthquake both occurred 20 to 30 km (13 to 19 mi) west of, the surface trace of the Hite Fault. However, there is no clear evidence to associate these events with the Hite Fault (NRC, 1982, p. G-22).

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1.4.1.1.4 Characteristics of earthquakes

1.4.1.1.4.1 General characteristics

The historic record of events with epicentral intensities of MM IV or greater (Fig. 1.4-5) and the seismographic record of events of magnitude 3 or greater (Fig. 1.4-2, 1.4-3, 1.4-6, 1.4-7) are remarkably similar, and indicate that the major seismicity of the Columbia Plateau is broadly scattered. The seismographic record, which commenced in 1969 (see Section 1.4.1.1.2), reveals that areas of concentrated seismicity occur near Lake Chelan and in the central Columbia Plateau. The seismicity near Lake Chelan is not considered further because it occurs within a tectonic province (the North Cascades Tectonic Province) that is distinct from the Columbia Plateau (WPPSS 1981, pp. 2.5J-13 to -14; NRC 1982, pp 2-31 to -32, and G-24 to -25), and is distant enough that its effects at the Hanford Site are not as important as that due to the central plateau seismicity (WPPSS, 1981, p. 2.5J-14).

Most of the currently observed seismicity of the central Columbia Plateau is concentrated between the Saddle Mountains and Frenchman Hills, and between the Saddle Mountains and the Gable Mountain-Gable Butte area. The regional detection threshold has varied over time as the seismographic coverage has evolved (see WPPSS, 1981, Table 2.5J-1) but for events of magnitude 2 or greater, concentrations have persisted (WPPSS, 1981, p. 2.5J-14). Events of magnitude less than 2 may occur beyond the vicinity of the Hanford Site, particularly to the west and southwest, but the sparseness of coverage in these areas (see Fig. 1.4-4) does not guarantee a complete record.

The densest groups of epicenters (see Fig. 1.4-3 and 1.4-7) are swarms. An earthquake swarm may be defined as a cluster of events of comparable magnitude that first wax and then wane in number with no one outstanding event; the main criterion here is that no "outstanding" (large) event occurs. An outstanding event is considered a mainshock, and any earthquakes that precede or follow it are considered foreshock or aftershock activity. However, because of the low seismicity rates and generally small magnitudes of events that have been observed in the central plateau region (roughly 90% have magnitudes of 2 or less), the distinction between swarm and nonswarm activity is not always clear. Thus, Malone et al. (1975) described 1973-74 Royal Slope swarm as having characteristics of both a swarm and a mainshock-aftershock sequence because the aftershocks of the first and largest event (coda-length magnitude 4.4) persisted much longer than expected for an event of that size.

Based on the seismographic record, Columbia Plateau seismicity segregates by depth into three zones: 0-4 km, 4-8 km, and deeper than 8 km (see WPPSS, 1981, Fig. 2.5J-11 to - 14). On the order of 90% of the seismicity occurs at depths less that 8 km, and most of this shallow seismicity (70-80%) occurs in the uppermost 4 km (2.5 mi) (Figure 1.4-8; WPPSS, 1981, pp. 2.5J-15 to -17; Rasmussen, 1987). No seismicity has been observed below the local Moho depth of 30 km. These shallow, intermediate, and deep zones coincide approximately with zones of basalt, sub-basalt sediment, and crystalline basement,

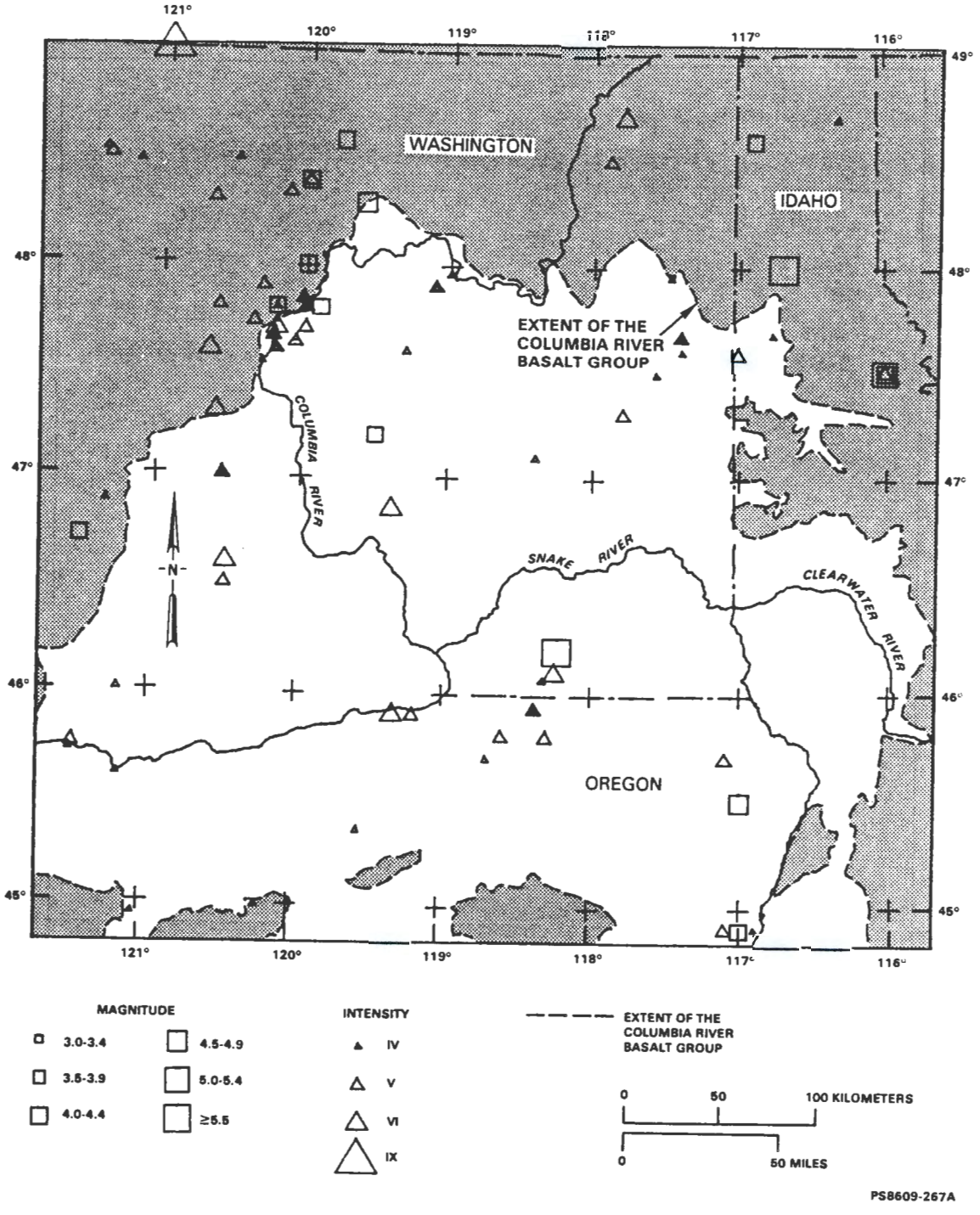

Figure 1.4-5. Historical seismicity of the Columbia Plateau and surrounding areas. All earthquakes between 1850 and 1969 with a modified Mercalli intensity of IV or larger with a magnitude of 3 or greater are shown (see Table 1.4-2(a)).

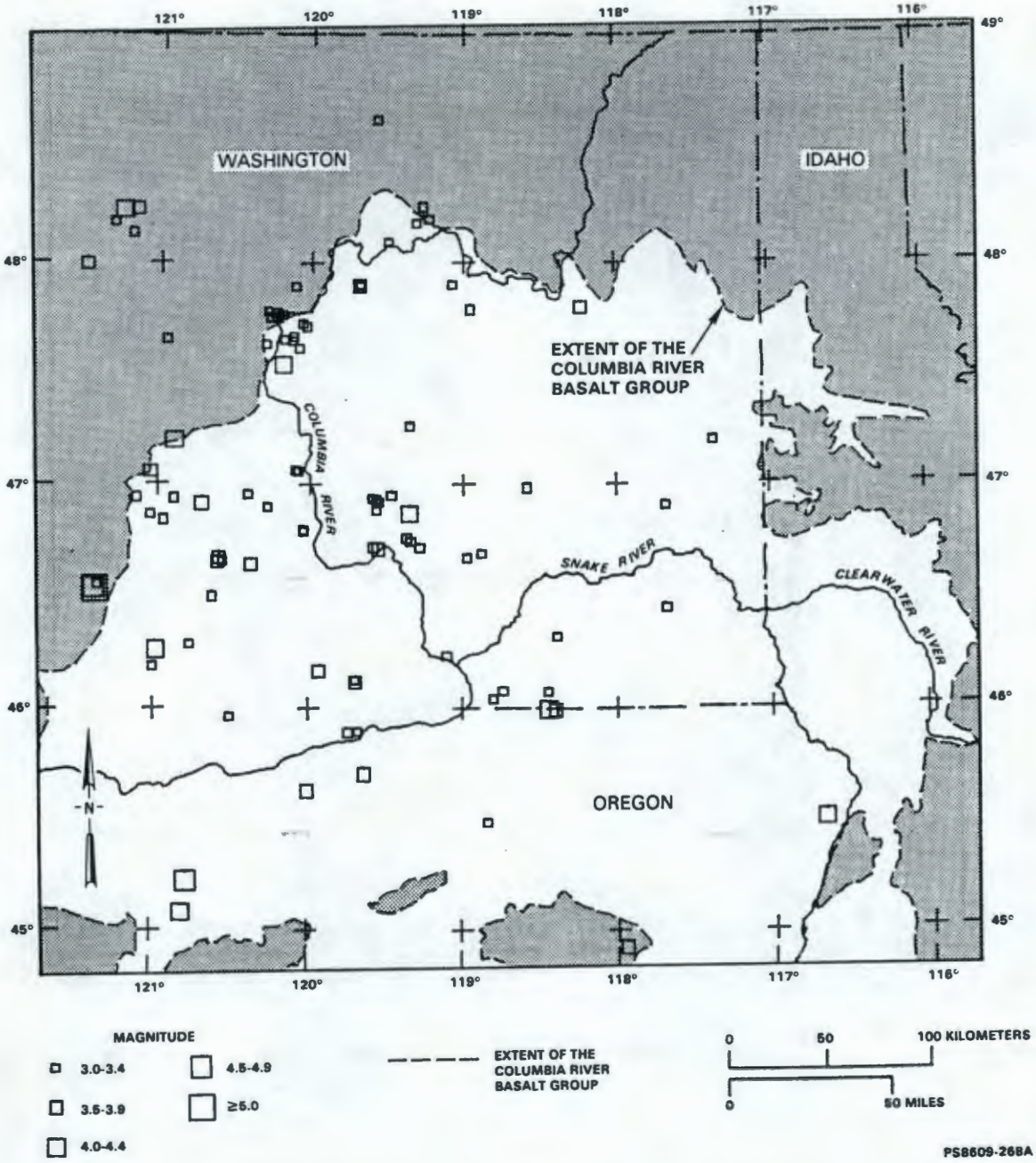

Figure 1.4-6. Recent seismographic seismicity of the Columbia Plateau and surrounding areas. All earthquakes between 1969 and 1986 with a modified Mercalli intensity of IV or larger or with a magnitude of 3 or greater are shown (see Table 1.4-2(b)).

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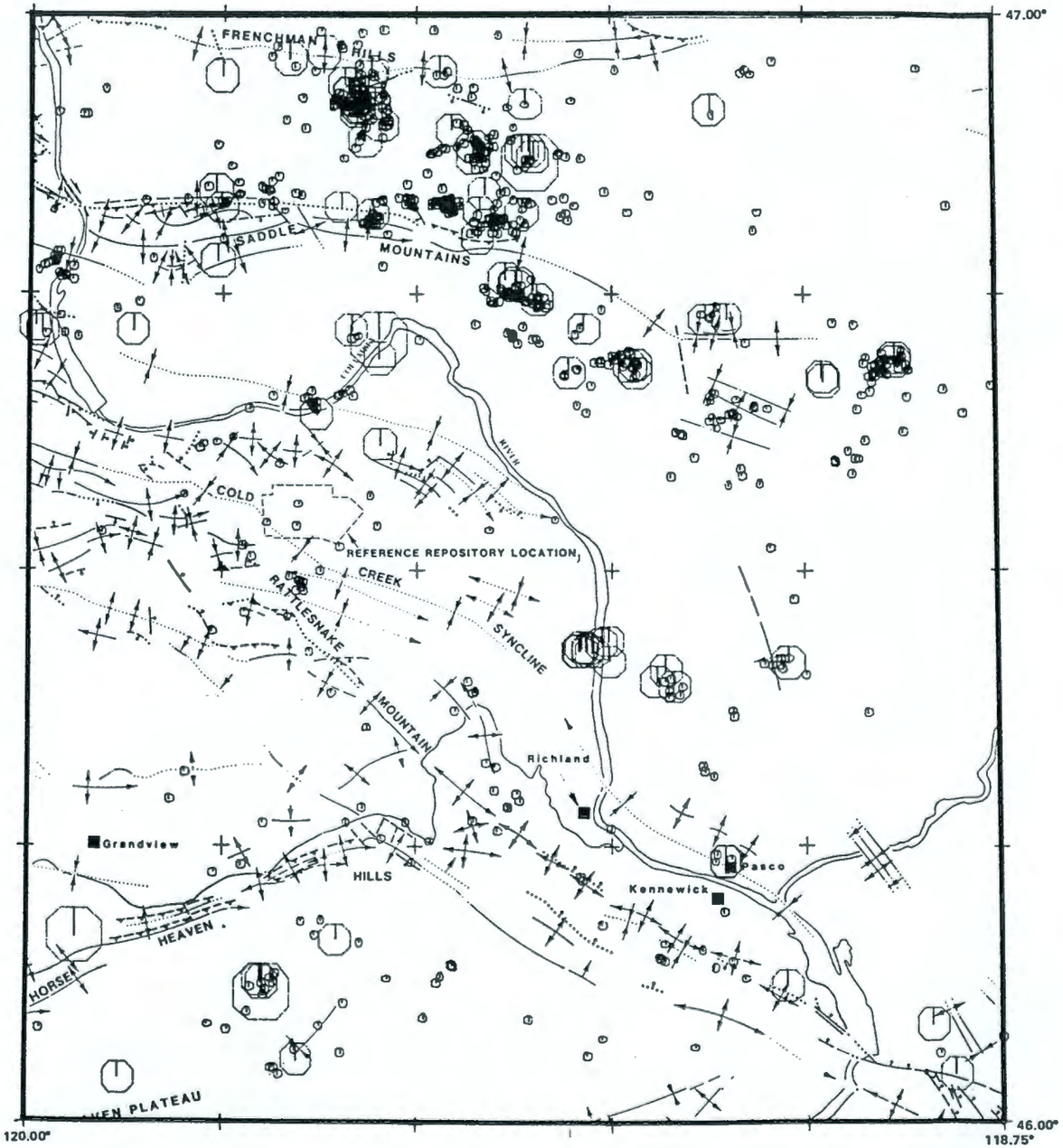


EXPLANATION

STRUCTURE SYMBOLS

- FAULT; DASHED WHERE APPROXIMATELY LOCATED, DOTTED WHERE CONCEALED
- FAULT; BAR AND BALL ON DOWNTHROWN SIDE
- STRIKE-SLIP FAULT; ARROWS SHOW DIRECTION OF RELATIVE HORIZONTAL MOVEMENT
- STRIKE-SLIP FAULT; DIRECTION OF RELATIVE HORIZONTAL MOVEMENT UNDETERMINED
- OBLIQUE-SLIP FAULT; ARROWS SHOW DIRECTION OF RELATIVE HORIZONTAL MOVEMENT, BAR AND BALL ON DOWNTHROWN SIDE
- THRUST FAULT; SAWTEETH ON UPPER PLATE
- ANTICLINE; SHOWING DIRECTION OF PLUNGE, DASHED WHERE APPROXIMATELY LOCATED, DOTTED WHERE CONCEALED
- SYNCLINE; SHOWING DIRECTION OF PLUNGE, DASHED WHERE APPROXIMATELY LOCATED, DOTTED WHERE CONCEALED
- MONOCLINE; SHOWING DIRECTION OF PLUNGE, ABRUPT DECREASE IN DIP IN THE DIRECTION OF ARROWS, DASHED WHERE APPROXIMATELY LOCATED, DOTTED WHERE CONCEALED
- MONOCLINE; ABRUPT INCREASE IN DIP IN THE DIRECTION OF ARROWS

MAGNITUDE

- 1.5-2.4
- 2.5-3.4
- 3.5-4.4

N

0 5 10 15 20 25 30 KILOMETERS

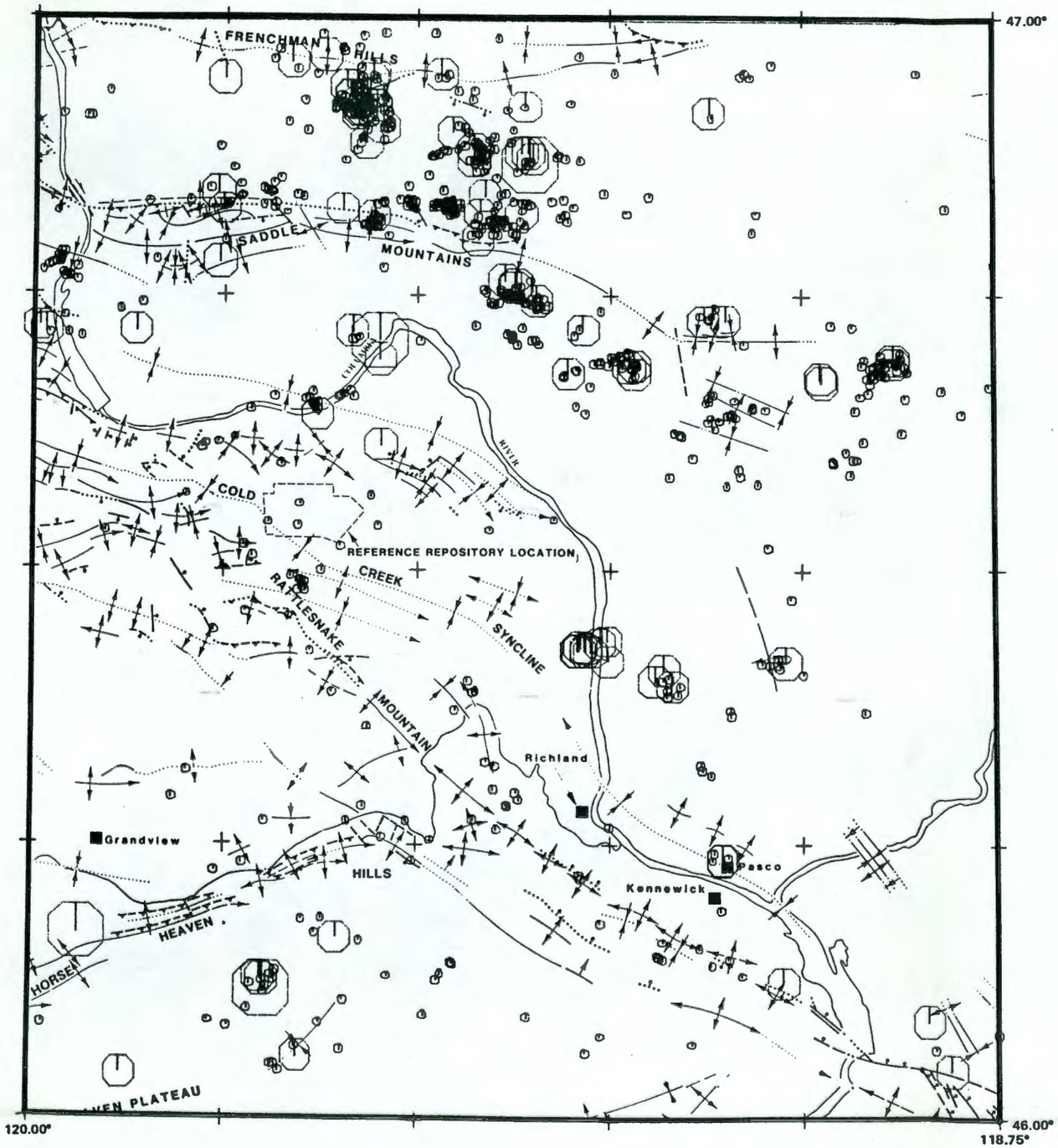
0 5 10 15 20 MILES

PS8709-6A

Figure 1.4-7. Epicenter plot for all central Columbia Plateau events that occurred between 1969 and mid-1987 with magnitudes greater than or equal to 1.5. Earthquakes in the Wooded Island swarm area (see Table 1.4-3) that have magnitudes smaller than 2.5 have been excluded from this plot for clarity. The source for the events plotted is the University of Washington Geophysics Program on-line earthquake catalog.

9 2 1 2 5 0 2 0 7 1 5

9 2 1 2 5 0 2 0 7 1 5



EXPLANATION

STRUCTURE SYMBOLS

FAULT; DASHED WHERE APPROXIMATELY LOCATED, DOTTED WHERE CONCEALED

FAULT; BAR AND BALL ON DOWNTHROWN SIDE

STRIKE-SLIP FAULT; ARROWS SHOW DIRECTION OF RELATIVE HORIZONTAL MOVEMENT

STRIKE-SLIP FAULT; DIRECTION OF RELATIVE HORIZONTAL MOVEMENT UNDETERMINED

OBLIQUE-SLIP FAULT; ARROWS SHOW DIRECTION OF RELATIVE HORIZONTAL MOVEMENT, BAR AND BALL ON DOWNTHROWN SIDE

THRUST FAULT; SAWTEETH ON UPPER PLATE

ANTICLINE; SHOWING DIRECTION OF PLUNGE, DASHED WHERE APPROXIMATELY LOCATED, DOTTED WHERE CONCEALED

SYNCLINE; SHOWING DIRECTION OF PLUNGE, DASHED WHERE APPROXIMATELY LOCATED, DOTTED WHERE CONCEALED

MONOCLINE; SHOWING DIRECTION OF PLUNGE, ABRUPT DECREASE IN DIP IN THE DIRECTION OF ARROWS, DASHED WHERE APPROXIMATELY LOCATED, DOTTED WHERE CONCEALED

MONOCLINE; ABRUPT INCREASE IN DIP IN THE DIRECTION OF ARROWS

MAGNITUDE

1.5-2.4

2.5-3.4

3.5-4.4

N

0 5 10 15 20 25 30 KILOMETERS

0 5 10 15 20 MILES

PS8709-6A

Figure 1.4-7. Epicenter plot for all central Columbia Plateau events that occurred between 1969 and mid-1987 with magnitudes greater than or equal to 1.5. Earthquakes in the Wooded Island swarm area (see Table 1.4-3) that have magnitudes smaller than 2.5 have been excluded from this plot for clarity. The source for the events plotted is the University of Washington Geophysics Program on-line earthquake catalog.

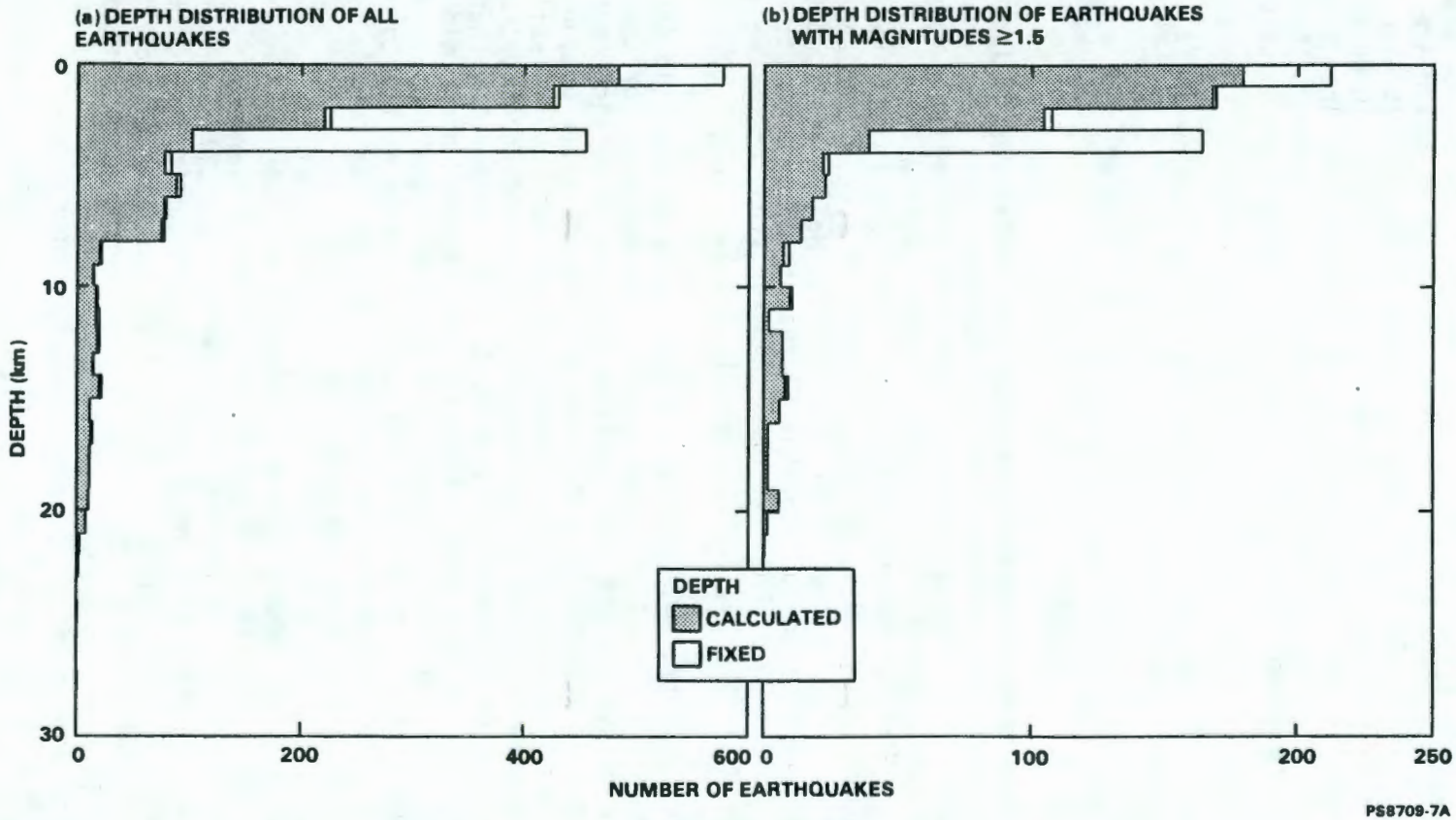


Figure 1.4-8. Depth distribution for (a) all central Columbia Plateau earthquakes (see Fig. 1.4-7) and (b) earthquakes in the Columbia Plateau with magnitudes greater than 1.5 (see Fig. 1.4-9 through 1.4-11). The actual depths of some events are unknown and have been fixed during the location process. The source for the events plotted is the University of Washington Geophysics Program on-line earthquake catalog.

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respectively (WPPSS, 1981, Fig. 2.5J-11 to -12). With few exceptions the dense epicenter clusters evident in Figure 1.4-3, -9, and -10, which are mostly swarms, occur in this uppermost zone, although clustering is also seen in the intermediate zone (WPPSS, 1981, p. 2.5J-18). The only noticeable clusterings in the deepest zone have been observed south of the Horse Heaven Hills near Prosser, at the east end of Saddle Mountains, and between the Saddle Mountains and Frenchman Hills about 10 km (6.2 mi) east of Royal City (Fig. 1.4-11).

In the subsequent discussions, the seismicity of the shallow and intermediate zones are discussed together.

1.4.1.1.4.2 Earthquake swarms and shallow seismic activity (8 km or less)

Most central Columbia Plateau earthquakes are located at depths less than 8 km (5 mi) and occur north and northeast of the Columbia River. The shallowest seismicity comprises mostly swarms. The earliest reliable report of swarm activity in the Columbia Plateau states that between January and March, 1955, over 200 events of MM intensity III or less were felt in the Othello area (Murphy and Cloud, 1955, p. 35). Studies of specific Columbia Plateau swarms using seismographic data are Pitt (1971), Malone et al. (1975), and Rothe (1978). A general study of Columbia Plateau shallow seismicity is found in UWGP (1979, pp. 21-28). The most comprehensive study of Columbia Plateau seismicity to date is WPPSS (1981, Appendix 2.5J).

Using well-located events, UWGP (1979) outlined 13 swarm areas in the Columbia Plateau, which are listed in Table 1.4-3. The boundaries of the areas, which were subjective to some degree, have a typical dimension on the order of 10 km (6.2 mi) on a side. They did not analyze the distribution of swarm depths or the vertical extent of individual swarms, but they classified the swarms as shallow seismicity, which were defined as having focal depths of less than approximately 6 km (3.7 mi (UWGP, 1979, p. 24). They noted that of these 13 swarm areas, only 2, West Saddle Mountain and Coyote Rapids, had not been the site of more than one swarm in the decade preceding the study. However, subsequent to this report, a six-event swarm occurred at the Coyote Rapids area between October 20 and November 1, 1983, the largest event of which had coda-length magnitude 3.4 (see UWGP, 1984, p. 55).

A Washington Public Power Supply System's study (WPPSS, 1981, Appendix 2.5J) established additional objective criteria for swarm identification and investigated the depths of the swarms carefully. The Washington Public Power Supply System study established 28 additional swarm areas (21 in the central plateau region), and modified the boundaries of four of the UWGP's areas; however, the typical dimension of these swarms remained on the order of 10 km (6.2 mi) on a side. Individual swarms were found to cluster within areas on the order of 25 km^2 (9.65 mi^2) (WPPSS, 1981, p. 2.5J-26) and have a vertical extent on the order of the depth precision, i.e., 2 to 4 km (1.3 to 2.5 mi) or less. With only four exceptions, the swarms identified in the Washington Public Power Supply System study occurred at depths of 5 km (3 mi) or less; several have been confined to depths less than 2 km (1.3 mi) (WPPSS, 1981, p. 2.5J-27).

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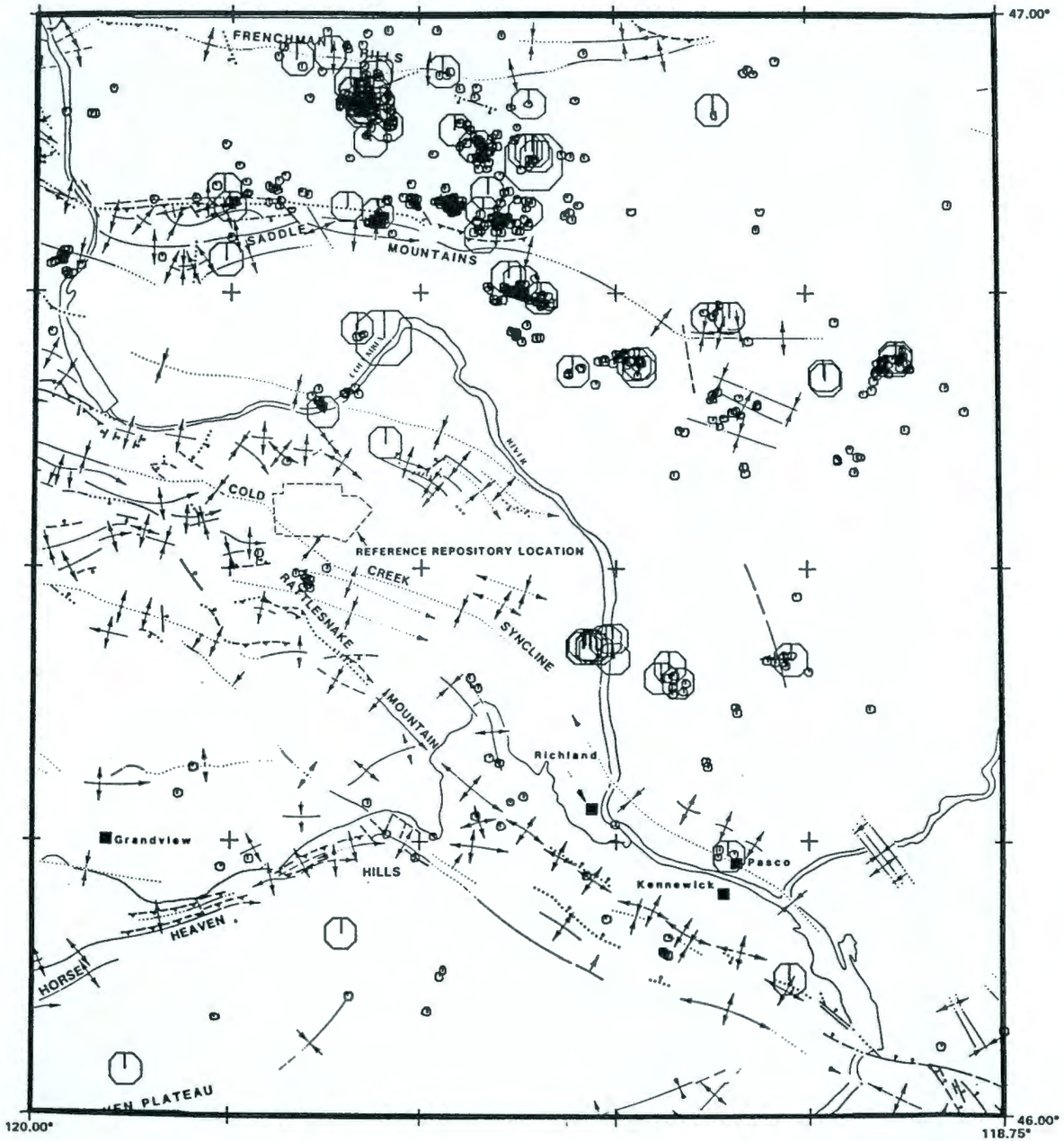

EXPLANATION

STRUCTURE SYMBOLS

- FAULT; DASHED WHERE APPROXIMATELY LOCATED, DOTTED WHERE CONCEALED
- FAULT; BAR AND BALL ON DOWNTHROWN SIDE
- STRIKE-SLIP FAULT; ARROWS SHOW DIRECTION OF RELATIVE HORIZONTAL MOVEMENT
- STRIKE-SLIP FAULT; DIRECTION OF RELATIVE HORIZONTAL MOVEMENT UNDETERMINED
- OBLIQUE-SLIP FAULT; ARROWS SHOW DIRECTION OF RELATIVE HORIZONTAL MOVEMENT, BAR AND BALL ON DOWNTHROWN SIDE
- THRUST FAULT; SAWTEETH ON UPPER PLATE
- ANTICLINE; SHOWING DIRECTION OF PLUNGE, DASHED WHERE APPROXIMATELY LOCATED, DOTTED WHERE CONCEALED
- SYNCLINE; SHOWING DIRECTION OF PLUNGE, DASHED WHERE APPROXIMATELY LOCATED, DOTTED WHERE CONCEALED
- MONOCLINE; SHOWING DIRECTION OF PLUNGE, ABRUPT DECREASE IN DIP IN THE DIRECTION OF ARROWS, DASHED WHERE APPROXIMATELY LOCATED, DOTTED WHERE CONCEALED
- MONOCLINE; ABRUPT INCREASE IN DIP IN THE DIRECTION OF ARROWS

MAGNITUDE

- 1.5-2.4
- 2.5-3.4
- 3.5-4.4

N

0 5 10 15 20 25 30 KILOMETERS

0 5 10 15 20 MILES

PS8709-8A

Figure 1.4-9. Shallow zone earthquakes with focal depths between 0 and 4 km (2.5 mi) and magnitudes greater than 1.5 in the central Columbia Plateau, 1969 to mid-1987. The source for the events plotted is the University of Washington Geophysics Program on-line earthquake catalog.

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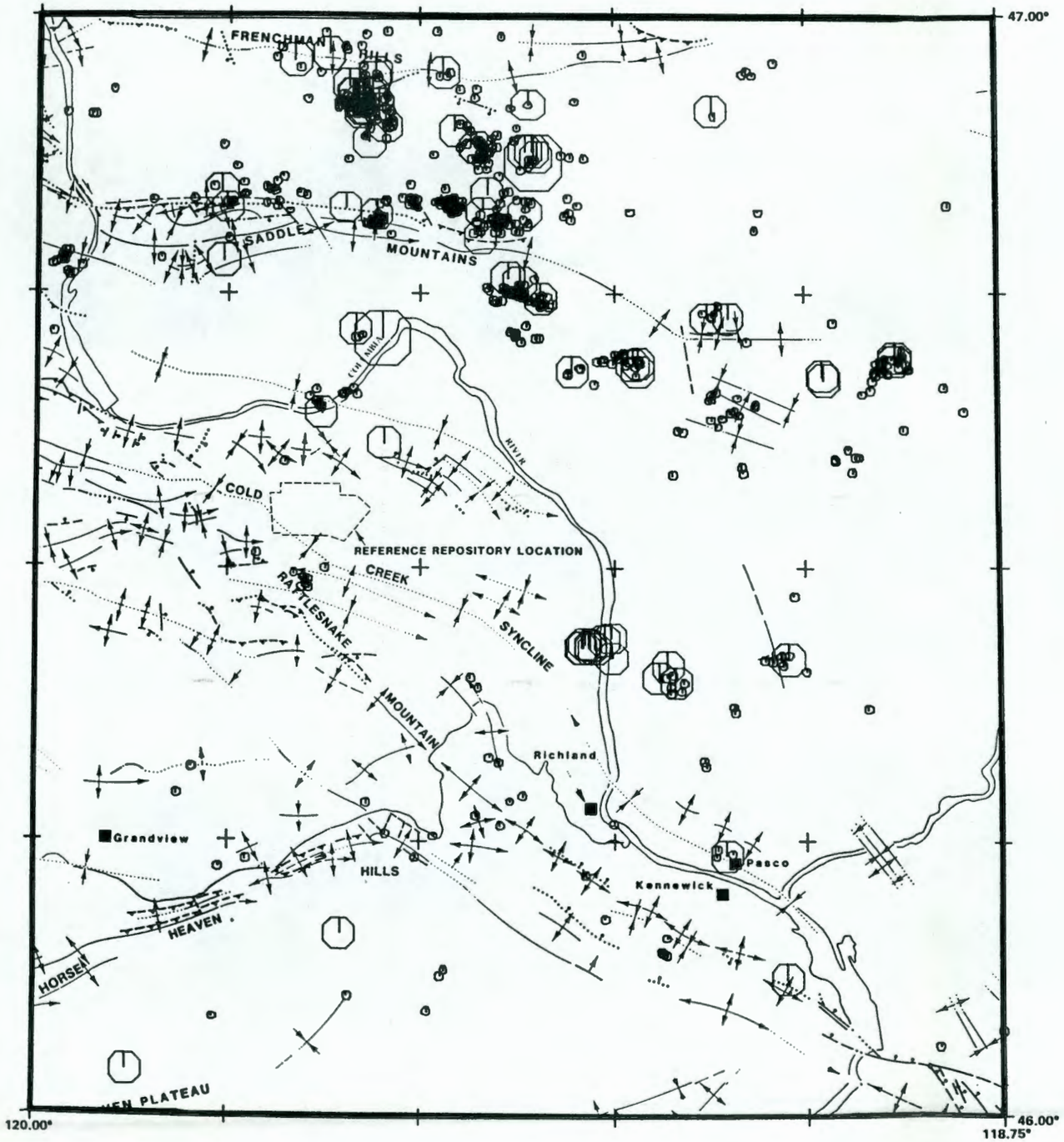

EXPLANATION

STRUCTURE SYMBOLS

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OBLIQUE-SLIP FAULT; ARROWS SHOW DIRECTION OF RELATIVE HORIZONTAL MOVEMENT, BAR AND BALL ON DOWNTHROWN SIDE

THRUST FAULT; SAWTEETH ON UPPER PLATE

ANTICLINE; SHOWING DIRECTION OF PLUNGE, DASHED WHERE APPROXIMATELY LOCATED, DOTTED WHERE CONCEALED

SYNCLINE; SHOWING DIRECTION OF PLUNGE, DASHED WHERE APPROXIMATELY LOCATED, DOTTED WHERE CONCEALED

MONOCLINE; SHOWING DIRECTION OF PLUNGE, ABRUPT DECREASE IN DIP IN THE DIRECTION OF ARROWS, DASHED WHERE APPROXIMATELY LOCATED, DOTTED WHERE CONCEALED

MONOCLINE; ABRUPT INCREASE IN DIP IN THE DIRECTION OF ARROWS

MAGNITUDE

1.5-2.4

2.5-3.4

3.5-4.4

N

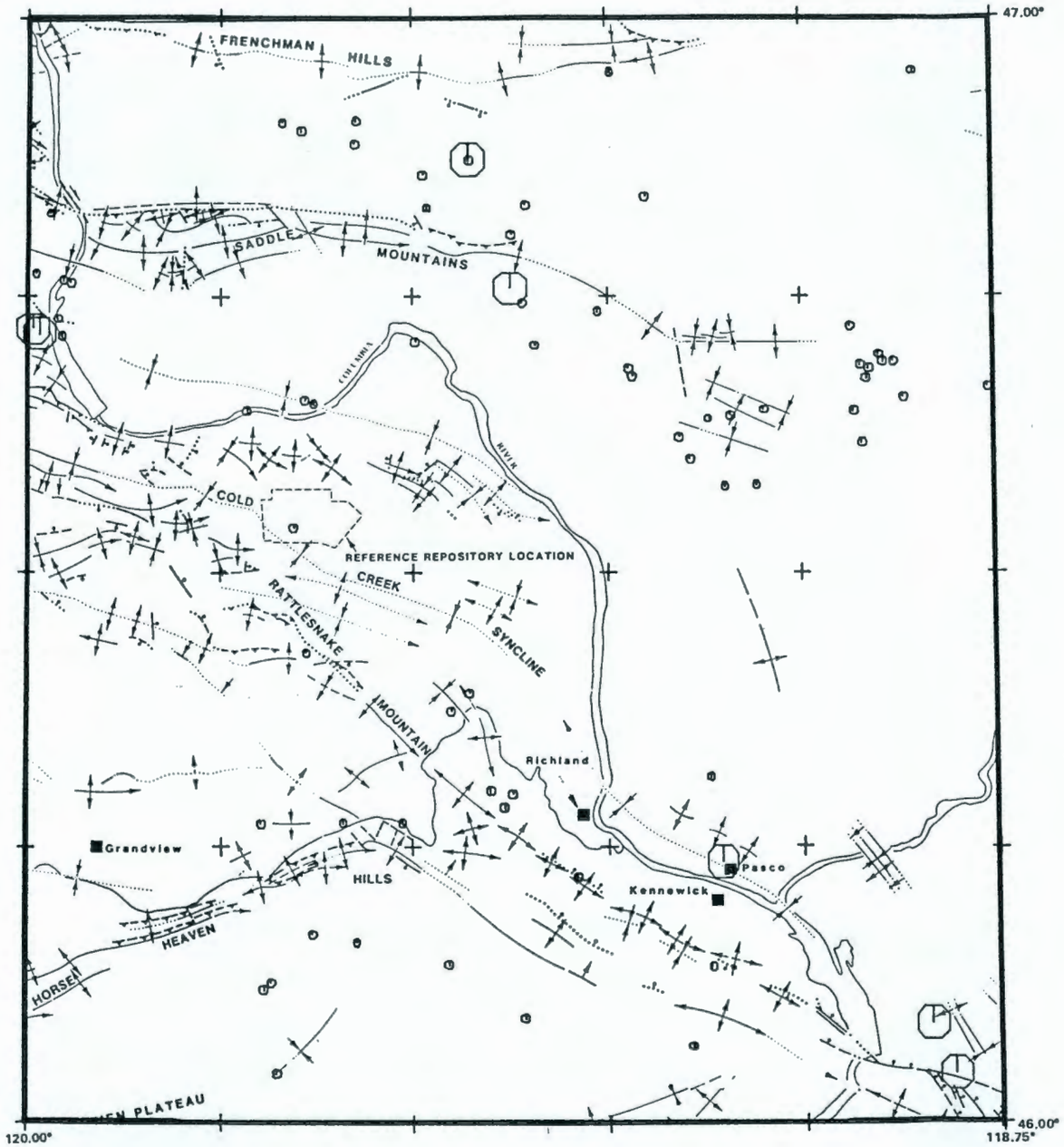
0 5 10 15 20 25 30 KILOMETERS

0 5 10 15 20 MILES

PS8709-8A

Figure 1.4-9. Shallow zone earthquakes with focal depths between 0 and 4 km (2.5 mi) and magnitudes greater than 1.5 in the central Columbia Plateau, 1969 to mid-1987. The source for the events plotted is the University of Washington Geophysics Program on-line earthquake catalog.

9 2 1 2 5 0 2 0 7 1 8



EXPLANATION

STRUCTURE SYMBOLS

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- MONOCLINE; ABRUPT INCREASE IN DIP IN THE DIRECTION OF ARROWS

MAGNITUDE

- 1.5-2.4
- 2.5-3.4
- 3.5-4.4

N

0 5 10 15 20 25 30 KILOMETERS

0 5 10 15 20 MILES

PS8709-9A

Figure 1.4-10. Intermediate zone earthquakes with focal depths between 4 and 8 km (2.5 and 5 mi) and magnitudes greater than 1.5 in the central Columbia Plateau, 1969 to mid-1987. The source for the events plotted is the University of Washington Geophysics Program on-line earthquake catalog.

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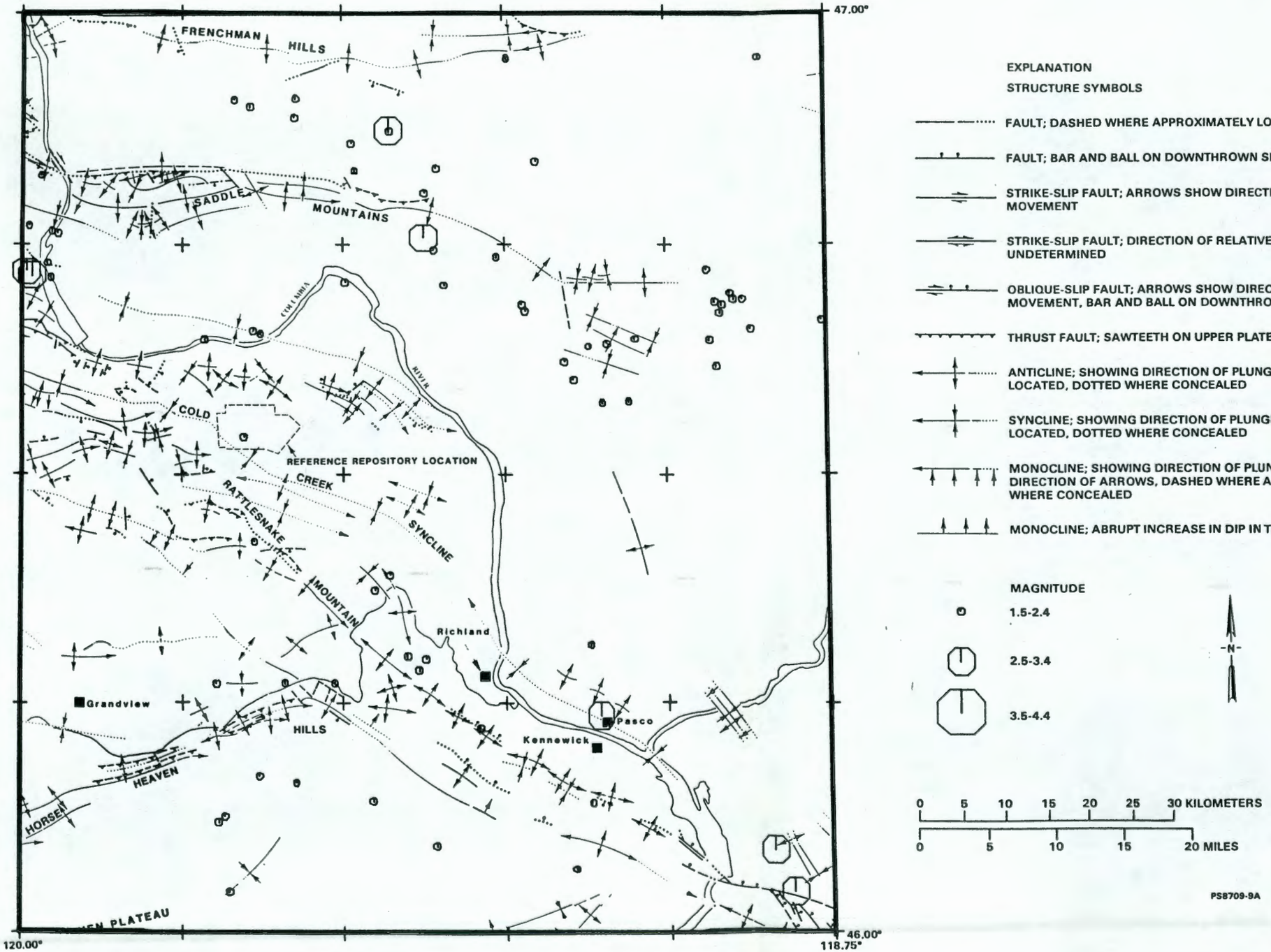
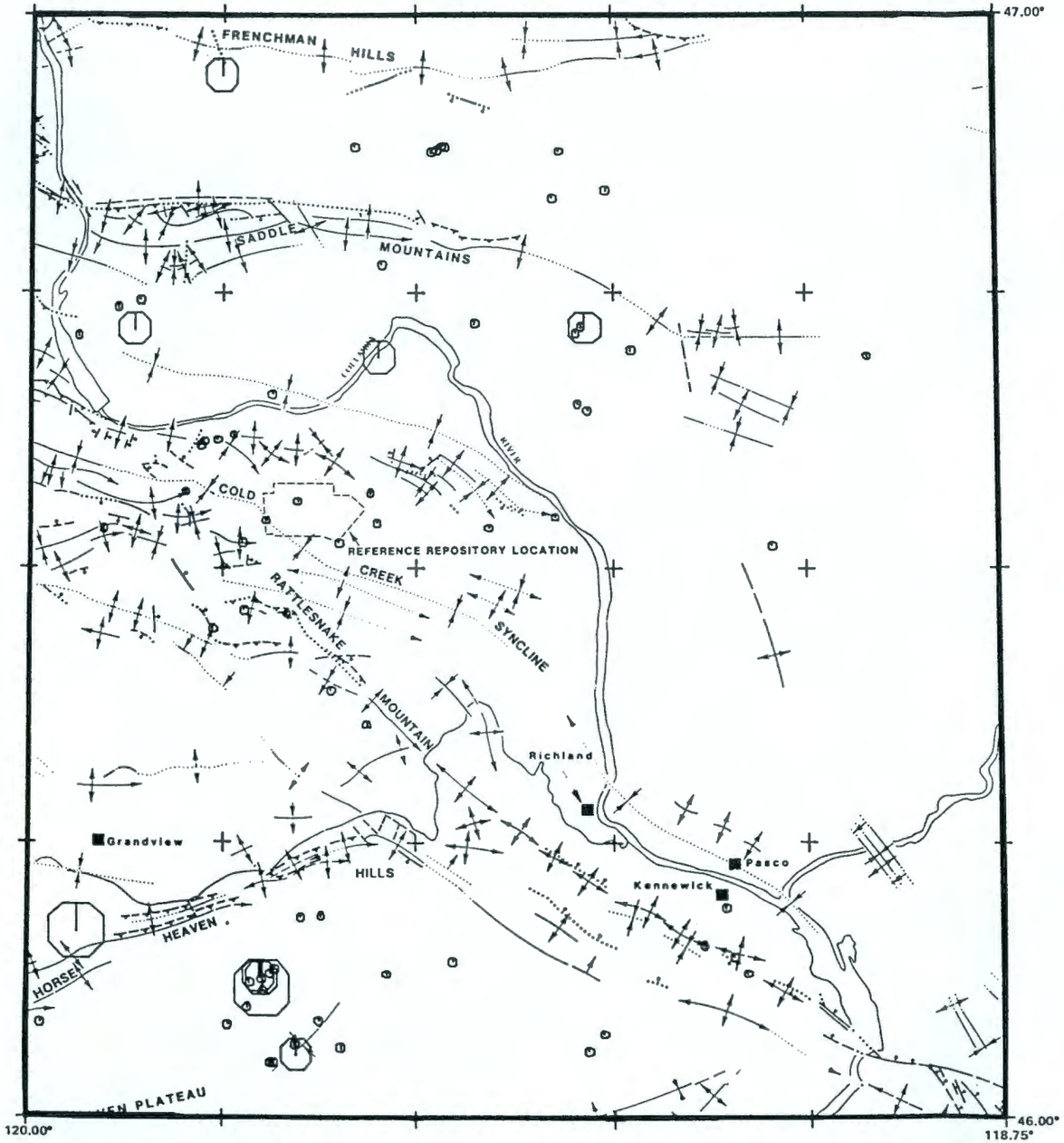


Figure 1.4-10. Intermediate zone earthquakes with focal depths between 4 and 8 km (2.5 and 5 mi) and magnitudes greater than 1.5 in the central Columbia Plateau, 1969 to mid-1987. The source for the events plotted is the University of Washington Geophysics Program on-line earthquake catalog.

9 2 1 2 5 0 2 0 7 1 9

9 2 1 2 5 0 2 0 7 2 0



EXPLANATION

STRUCTURE SYMBOLS

- FAULT; DASHED WHERE APPROXIMATELY LOCATED, DOTTED WHERE CONCEALED
- FAULT; BAR AND BALL ON DOWNTHROWN SIDE
- STRIKE-SLIP FAULT; ARROWS SHOW DIRECTION OF RELATIVE HORIZONTAL MOVEMENT
- STRIKE-SLIP FAULT; DIRECTION OF RELATIVE HORIZONTAL MOVEMENT UNDETERMINED
- OBLIQUE-SLIP FAULT; ARROWS SHOW DIRECTION OF RELATIVE HORIZONTAL MOVEMENT, BAR AND BALL ON DOWNTHROWN SIDE
- THRUST FAULT; SAWTEETH ON UPPER PLATE
- ANTICLINE; SHOWING DIRECTION OF PLUNGE, DASHED WHERE APPROXIMATELY LOCATED, DOTTED WHERE CONCEALED
- SYNCLINE; SHOWING DIRECTION OF PLUNGE, DASHED WHERE APPROXIMATELY LOCATED, DOTTED WHERE CONCEALED
- MONOCLINE; SHOWING DIRECTION OF PLUNGE, ABRUPT DECREASE IN DIP IN THE DIRECTION OF ARROWS, DASHED WHERE APPROXIMATELY LOCATED, DOTTED WHERE CONCEALED
- MONOCLINE; ABRUPT INCREASE IN DIP IN THE DIRECTION OF ARROWS

MAGNITUDE

- 1.5-2.4
- 2.5-3.4
- 3.5-4.4

N

0 5 10 15 20 25 30 KILOMETERS

0 5 10 15 20 MILES

PS8709-10A

Figure 1.4-11. Earthquakes with focal depths greater than 8 km (5 mi) and magnitudes greater than 1.5 in the central Columbia Plateau, 1969 to mid-1987. The source for the events plotted is the University of Washington Geophysics Program on-line earthquake catalog.

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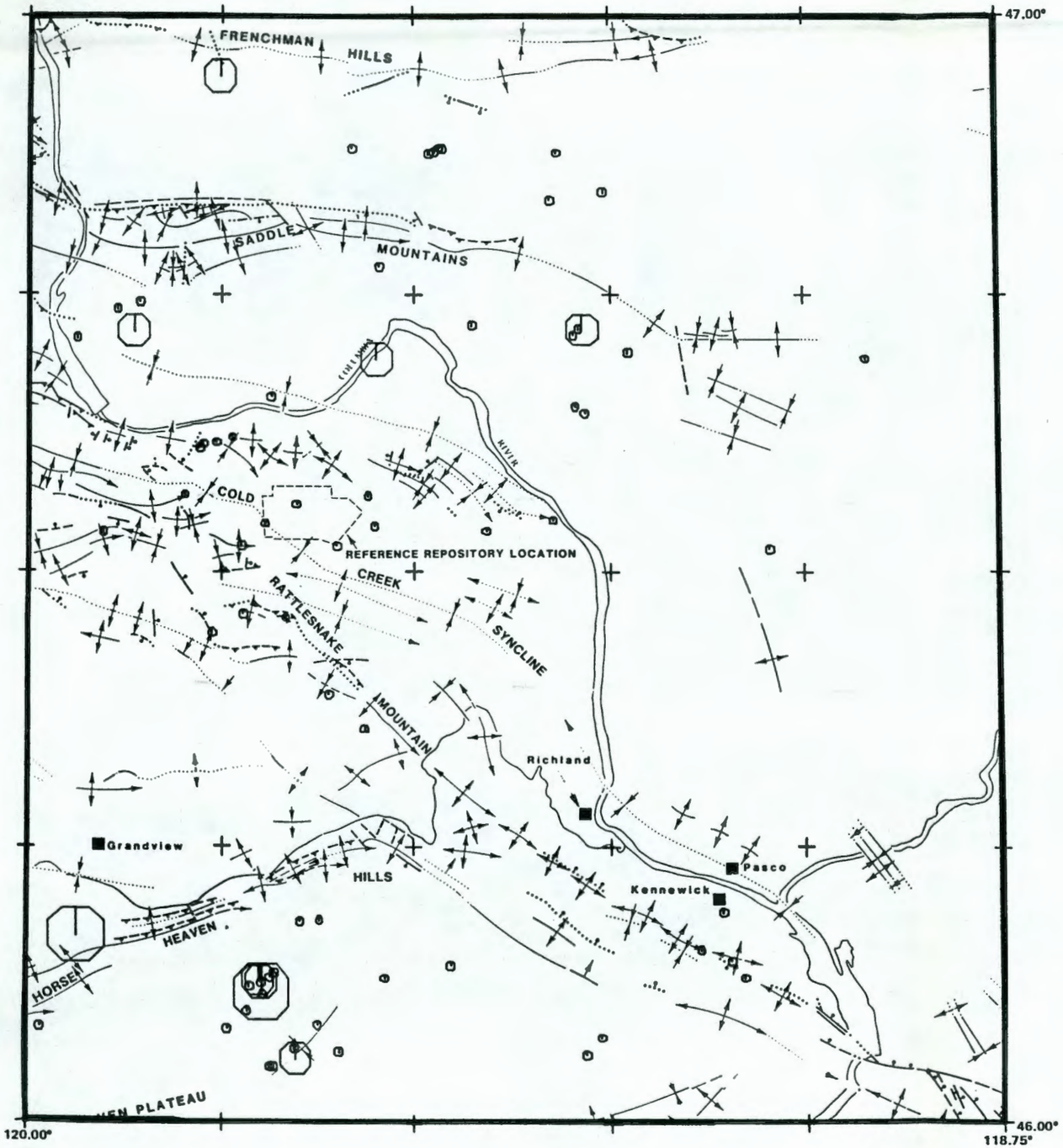

EXPLANATION

STRUCTURE SYMBOLS

- FAULT; DASHED WHERE APPROXIMATELY LOCATED, DOTTED WHERE CONCEALED
- FAULT; BAR AND BALL ON DOWNTHROWN SIDE
- STRIKE-SLIP FAULT; ARROWS SHOW DIRECTION OF RELATIVE HORIZONTAL MOVEMENT
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- MONOCLINE; ABRUPT INCREASE IN DIP IN THE DIRECTION OF ARROWS

MAGNITUDE

- 1.5-2.4
- 2.5-3.4
- 3.5-4.4

-N-

0 5 10 15 20 25 30 KILOMETERS

0 5 10 15 20 MILES

PS8709-10A

Figure 1.4-11. Earthquakes with focal depths greater than 8 km (5 mi) and magnitudes greater than 1.5 in the central Columbia Plateau, 1969 to mid-1987. The source for the events plotted is the University of Washington Geophysics Program on-line earthquake catalog.

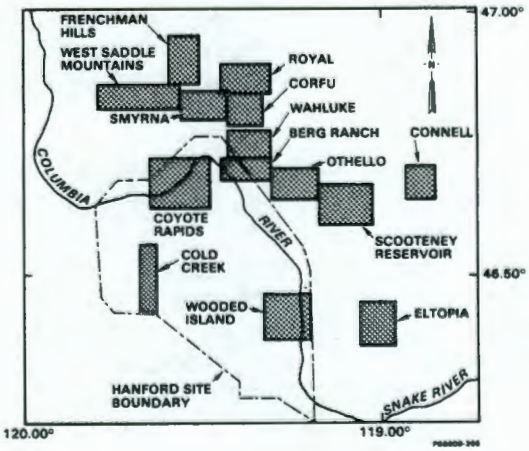
Table 1.4-3. Swarm activity 1969 through 1983 in the central Columbia Plateau

Swarm	Latitude north		Latitude west		Area (km^2)	Number of events	Years of swarms*
	South	North	East	West			
West Saddle Mountain	46.820	46.865	119.564	119.797	91.6	46	1969-1974
Frenchman Hills	46.865	46.960	119.514	119.600	71.3	40	1970-1979
Smyrna	46.800	46.855	119.433	119.564	62.9	163	1970-1978
Royal	46.850	46.910	119.317	119.450	69.7	100	1970-1980
Corfu	46.790	46.850	119.331	119.433	53.4	175	1970-1971
Wahluke	46.729	46.780	119.314	119.431	52.1	134	1970-1974
Berg Ranch	46.685	46.728	119.317	119.417	37.6	44	1971-1974
Othello	46.650	46.710	119.183	119.317	70.2	72	1970-1976
Scootney Reservoir	46.600	46.680	119.047	119.183	85.0	76	1969-1973
Connell	46.650	46.715	118.850	118.933	47.1	47	1970-1975
Wooded Island	46.390	46.470	119.200	199.333	92.9	179	1969-1975
Eltopia	46.370	46.455	118.964	119.067	76.4	63	1972-1975
Coyote Rapids	46.635	46.730	119.483	119.650	138.5	63	1970-1983
Cold Creek	46.470	46.570	119.60	119.68	71.8	16	1969-1979

Sources: UWGP, 1979, 1980, 1981, 1982, 1983; Rasmussen, 1987. PST88-2014-1.0-2

NOTE: To convert square kilometers to square miles, multiply by 0.386.

*Reflects the total period of recorded swarm activity and may include more than one swarm period.



9 2 1 2 5 0 2 0 7 2 1

Deep swarms (i.e., sub-basalt) are reported near Scootney Reservoir and Connell at the east end of the Saddle Mountains at depths between 6 to 12 km (3.5 to 7.5 mi), and at two adjacent areas south of the Horse Heaven Hills near Prosser between depths of 6.5 to 12.0 km (4 to 7.5 mi; WPPSS, 1981, Appendix 2.5J). Depth precision for these locations is 2 to 4 km (1.3 to 2.5 mi), so it is possible that these swarms actually occurred at depths less that 10 km (6.2 mi), above the crystalline basement. In late 1982, after the 1981 WPPSS study, a nine-event deep swarm occurred between the Royal and Frenchman Hills swarm areas identified by UWGP (1979) at depths of 11.5 to 14.5 km (7 to 9 mi). The largest magnitude was coda-length 2.3 (UWGP, 1983, pp. 12, 66-67).

The spatial distribution of swarms is of interest because alignments and planes in hypocenter distributions can correspond to planes of slip. On a regional scale, there is generally no association of swarms with mapped faults. However, a clear alignment of epicenters parallels the Saddle Mountain axis between the Saddle Mountains and Frenchman Hills (see Fig. 1.4-9). Based on current locations, the events comprising this alignment do not define significant planes (WPPSS, 1981, p. 2.5J-39), although strong lateral heterogeneities in this area (UWGP, 1977, pp. 27-34; Rodi et al., 1980; Rohay et al., 1985) may induce significant uncertainties and errors in the computed locations.

On the scale of the swarm dimension, swarms generally do not exhibit consistent spatial patterns. The few patterns that have been reliably identified fall within a wedge of easterly to northeasterly azimuths. This is true for some subsets of the 1975 Wooded Island swarm (Rothe, 1978) and of one Scootney and two Eltopia swarms (WPPSS, 1981, pp. 2.5J-26 to -27). Some of the swarms exhibit a dispersal of seismicity from a center of activity, to the east and west, and to the northeast.

To date, the only reliable identification of swarm slip planes is for the 1973 Eltopia swarm (Malone et al., 1975), which was monitored in detail with a temporary seismic network. In that swarm, no single composite fault-plane solution satisfied the first motions of all events, but well-constrained solutions did fit three mutually exclusive subsets. The hypocenters of each subset lay quite closely to a plane which was parallel to one defined by the corresponding fault-plane solution, strongly suggesting that it was the plane of slip. These three planes had azimuths of northeast, east-northeast, and east, and dipped steeply (40° or more).

The dominantly reverse single-event and composite focal mechanisms estimated for the central Columbia Plateau seismicity (see discussion in Section 1.4.1.2.3) suggest that slip during swarms occurs along planes striking in easterly to northeasterly directions. Also implied by these fault-plane solutions is a generally north-south and horizontal orientation of maximum compressive stress, but this does not necessarily have to coincide with the regional stress regime. However, independent estimates of shallow, regional stress from borehole breakout measurements reported by Paillet and Kim (1987) indicate fairly unambiguously that the stress at very shallow depths (about 1 km (0.6 mi)) is oriented roughly north-south. See Sections 1.3.2.3 and 1.3.2.4 for a description of evidence for defining the present stress regime.

9 2 1 2 5 0 2 0 7 2 2

Since 1969, when the collection of local Columbia Plateau seismographic data began, most swarm events have been observed to have coda-length magnitudes of about 1.5 or less. The largest swarm event has been the 4.4 coda-length magnitude 1973 Royal Slope shock, which in some ways exhibited mainshock characteristics (see Section 1.4.1.1.4.4). As stated previously, only about 10% of the seismicity at depths less than 8 km (5 mi) exceed (coda-length) magnitude 2.0.

1.4.1.1.4.3 Deep seismicity

Below about 8 km (5 mi) depth, the seismicity in the central Columbia Plateau displays characteristics that are quite distinct from shallower seismicity. Deeper seismicity is generally diffusely distributed throughout the Columbia Plateau (see Fig. 1.4-11). As discussed above in Section 1.4.1.1.4.2, the few "deep" clusters may in fact be occurring at shallower depths. These clusters occur at the eastern end of the Saddle Mountains where the Scootney Reservoir and Connell swarm areas extend to 10 and 12 km (6.2 and 7.5 mi), respectively, at a single area between the Frenchman Hills and the Saddle Mountains near Corfu, and south of the Horse Heaven Hills near Prosser. The numbers of events in these deep clusters are far fewer than the number in shallower swarms.

The few focal mechanisms that have been developed for the deep seismicity (WCC, 1980b, p. 4) reflect reverse slip on east-to-northeast striking planes, and are generally similar to shallow mechanisms (WPPSS, 1981, pp. 2.5J-37 and 2.5J-38).

1.4.1.2 Relationship of seismicity to geologic and tectonic characteristics of candidate area

Perkins et al. (1980), in estimating the ground motion in the Pacific Northwest, average details of seismicity and physiography over broad regions to define seismogenic zones. Their approach is empirical and generally does not attempt to explain the causes of seismicity. The region that includes the Hanford Site (their zone 5) is delineated to the north by the increased seismicity of the North Cascades and elsewhere by contacts of the Columbia Plateau with other geologic provinces. The seismicity of zone 5 is modeled as a uniform distribution of near-surface earthquakes, in recognition of the low occurrence rates and magnitudes of earthquakes, and of the lack of demonstrably active seismogenic structures. Furthermore, their uniform seismicity statistics for the four zones east of the Cascade Range have been defined despite the substantial differences among the zones in the detailed seismicity and geology. This averaged characterization is repeated in the final U.S. Geological Survey review of the geology and seismology of Washington Public Power Supply System Project WNP-2, which was written by essentially the same authors, in their statement that "the rate of occurrence of magnitude... 3 to 4 events is about the normally expected level of activity for a broad area in Washington State east of the Cascades" (NRC, 1982, p. G-16).

On the basis of instrumentally recorded seismicity, Woodward-Clyde Consultants identified two areas of concentrated activity within the boundaries of the Columbia Plateau: one on the northwest periphery of the plateau near Lake Chelan, and the other in the central Columbia Plateau, which encompasses the Hanford Site (WPPSS, 1981, p. 2.5J-13). The central Columbia Plateau is a rectangular region that includes the Frenchman Hills to the northwest and Wallula Gap to the southeast. The regions of greatest seismic activity within this rectangle lie between, and en echelon to the southeast of, Saddle Mountain and Frenchman Hills (see Fig. 1.4-7). The shallow depths of most of this activity are in the basalt layer.

Reliable fault plane solutions and composites of the swarm events suggest a variety of slip planes, even within individual swarms, but all are consistent with the regionally observed north-south compression (Malone et al., 1975; Rothe, 1978; Rohay and Davis, 1983). Rothe (1978) has proposed that this multiplicity of fault planes results from slip on columnar joint faces in the basalt in response to the regional north-south compression.

9 2 1 2 0 2 7 2 4

1.4.1.2.1 Seismicity and crustal structure

Interpretation of the crustal structure of the Columbia Plateau is based on seismic refraction, magnetotelluric surveys, distribution of earthquakes, and seismic characteristics of earthquakes in the Columbia River basalt (Fig. 1.4-12). Based on seismic velocities, the central Columbia Plateau has an upper layer, approximately 4 km (2.5 mi) thick with a velocity of 5.2 km/s (3.2 mi/s), that is interpreted to be Columbia River basalt (Rohay et al., 1985, p. 17). Magnetotelluric data indicate that below the basalt lies a conductive layer 3- to 5-km (1.9- to 3.1-mi) thick considered to be a late Mesozoic to early Tertiary sedimentary sequence (Mitchell and Bergstrom, 1983, pp. 4-11 to 4-13).

The largest magnitude and numbers of earthquakes observed since the start of detailed monitoring at the Hanford Site in 1969 occur at depths less than approximately 5 km (3.1 mi). At greater depths, fewer and generally lower magnitude events are seen, suggesting that the majority of the earthquakes in the central Columbia Plateau, particularly the microearthquake swarms, are occurring within the Columbia River basalt.

Based on the analysis of the 1975 Wooded Island swarm, Rothe (1978, pp. 152-166) proposed that swarms in the Columbia Plateau are a result of slip caused by regional north-south compression along vertical columnar joints in the basalt. Correlations among event depths, high seismic velocities, and well logs imply that the Wooded Island swarm occurred within basalt flows. Magnitudes for this swarm clustered around a value of coda-length magnitude 1.5, causing a break in the b-value. Laboratory studies by Mogi (1963) suggest that a break in b-values is indicative of a regular seismogenic structure with some characteristic dimension (i.e., the flow thickness). The observed vertical migration of swarm activity between flows was explained by Rothe (1978, pp. 152-166) as a result of aseismic stress propagation in the

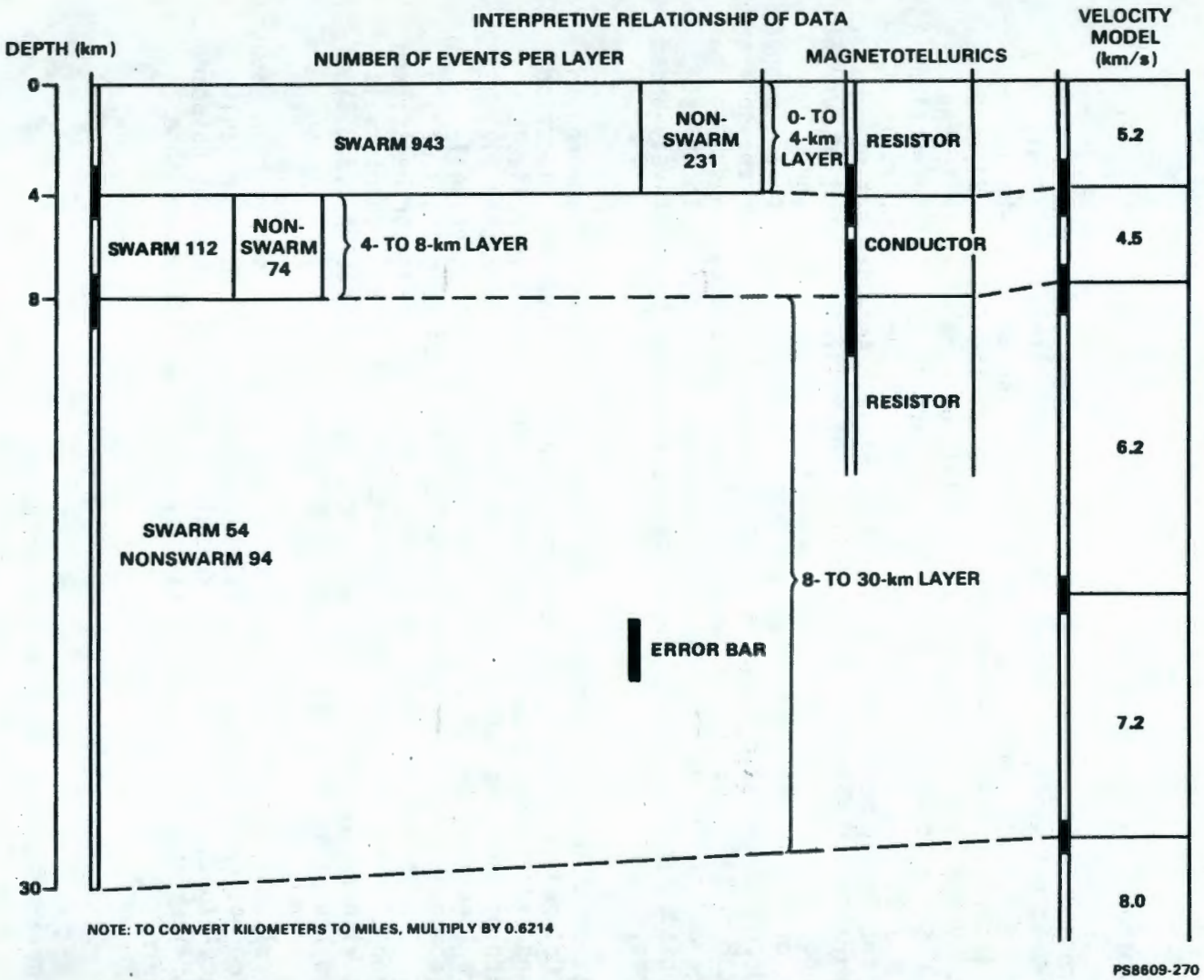


Figure 1.4-12. An interpretive correlation between the depths of all earthquakes observed in the period September 1971 to September 1982, the present general magnetotelluric model, and the new compressional velocity model. Note that the surface sediment layer has been omitted from this correlation.

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weathered zones, interbeds, and breccias. The higher b-values of swarms compared to nonswarm events may be explained in part by the characteristic magnitude exhibited by the former.

1.4.1.2.2 Patterns in earthquake distributions

As discussed in Section 1.4.1.1.4.2, approximately 90% of the central Columbia Plateau seismicity occurs at depths shallower than 8 km (5 mi), and about 75% at depths shallower than 4 km (2.5 mi). The observed shallow activity is located primarily north and northeast of the Columbia River horn (see Fig. 1.4-9 and -10) and appears to parallel contours of depth to the crystalline basement developed in a recent time-term analysis of refraction data (see Rohay et al., 1985). The activity north of the horn occurs in the vicinity of the Saddle Mountains and Frenchman Hills. An alignment of epicenters parallels the Saddle Mountain anticline axis, but, based on current locations, does not appear to define any planar surfaces. Also, the distribution of the larger events does not appear to be related to faults that have been mapped on the Saddle Mountains or Frenchman Hills. However, such an associatin cannot be ruled out, because locations in this area are subject to uncertainties due to strong lateral heterogeneities in seismic velocities. Swarm locales south of the Saddle Mountains are separated by relatively broad aseismic areas.

Delineation of patterns suggestive of faulting surfaces is hampered in the central Columbia Plateau by the combination of low seismicity, location precision, and small swarm dimensions and magnitudes. The only reliable identification of faulting surfaces is for the previously discussed 1973 Eltopia swarm (see Section 1.4.1.1.4.2), in which planes of three well-constrained composite focal mechanisms parallel planar distributions of hypocenters. The strikes of these three planes are east, east-northeast, and northeast, and all dip steeply at 40° or more. None of these mechanisms is inconsistent with the observed local tectonic stress (see Section 1.3.2.3) if it is assumed that slip occurred on a variety of surfaces.

In general, the pattern and distribution of earthquakes deeper than about 8 km (5 mi) do not exhibit an obvious relationship to known folds or faults having surface expression. Also, this seismicity generally does not coincide with areas of intense shallow swarm activity, but rather, it occurs in a diffuse pattern.

1.4.1.2.3 Focal mechanism and stress orientation

Focal mechanisms for earthquakes in the Columbia Plateau and its periphery are listed in Tables 1.4-4 through 1.4-6 and shown in Figure 1.4-13 through 1.4-16. They have been determined by several investigators both for individual events of magnitude greater than approximately 3.0, and for composites of smaller events associated with either swarms or small areas of persistent activity. The absence of focal mechanism solutions for the area

Table 1.4-4. Eastern Washington regional focal mechanisms (sheet 1 of 2)

Event location	Date	P-axis		T-axis		Plot type[a]	Grade[b]	Comments	Source
		Azimuth	Plunge	Azimuth	Plunge				
Lake Chelan	1977	139	06	257	78	2	AAB = A	Composite	UWGP, 1978, p. 60
Naches	6/27/78	326	16	221	42	1	BBC = B	M = 3.4, z-14 km 8.7 mi)	UWGP, 1978, p. 80
Cle Elum	6/77-1/78	344	19	119	64	1	CDA = C	Composite	WCC, 1978, p. 23
Chief Joseph Dam	01/19/79	308	01	216	62	2	CAD = C	M = 3.9	UWGP, 1979, p. 60
Milton-Freewater (Walla Walla)	04/08/79	264	06	164	55	1	BBB-B	M = 4.2	WCC, 1980b, fig. 21
Milton-Freewater	07/16/36	056	25	163	34	1	--	Ms = 5.75	WCC, 1980b, fig. 22
Selah	12/10/79	276	14	166	54	1	BCC = C	M = 3.4	WCC, 1980d, fig. 1
Goat Rocks foreshock	05/28/81	000	00	090	00	3	ABA = A	M = 4.6	UWGP, 1981, p. 18
Goat Rocks main shock	05/28/81	356	07	091	22	3	ABA = A	M = 5.0	UWGP, 1981, p. 19
Toppenish Ridge	02/02/81	003	25	267	11	3	BBA = B	M = 4.0	UWGP, 1981, p. 19
Cle Elum	02/18/81	180	39	000	52	3	CCA = C	M = 4.2	UWGP, 1981, p. 20
Goldendale	06/14/81	356	14	244	58	3	CDB = C	M = 3.2	UWGP, 1981, p. 20
Walla Walla	03/22/83	116	08	207	02	3	BBC = B	M = 3.8	UWGP, 1983, p. 18
Wenatchee	04/11/84	358	22	093	03	3	ABB = B	M = 4.3	UWGP, 1984, p. 23
Entiat	1983-1984?	313	44	054	10	3	CBC = C	Composite	UWGP, 1984, p. 23
Yakima	11/14/83	200	25	021	65	3	BCC = C	M = 3.8	UWGP, 1984, p. 24
Ellensburg	12/5/83	009	00	099	00	3	BAC = B	M = 3.8	UWGP, 1984, p. 24

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Table 1.4-4. Eastern Washington regional focal mechanisms (sheet 2 of 2)

Event location	Date	P-axis		T-axis		Plot type[a]	Grade[b]	Comments	Source
		Azimuth	Plunge	Azimuth	Plunge				
Hermiston	02/10/85	170	04	078	04	3	BAC = B	M = 3 9	UWGP, 1985, fig. II-5
Halfway	1983	040	62	254	23	1	ACB = B	Composite	UWGP, 1985, fig. V-7
Deschutes Valley	04/13/76	196	12	006	78	1	CDC = X	Composite	Couch et al., 1976, fig. 4

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NOTE: M = Magnitude
Z = Depth
Ms = Surface wave magnitude.

[a]Plot Type
1 = Lower hemisphere equal area (Schmidt)
2 = Upper hemisphere equal angle (Wulff)
3 = Upper hemisphere equal area (Schmidt)

[b]Grading system: Grade A has a constraint of 2° to 10°, a scatter of 0% to 5%, and a distribution greater than 12 in both fields. Grade B has a constraint of 10° to 20°, a scatter of 5% to 10%, and a distribution greater than 8 in both fields. Grade C has a constraint of 20° to 30°, a scatter of 10% to 20%, and a distribution greater than 4 in both fields. Grade D has a constraint greater than 30°, a scatter greater than 20%, and a distribution less than 4 in one field. X represents an average grade less than C. Constraint is estimated dip and azimuth variation to change scatter or distribution one grade. Scatter is the number of misfits per number of fits. Distribution is the number of fits minus the number of misfits.

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Table 1.4-5. Central Columbia Plateau shallow earthquake focal mechanisms

Event location	Date	P-axis		T-axis		Plot type[a]	Grade[b]	Comments	Source
		Azimuth	Plunge	Azimuth	Plunge				
Eltopia swarm	6/73-7/73	348	02	257	47	2	BBA = B	Composite	Malone et al., 1975, Fig. 3
Eltopia swarm	6/73-7/73	332	34	188	50	2	BCB = B	Composite	Malone et al., 1975, Fig. 3
Eltopia swarm	6/73-7/73	006	05	220	85	2	BAD = B	Composite	Malone et al., 1975, Fig. 3
Royal sequence	12/73	002	05	204	85	2	BBA = B	Composite	Malone et al., 1975, Fig. 5
Royal sequence	1/74-2/74	170	26	329	63	2	BBC = B	Composite	Malone et al., 1975, Fig. 5
Royal main shock	12/20/73	185	08	298	70	1	BAB = B	M = 4.4	Rohay, 1987, Fig. 3
Royal swarm	9/4/74	184	24	354	65	1	CAD = C	M = 2.8	WPPSS, 1981, Fig. 2.5, p. J-34
Scooteney swarm	2/15/73	098	10	307	78	1	DCC = X	M = 1.4	WPPSS, 1981, Fig. 2.5, p. J-32
Smyrna swarm	9/22/72	072	05	332	63	1	CBC-C	M = 2.5	WPPSS, 1981, Fig. 2.5, p. J-35
Wahluke swarm	10/18/72	180	08	003	81	1	BAC = B	M = 1.7	WPPSS, 1981, Fig. 2.5, p. J-33
Wahluke swarm	10/19/72	285	08	129	80	1	CCC = C	M = 1.4	WPPSS, 1981, Fig. 2.5, p. J-33
Wahluke swarm	11/30/72	335	06	076	59	1	ABC = B	M = 2.0	WPPSS, 1981, Fig. 2.5, p. J-33
Wahluke swarm	12/3/72	118	06	295	84	1	DCC = X	M = 1.4	WPPSS, 1981, Fig. 2.5, p. J-33
Wahluke swarm	12/15/72	284	04	067	84	1	CCC = C	M = 1.0	WPPSS, 1981, Fig. 2.5, p. J-33
Coyote Rapids swarm	10/25/71	338	05	200	83	1	AAB = A	M = 3.8	Rohay, 1987, Fig. 4
Cold Creek swarm	9/79	162	15	342	75	1	DCD = X	Composite	UWGP, 1980, Fig. II-1
Vantage swarm	1984-1985	163	27	327	62	3	BBA = B	Composite	UWGP, 1980, Fig. V-3

NOTE: M = Magnitude.

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[a]Plot Type

1 = Lower hemisphere equal area (Schmidt)
2 = Upper hemisphere equal angle (Wulff)
3 = Upper hemisphere equal area (Schmidt)

[b]Grading system: Grade A has a constraint of 2° to 10°, a scatter of 0% to 5%, and a distribution greater than 12 in both fields. Grade B has a constraint of 10° to 20°, a scatter of 5% to 10%, and a distribution greater than 8 in both fields. Grade C has a constraint of 20° to 30°, a scatter of 10% to 20%, and a distribution greater than 4 in both fields. Grade D has a constraint greater than 30°, a scatter greater than 20%, and a distribution less than 4 in one field. X represents an average grade less than C. Constraint is estimated dip and azimuth variation to change scatter or distribution one grade. Scatter is the number of misfits per number of fits. Distribution is the number of fits minus the number of misfits.

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Table 1.4-6. Central Columbia Plateau deep earthquake focal mechanisms

Event location	Date	P-axis		T-axis		Plot type[a]	Grade[b]	Comments	Source
		Azimuth	Plunge	Azimuth	Plunge				
NW Hanford-Midway	8/30/75	035	00	120 or 300	70	2	DAC = C	Composite, z = 9-10 km, two possible T axes	WPPSS, 1977, Fig. 2R, J-8
Horse Heaven Hills	6/28/75	324	01	060	75	2	BAC = B	M = 3.8, z = 10 km	WPPSS, 1977, Fig. 2R, J-9
Prosser/Horse Heaven Hills	1969-1979	187	02	072	86	1	BBC = B	Composite, z > 9 km	WCC, 1980b, Fig. 16
Rattlesnake Mountain	1969-1979	166	28	298	52	1	BCA = B	Composite, z > 9 km	WCC, 1980b, Fig. 15
Yakima/Umtanum/Gable	1969-1979	162	16	293	67	1	BDA = B	Composite, z > 9 km	WCC, 1980b, Fig. 18
Eltopia	1969-1979	291	43	032	10	1	CCD = X	Composite, z > 9 km	WCC, 1980b, Fig. 19
Corfu/Royal/Othello	1969-1979	168	05	047	80	1	BCA = B	Composite, z > 9 km	WCC, 1980b, Fig. 20
Sunnyside	1971-1972	198	33	100	15	1	CDC = X	Composite, z > 9 km	WCC, 1980b, Fig. 13
Yakima Ridge	9/23/81	186	05	342	85	3	BAC = B	M = 2.3, z = 17 km	UWGP, 1982, p. 20

NOTE: M = Magnitude.
D = Depth.

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[a]Plot Type
1 = Lower hemisphere equal area (Schmidt)
2 = Upper hemisphere equal angle (Wulff)
3 = Upper hemisphere equal area (Schmidt)

[b]Grading system: Grade A has a constraint of 2° to 10°, a scatter of 0% to 5%, and a distribution greater than 12 in both fields. Grade B has a constraint of 10° to 20°, a scatter of 5% to 10%, and a distribution greater than 8 in both fields. Grade C has a constraint of 20° to 30°, a scatter of 10% to 20%, and a distribution greater than 4 in both fields. Grade D has a constraint greater than 30°, a scatter greater than 20%, and a distribution less than 4 in one field. X represents an average grade less than C. Constraint is estimated dip and azimuth variation to change scatter or distribution one grade. Scatter is the number of misfits per number of fits. Distribution is the number of fits minus the number of misfits.

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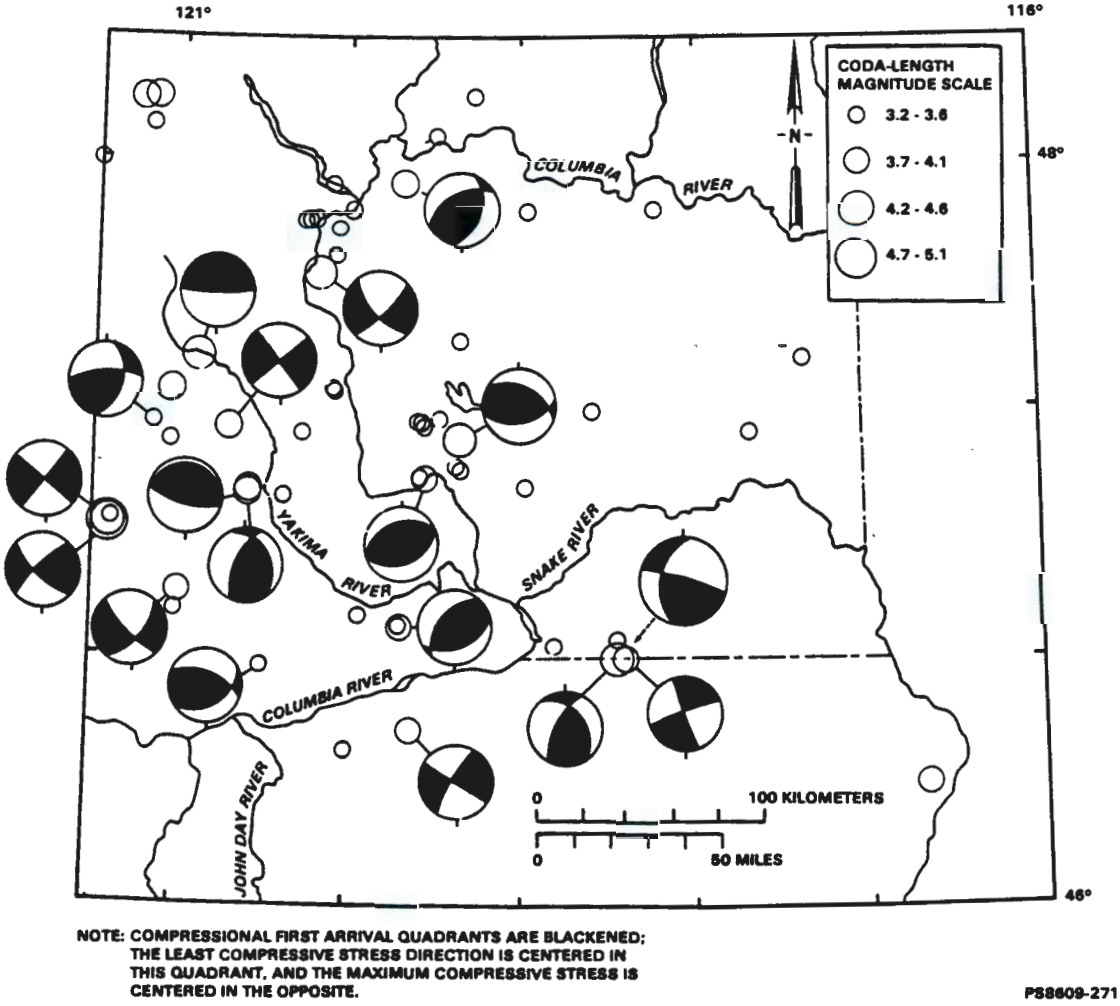

Figure 1.4-13. Summary of selected eastern Washington earthquake focal mechanisms. All single-event focal mechanisms are shown for earthquakes with coda-length magnitude of 3.2 and larger, as lower hemisphere, equal-area projections.

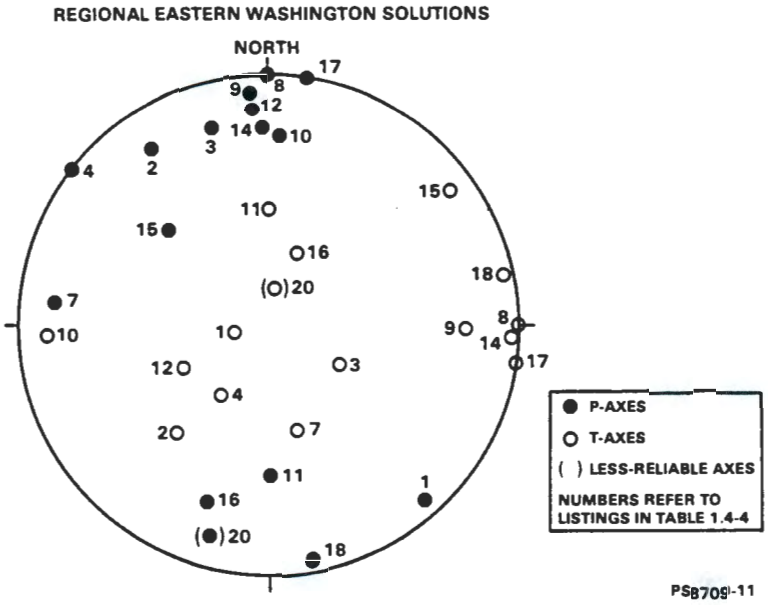

Figure 1.4-14. Eastern Washington regional earthquake compression (P) and tension (T) axes. Numbers refer to event numbers given in Table 1.4-4. Events 5, 6, 13, and 19 of that table have been excluded from this figure. The less reliable data in parentheses correspond to an average quality of "x" (see footnotes in Table 1.4-4).

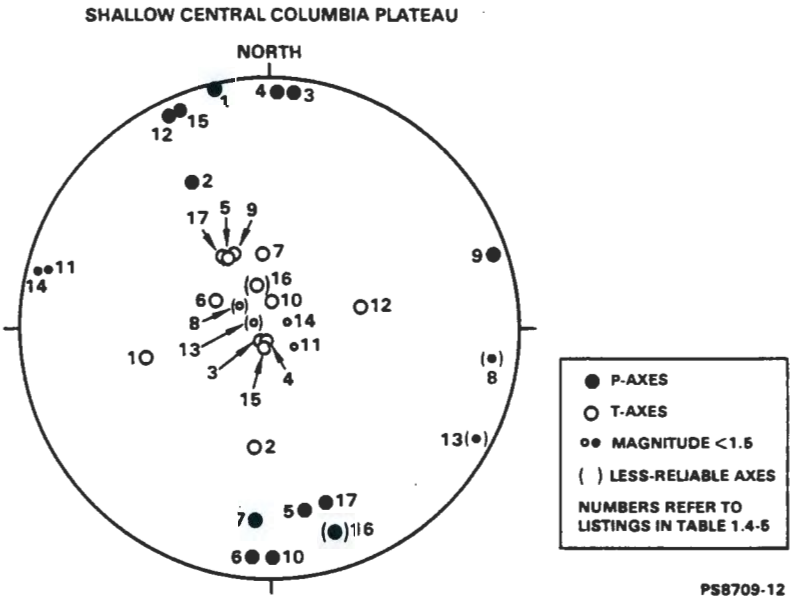

Figure 1.4-15. Central Columbia Plateau shallow earthquake compression (P) and tension (T) axes. Numbers refer to event numbers given in Table 1.4-5. The less reliable data in parentheses correspond to an average quality of "x" (see foonotes in Table 1.4-5).

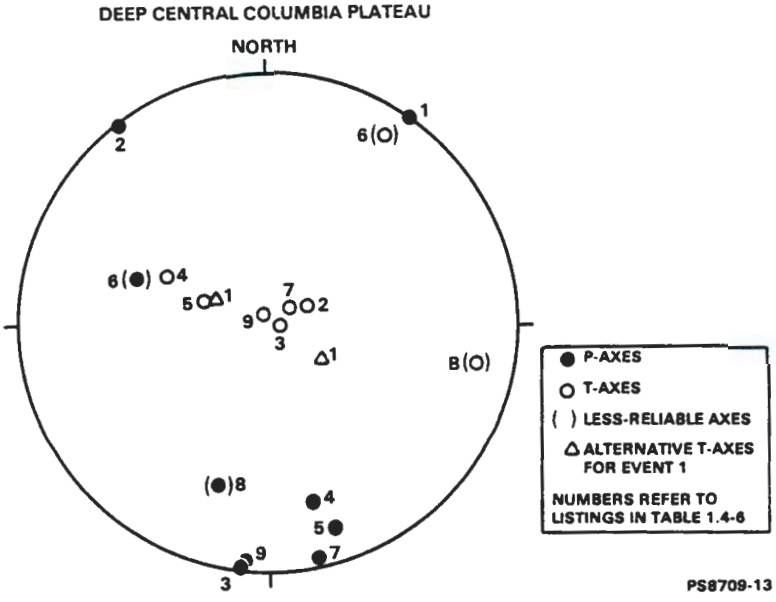

Figure 1.4-16. Central Columbia Plateau earthquake compression (P) and tension (T) axes. Numbers refer to event numbers given in Table 1.4-6. The less reliable data in parentheses correspond to an average quality of "x" (see footnotes in Table 1.4-6).

east of the Pasco Basin, which is evident in Figure 1.4-13, is due to the relatively low level of seismicity in the area and to the sparseness of the seismic network in that area (see Fig. 1.4-4).

Analysis of first motions from earthquakes in the southeastern Cascade Range in Washington and along the western border of the Columbia Plateau tend to yield nearly pure strike-slip solutions, with conjugate northwest-striking right-lateral slip or northeast-striking left-lateral slip (see Fig. 1.4-13 and 1.4-14). Most focal mechanisms in the central Columbia Plateau indicate reverse slip along steeply-dipping, east- to northeast-striking planes (see Fig. 1.4-13, 1.4-15, and 1.4-16), with little difference between shallow (see Fig. 1.4-15) and deep (see Fig. 1.4-16) events.

Detailed studies of several earthquake swarms have shown that no single focal mechanism will fit all events (Malone et al., 1975, pp. 855-865; Rothe, 1978, pp. 123-128). In addition, there is sufficient variation in the focal mechanisms of small earthquakes to indicate that these events occur on a variety of fault orientations, suggesting some inhomogeneity in the stress field or variability in the orientation of potential faulting surfaces, such as columnar jointing (Rothe, 1978, pp. 150-154).

Epicenter plots for several individual swarms exhibit an elongated pattern oriented east-west; however, focal mechanism solutions suggest that rupture has occurred on several planes, rather than a single plane, within

these swarm areas. This is most strongly demonstrated by the first motion data for the 1972-1973 Eltopia swarm (discussed in Section 1.4.1.1.1.2).

The east-west compression that is determined for events in the Waitsburg and Walla Walla (Washington), and Milton-Freewater (Oregon) areas differs from solutions for the central Columbia Plateau (see Table 1.4-4). These earthquakes may be associated with the Hite Fault System, which strikes roughly northeast-southwest; one of the inferred fault planes for the focal mechanism solutions is parallel to this strike (WCC, 1980c, pp. 32-34). Aftershocks of the 1936 event appeared to migrate in a southwesterly direction (WPPSS, 1981, Amendment 18, p. 2.5-119), but location accuracy is poor. The coda-length magnitude 4.1 event of 1979 near College Place, Washington, did not have any aftershocks associated with it, which is unusual for an event of this size, so selection of the Hite Fault orientation for the actual fault plane is tentative. Detailed, temporary monitoring of this area did not detect any subsequent small earthquakes (WCC, 1980c, p. 4), nor has there been any concentration of events evident since 1969, using the regional network data, that could assist in defining a fault plane for these events (see Fig. 1.4-6).

Although focal mechanisms solutions vary widely across the Columbia Plateau, in the central plateau the principal compression axes of most are nearly horizontal and oriented approximately north-south (see Fig. 1.4-13 to 1.4-16). Notable exceptions occur southeast of Hanford Site near Walla Walla and to the west at Selah. The Walla Walla area events, which include the Richter magnitude 5-3/4 Milton-Freewater event of 1936, may be associated with the northeast-trending Hite Fault System; the Selah event is enigmatic in light of the virtually colocated, yet distinctly different Yakima event.

Focal mechanisms are commonly used to infer the local stress state that is responsible for the earthquakes. There are limitations to this inference, since the principal tensor axes of a mechanism corresponds to the local principal stress axes only if the fault plane is a plane of maximum shear (McKenzie, 1969). However, if numerous focal mechanism solutions are available in an area where there is no preferred orientation to pre-existing zones of weakness, the average orientation of principal stress directions should approximate the regional stress field. This may be true for the central Columbia Plateau; a principal compression axis that is horizontal and generally oriented north-south, which is consistent with a similar stress orientation postulated from both geologic data (see Section 1.3.2.2.1) and rock mechanics data (see Sections 1.3.2.3.4, 1.3.2.3.5, and 2.6).

The difference in orientation of the axes of least compression, from vertical in the central Columbia Plateau to east-west on the margin of the southern Washington Cascades, suggests that deformation in the southern Cascade Range is predominantly from strike-slip movement on northwest-southwest oriented fault planes (UWGP, 1981, pp. 11-20). Right-lateral, strike-slip faulting has been postulated along the Rattlesnake-Wallula alignment in the central Columbia Plateau (Farooqui, 1980). Composite focal mechanisms for deep events in proximity to the Rattlesnake-Wallula alignment indicate roughly equal parts of strike-slip and reverse movement (see Fig. 1.4-16).

1.4.1.3 Determination of earthquake-generating potential of geologic structures and seismo-tectonic zones within the candidate area

Estimates for the earthquake potential of structures and zones in the central Columbia Plateau have been developed during the licensing of nuclear powerplants at the Hanford Site. The NRC (1982, pp. 2-22 to 2-30), in its review of the operating license application for the Washington Public Power Supply System Project WNP-2 at the Hanford Site, concluded that four earthquake sources should be considered for the purpose of seismic design: the Rattlesnake-Wallula alignment, Gable Mountain, a floating earthquake in the tectonic province, and a swarm area.

For the Rattlesnake-Wallula alignment, the northern end of which is near the reference repository location, the NRC assumed strike-slip motion with minor amounts of oblique slip and a seismogenic length of 120 km (74.5 mi). Using the relationship developed by Slemmons between fault length and surface-wave magnitude (NRC, 1982, Appendix H) yields a surface-wave magnitude of 6.5. This value is also supported by two other empirical magnitude relations, one involving slip rate and the other involving rupture of fractional fault lengths.

Of the five Gable Mountain faults, the NRC assumed that the Central Fault, which has the largest area, is capable of generating the largest event (NRC, 1982, pp. 2-27 to 2-29). The empirical relationships described in NRC (1982, Appendix H) are for faults with large areas and may not be valid for the small dimensions of these faults. However, the NRC staff extended the reverse-oblique slip data of Wyss (1979, pp. 336-340) on fault area versus maximum magnitude to the lower values appropriate to the Gable Mountain faults and estimated a maximum surface-wave magnitude of 5.0.

The floating earthquake for the tectonic province was developed from the largest event felt or recorded on the Columbia Plateau, which occurred in 1936 near Milton-Freewater, Oregon, and had a surface-wave magnitude of 5 3/4 (Gutenberg and Richter, 1965, p. 164; NRC, 1982, p. 2-25). The conjugate fault planes for this event indicate right-lateral strike-slip to the northeast or left-lateral strike-slip to the northwest, both with some oblique slip. Because of uncertainty in the association of this event with a specific structure, the NRC stance was that a similar event could occur in the immediate vicinity of the Washington Public Power Supply System WNP-2 site.

The magnitude and location characteristics of the hypothetical swarm were based on the observed seismicity. The largest Columbia Plateau swarm event thus far observed (1973 Royal Slope earthquakes) had a coda-length magnitude of 4.4 (Malone et al., 1975). The NRC has interpreted this event (NRC, 1982, pp. 2-26 to 2-27) as a Richter magnitude 4.0 to reflect the relative overestimation by the coda-length scale. On the basis of studies that suggest that swarms preferentially occur in areas of irrigation (WPPSS, 1981, pp. 2.5J-39 to 2.5J-49), the NRC adopted the distance to the nearest areas of irrigation (3 km (1.9 mi)) as the minimum distance of the maximum swarm event to the WNP-2 site.

The maximum magnitudes for the potentially seismogenic structures identified above were estimated from empirical fault dimension-magnitude relationships. This approach was adopted because no significant seismicity is located on the structures. However, the applicability of relationships in these cases is questionable (NRC, 1982, Appendix H) because they were developed for larger events and fault surfaces than those of the Columbia Plateau, and furthermore, they were developed for plate boundaries rather than plate interiors. Nonetheless, the resultant maximum magnitude values were adopted by the NRC as conservative estimates.

1.4.1.4 Earthquake-induced phenomena within the candidate area that may affect site

The potential for geologic failures (e.g., sediment liquefaction and landsliding) to adversely affect a repository in basalt is low. Liquefaction would be confined to suprabasalt and interbedded sedimentary units. This would limit potential liquefaction to fine-grained, unconsolidated, saturated sediments below the top of the unconfined aquifer, which is at an elevation of 145 m (475 ft) within the reference repository location. The apparent absence of soft-sediment deformation in the core samples available from the interbedded and suprabasalt sediments suggests that liquefaction has not occurred in these units. The only observations suggesting that are even suggestive of liquefaction are clastic dikes, which are likely a result of cataclysmic flooding during the Pleistocene, but which may be related to seismicity in some manner as well. The high confining pressure reduces the probability of liquefaction from occurring because of the high intergranular pressures; however, if a saturated, granular, unconsolidated material existed, liquefaction could occur with a vibratory load sufficient to overcome the intergranular pressures. The basalt interbed sediments are saturated, but were naturally deposited and probably have grain-to-grain contact if it is granular material. These sediments have been in their present environment for millions of years and, if there have ever been moderate or large earthquakes, some additional compaction has occurred, thus reducing the liquefaction potential. The lack of saturated surface material would preclude liquefaction at or near the surface of the reference repository location during the preclosure period.

No evidence of landslides exists at the reference repository location. The closest areas where large landslides have occurred are the northern flank of Rattlesnake Mountain, at a distance of approximately 5 km (3.1 mi); the north flank of Yakima Ridge at approximately 6.5 km (4.0 mi); the north flank of Umtanum Ridge at approximately 5 km (3.1 mi); and along the east bank of the Columbia River at the White Bluffs, approximately 18 km (12 mi) northeast of the site (see Fig. 1.1-8; Myers/Price et al., 1979, Plate 3-1).

Mass movement continues to be active today along the White Bluffs, probably the result of saturation of bedding planes by irrigation-fed groundwater. This causes increased pore pressure and reduced shear strength, which leads to slope failure (Schuster and Hayes, 1984, p. 431).

No evidence is available to correlate past or present landslide activity with seismic activity. This may be a result of the low level of seismicity in the candidate area and the significant erosion that occurred during Pleistocene flooding, which destroyed many surface features.

1.4.1.5 Seismic hazard in the candidate area

This section is intended to describe estimates of recurrence intervals for "maximum probable" or "maximum credible" earthquakes from seismogenic sources within the candidate area, and to evaluate the effects of these earthquakes on the site. The estimates and evaluations are to use both deterministic and probabilistic approaches to assess geologic, tectonic, and seismologic information. Much of the information used to make final estimates of ground motion at the site from potential hazards will be evaluated during site characterization. Plans to characterize the recurrence intervals of the maximum earthquakes from potential earthquake sources and evaluate primary and secondary effects are described in Subsection 8.3.1.2.4.3.2.

1.4.1.5.1 Recurrence relationships

Reliable recurrence calculations are available for events of coda-length magnitude less than 4.5 in the Pasco Basin. Extrapolation of these calculations to magnitudes greater than 4.5 for the Columbia Plateau is probably not valid because the data suggest that earthquake processes may be different at higher magnitudes (Rothe, 1978, Chapter VII).

Recurrence curves computed by the University of Washington Geophysics Program (UWGP, 1979, pp. 26-27 and 37) for seismicity within the Columbia Plateau yield b-values of 1.09 to 1.15 for shallow events, 0.80 for deep events, and 0.88 for events near Lake Chelan, on the northwestern periphery of the Columbia Plateau. The depths of the Lake Chelan events place them within the basement rock corresponding to the adjacent North Cascade tectonic province (e.g., NRC, 1982, p. 2-21).

Rothe (1978) determined best-fit b-values of 0.92 and 0.98 for the 1969-1970 and 1975 Wooded Island swarms. In detail, the recurrence curves of these swarms display an apparent slope break at a coda-length magnitude of approximately 1.5. The low-magnitude slopes were 0.68 and 0.76 for the 1969-1970 and 1975 swarms, respectively, while the high-magnitude slopes were 1.79 and 1.23, respectively (Rothe, 1978, pp. 117-119).

A recurrence study for small earthquakes in the central Columbia Plateau yielded a b-value of 1.0 for shallow (0 to 3 km (0 to 1.8 mi)) events, 0.72 for deep events, and 0.85 for all events (WPPSS, 1981, pp. 2.5J-16 to -18 and Fig. 2.5J-16 to -18).

Past determinations of recurrence intervals in eastern Washington State vary depending on the investigator, the areas studied, and method of analysis. Some recurrence intervals for events in the Pasco Basin, Columbia Plateau, and specific structures are found in WPPSS (1981, pp. 49-52 and Fig. 2.5-16, 2.5-17, 2.5-18, and 2.5-29), NRC (1982, pp. 20-32), and Rasmussen (1987, pp. 9 and 19-27).

There are not enough observational data to obtain reliable recurrence intervals for events with magnitudes greater than approximately 4.5. For site characterization, the maximum-magnitude events on known geologic structures will be assumed for the preclosure time period, unless subsequent geologic evidence permits a reliable estimate of the recurrence of such events. Plans for further investigation of recurrence intervals are described in Section 8.3.1.2.4.3.2.

The methodology used in the seismic exposure evaluation of the Washington Public Power Supply System Project WNP-2 and WNP-1/WNP-4 nuclear plants, which are approximately 20 km (12 mi) east of the reference repository location, is described in WPPSS (1981, Appendix 2.5K, Amendment 18). This study estimates maximum accelerations at these nuclear plants for potential earthquake sources on various geologic structures (see Fig. 1.3-12 for location map), but not for possible swarm activity or a floating tectonic event.

Instrumentally recorded seismicity alone was not sufficient to provide recurrence estimates for individual structures. The Washington Public Power Supply System based their recurrence intervals for earthquakes on specific structures on stratigraphic data as well as instrumental data. The earthquake recurrence characteristics they determined for specific structures are as follows (WPPSS, 1981, Appendix 2.5K, pp. 2.5K-49 to 2.5K-53):

- On the central fault of Gable Mountain--10,000 yr for a magnitude 5.0.
- In the Finley Quarry area--at least several tens of thousands of years, and possibly longer for a surface rupture.
- For surface rupture on the Wallula Fault Zone--in excess of 10,000 yr, and may be much longer.
- For surface rupture on the Toppenish Ridge--on the order of thousands to a few tens of thousands of years.
- For surface rupture on Ahtanum Ridge--on the order of at least tens of thousands of years.

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1.4.1.5.2 Effects of seismicity on underground openings

A brief summary of the effects of earthquakes on underground openings in general is presented to provide perspective on the problem of seismic hazards.

Repository subsurface facilities may respond to earthquake ground motion differently than surface facilities. The potential for damage to surface and underground equipment during construction and emplacement of wastes must be considered during engineering design. Qualitative reports on the effects of large earthquakes in mines indicate that little damage generally occurs, except near portals or where the rupturing fault intersects or comes close to the mine (Marine, 1981, p. 43-52). However, few analyses are available that can be used to demonstrate tunnel stability during earthquake ground motions. Both temporary and long-term changes in the flow rate of groundwater into mines have been observed as effects of earthquakes. These changes were caused by faulting, with permanent displacements in rock. The expected effects of swarm earthquakes, including displacements at the reference repository location, will be the subject of a major study for the BWIP. The specific earthquake faulting parameter studies are described in detail in Section 8.3.1.2.4.3.3.4.

Although specific techniques to analyze the stability of underground openings in basalt have not yet been developed, earthquake data are being gathered for use in addressing the problem. The BWIP program to further characterize microseismicity, and to evaluate the potential effects of microearthquakes on the stability of underground openings, is outlined in Section 8.3.1.2.4.3.3.6.

1.4.2 SEISMOLOGY OF THE SITE

1.4.2.1 Seismicity of the site

1.4.2.1.1 Introduction

The reference repository location is located in an area of relatively low seismicity with respect to the surrounding area in the central Columbia Plateau. Earthquake activity around the reference repository location is confined to the crust, which is 30 km (19 mi) thick, and is characterized primarily by shallow swarms of microearthquakes that occur predominantly in the basalts. Focal mechanisms for basalt and sub-basalt events indicate north-south compression and reverse faulting along nearly east-west planes. The seismicity of the reference repository location for the period 1969 to 1983, including both shallow and deep events, is shown in Figure 1.4-17 and listed in Table 1.4-7.

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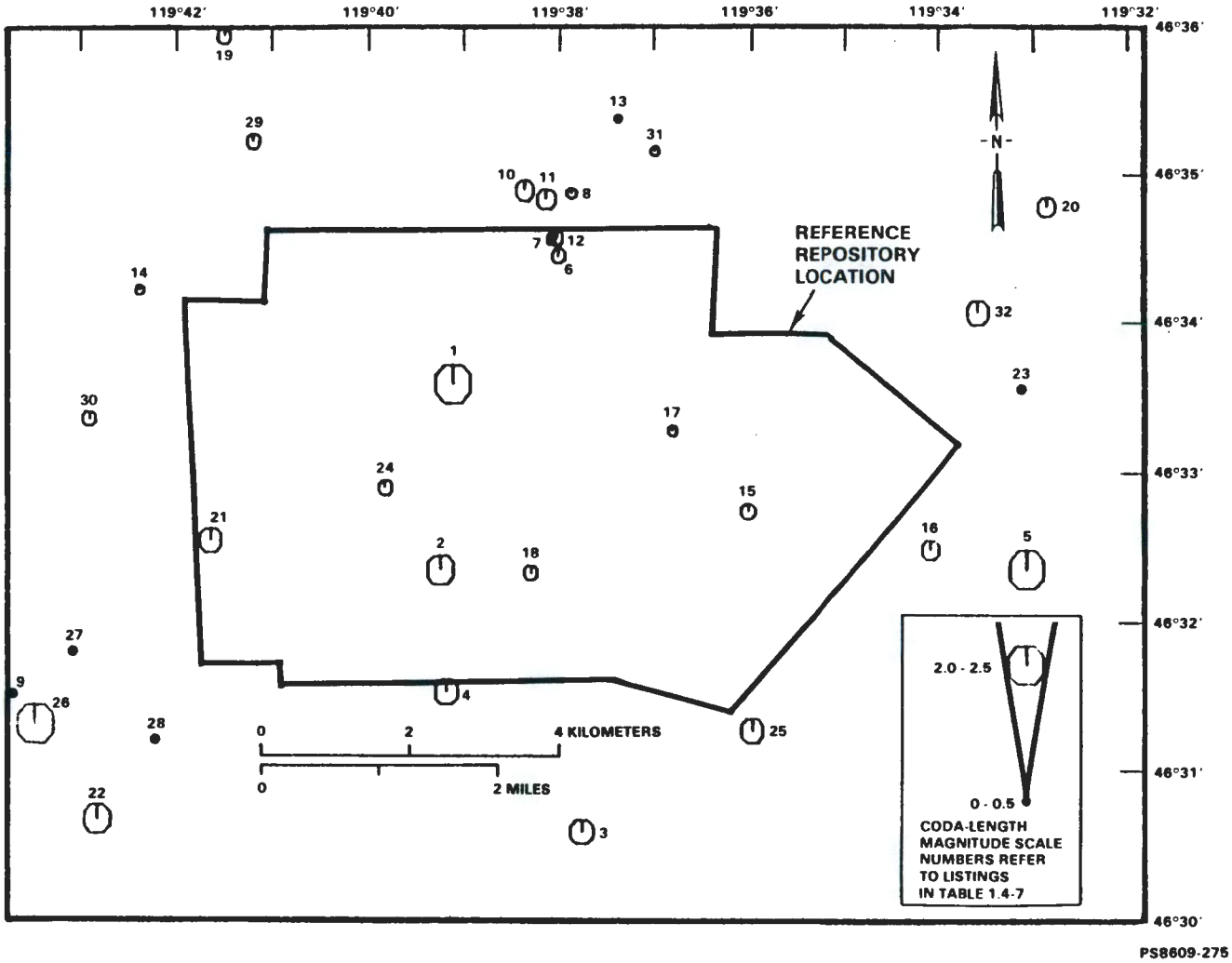

Figure 1.4-17. All events in and near the reference repository location from 1969 through 1983 (see Table 1.4-7 for listing of these events and their hypocenters).

CONSULTATION DRAFT

Table 1.4-7. Events in and near the reference repository location

Event numbers (see Fig. 1.4-17)	Date	Universal time	Second	Latitude	Longitude	Depth		Magnitude*
						km	mi	
1	11/10/69	00:56	15.34	46°33.61′ N.	119°39.11′ W.	10.28	6.39	2.2
2	11/18/69	18:17	37:26	46°32.36′ N.	119°39.24′ W.	7.48	4.65	1.6
3	11/21/69	04:23	57.87	46°30.62′ N.	119°37.75′ W.	6.57	4.08	1.4
4	11/26/69	12:16	25.82	46°31.56′ N.	119°39.18′ W.	3.00	1.86	1.3
5	03/16/70	15:48	21.31	46°32.36′ N.	119°33.04′ W.	13.80	8.58	2.4
6	03/16/71	21:03	48.18	46°34.47′ N.	119°38.00′ W.	7.08	4.40	0.8
7	03/06/71	21:04	07.25	46°34.58′ N.	119°38.08′ W.	7.15	4.44	0.6
8	03/06/71	21:13	16.14	46°34.88′ N.	119°37.86′ W.	7.41	4.61	0.4
9	03/22/71	02:56	28.05	46°31.54′ N.	119°43.72′ W.	7.62	4.73	0.2
10	06/10/71	09:38	04.58	46°34.90′ N.	119°38.36′ W.	7.95	4.94	1.1
11	06/10/71	10:53	10.62	46°34.84′ N.	119°38.13′ W.	6.53	4.06	1.0
12	08/17/71	07:30	06.69	46°34.59′ N.	119°38.02′ W.	7.29	4.53	0.8
13	09/26/71	00:41	04.19	46°35.38′ N.	119°37.36′ W.	14.29	8.88	0.1
14	09/22/72	07:28	30.49	46°34.25′ N.	119°42.40′ W.	17.33	10.77	0.4
15	02/05/73	13:29	02.14	46°32.75′ N.	119°36.00′ W.	20.26	12.59	0.7
16	02/10/73	19:02	58.70	46°32.49′ N.	119°34.06′ W.	14.92	9.27	1.2
17	02/11/73	11:01	40.56	46°33.29′ N.	119°36.79′ W	11.14	6.92	0.4
18	04/22/74	00:49	23.37	46°32.34′ N.	119°38.29′ W	17.56	10.91	0.8
19	07/10/74	00:45	58.61	46°35.93′ N.	119°41.52′ W.	14.10	8.76	0.9
20	10/28/75	20:12	04.56	46°34.79′ N.	119°32.83′ W.	18.91	11 75	1.0
21	04/04/78	11:18	20.39	46°32.56′ N.	119°41.65′ W.	20.00	12.43	1.5
22	06/22/79	00:44	42.09	46°30.70′ N.	119°42.84′ W.	3.00	1.86	1.8
23	10/22/80	11:36	24.44	46°33.58′ N.	119°33.10′ W.	20.87	12 96	0.3
24	07/13/81	08:56	29.36	46°32.91′ N.	119°39.82′ W.	16.47	10.23	0.9
25	08/07/81	22:02	38.57	46°31.30′ N.	119°35.96′ W.	15.45	9.60	1.5
26	09/23/81	16:28	39.08	46°31.34′ N.	119°43.49′ W.	19.58	12.16	2.3
27	09/24/81	18:25	12.19	46°31.82′ N.	119°43.09′ W.	15.61	9.70	0.3
28	09/27/81	23:41	15.10	46°31.25′ N.	119°42.23′ W.	18.67	11.60	0.3
29	09/05/82	17:13	08.25	46°35.23′ N.	119°41.21′ W.	1.46	0.91	0.9
30	09/13/82	14:01	14.92	46°33.38′ N	119°42.92′ W.	19.24	11.96	0.9
31	12/05/83	23:18	31.24	46°35.16′ N.	119°36.98′ W.	16.64	10.34	0.6
32	12/18/83	11:18	57.53	46°34.09′ N.	119°33.56′ W.	15.65	9.72	1.5

NOTE: These hypocenters are preliminary and may be relocated (University of Washington Master File Revision 3; UWGP Annual Reports, UWGP, 1975, 1976, 1977, 1978, 1979, 1980, 1981, 1982, and 1983). PST87-2005-1.0-15

*Coda-length magnitude.

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Instrumental recording of earthquakes located near the reference repository location began in 1969 with the installation of the U.S. Geological Survey six-station regional network in the central Columbia Plateau. Since installation of the initial Hanford Site regional network, all earthquakes above magnitude 1.5 have been consistently located within 2 km (1.2 mi) epicentral accuracy. Hypocentral depths are accurate to 2 to 4 km (1.2 to 2.4 mi) (see Fig. 1.4-17). In mid-1982, accuracy for hypocenter locations was increased to 1 to 2 km (0.6 to 1.2 mi) in the reference repository location. Since the beginning of 1985, with the installation of the shallow-hole array, hypocenter locations in the reference repository location are accurate to about 50 m (165 ft).

1.4.2.1.2 Reference repository location seismic instrumentation

Monitoring of the reference repository location for the BWIP started in 1980 with the installation of a permanent four-station baseline network and a temporary six-station portable network (DOE, 1982, p. 3.7-65). The four-station baseline network consists of three short-period vertical stations. The portable network is composed of three-component, short-period instruments. Digital recording of seismic events, which permited routine determination of hypocenters, started in early 1982. This network improved location accuracy to better than 1 km (0.6 mi) and reduced the threshold for location of all events near the reference repository location to less than magnitude 1.0, compared to previous results from the existing regional network.

A seismic station was installed in borehole DC-3 at a depth of about 1,000 m (3,600 ft) in 1980, and was operating during March, April, and May of that year. Recordings of microearthquakes (all less than coda-length magnitude 1.0) were obtained, including recordings of numerous regional earthquakes that occurred near Mount St. Helens. The local earthquakes recorded by the deep borehole instrument were not detected by the surface networks. In September 1985, a three-component accelerometer was permanently installed at a depth of 1,000 m (3,600 ft) to record accelerations in the range of 0.5 to 0.00005 g.

In the fall of 1984, a shallow borehole seismic network was installed at the reference repository location to monitor the seismicity in even greater detail. This network consists of eight seismometers that are installed in the top of the basalt section at a depth of approximately 195 m (600 ft). The combination of the baseline network, the deep borehole seismometer, and the shallow borehole network is capable of locating all earthquakes above a threshold magnitude of 0.0 to a precision of approximately ±50 m (165 ft) (Rohay et al., 1983, p. 17).

1.4.2.1.3 Shallow seismicity

Two areas of shallow swarm activity, the Coyote Rapids and the Cold Creek swarm areas, are located within 10 km (6.2 mi) of the reference repository location (see inset figure of Table 1.4-3). The Coyote Rapids swarm area has been the site of several swarms since 1969, when instrumental monitoring of this area began. The seismicity studies conducted for the Washington Public Power Supply System sites identified seven swarms in the Coyote Rapids area during the period 1969 to 1980 (WPPSS, 1981, Table 2.5J-5). An additional swarm occurred in 1983 subsequent to that study (UWGP, 1983).

A total of 91 events have occurred in the Coyote Rapids swarm area during the period from 1969 to 1986 (Table 1.4-8), the bulk of which appear to congregate into two 5 to 10 km (3 to 6 mi), roughly east-west lineations at either end of the west leg of the Columbia River horn (see Fig. 1.4-7). The depth distribution of events in this area appears to be bimodal, with a sharp falloff from the surface and a broad maximum between 4 to 7 km (2.5 to 4.3 mi). Approximately 70% of the events were located in the upper 4 km (2.5 mi), and 98% (all but two events) in the upper 8 km (5 mi), although all may be at depths shallower than 8 km (5 mi). The depths of these two deepest events (numbers 2 and 13 in Table 1.4-8) are suspect because the seismographic network at the time was sparse, and because the earlier of the pair was located using an obsolete velocity model.

Most of the Coyote Rapids events (76 or approximately 85%) have magnitudes (coda-length) of 1.5 or less. The two largest events in this area occurred during swarms on October 25, 1971 (3.8 coda-length magnitude) and on October 20, 1983 (3.4 coda-length magnitude).

A second area, referred to as the Cold Creek swarm area (see Table 1.4-3 and inset figure) is located 5 to 8 km (3 to 5 mi) south of the reference repository location. Two periods of activity have occurred in this area: July to November 1979 and August 1981. A total of 15 events occurred in this area, all less than 5 km (3 mi) deep. The largest event had a 2.4 coda-length magnitude.

1.4.2.1.4 Deep seismicity

Seismic activity beneath the basalt at the reference repository location has been limited to two periods of small events since 1969. The first period was November 1969, when two events occurred below the central reference repository location and two below the area just to the south (see Fig. 1.4-17 and Table 1.4-7; events numbered 1 to 4). One of the events south of the reference repository location was located using a depth fixed at 3 km (1.9 mi) near the base of the basalt, and the other had a large depth error and may

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Table 1.4-8. Seismicity in the Coyote Rapids swarm area (sheet 1 of 3)

Event	Date	Time (GMT)	Latitude (North)	Longitude (West)	Depth (km)	Magnitude
01	06/03/69	04:03	46 43.11	119 36.06	3.00	1.3
02	09/02/69	21:31	46 41.50	119 32.90	12.98	2.8
03	09/26/69	14:06	46 42.65	119 34.99	1.50	1.4
04	08/27/70	11:12	46 39.63	119 35.65	0.29	1.9
05	09/04/70	05:31	46 41.54	119 37.00	3.00	1.2
06	11/25/70	07:07	46 39.47	119 35.63	5.23	1.3
07	11/26/70	04:59	46 39.56	119 35.90	0.15	2.0
08	11/26/70	06:31	46 39.33	119 35.75	3.00	1.4
09	11/26/70	07:21	46 39.50	119 36.02	2.91	2.1
10	01/08/71	08:50	46 39.49	119 34.68	5.64	1.1
11	01/14/71	15:45	46 39.49	119 34.79	6.08	0.8
12	01/20/71	17:52	46 39.49	119 34.86	3.00	0.5
13	02/20/71	12:12	46 39.70	119 34.84	8.46	0.9
14	02/26/71	05:13	46 39.52	119 34.66	6.44	1.3
15	02/26/71	10:46	46 39.47	119 34.93	3.00	1.5
16	04/14/71	07:23	46 38.84	119 37.52	3.92	0.8
17	05/03/71	19:53	46 39.20	119 37.68	4.00	1.7
18	10/09/71	06:10	46 38.18	119 29.86	1.22	0.4
19	10/25/71	18:49	46 42.52	119 32.90	0.07	3.8
20	10/25/71	19:10	46 42.66	119 33.09	3.00	0.9
21	10/27/71	21:11	46 42.68	119 33.13	3.95	0.8
22	10/31/71	02:02	46 42.50	119 33.20	1.36	0.1
23	11/03/71	18:24	46 42.81	119 33.18	5.05	0.4
24	12/18/71	08:14	46 43.22	119 33.61	5.06	0.2
25	01/30/72	10:36	46 42.54	119 32.97	3.00	0.3
26	02/14/72	07:41	46 42.33	119 33.50	3.00	0.3
27	03/12/72	23:34	46 39.34	119 36.81	0.41	0.3
28	05/18/72	13:51	46 42.68	119 32.84	3.00	0.4
29	06/27/72	01:22	46 39.08	119 37.31	2.67	1.0
30	09/04/72	16:49	46 39.25	119 36.90	0.75	0.3

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Table 1.4-8. Seismicity in the Coyote Rapids swarm area (sheet 2 of 3)

Event	Date	Time (GMT)	Latitude (North)	Longitude (West)	Depth (km)	Magnitude
31	11/01/72	22:23	46 39.43	119 37.56	5.85	0.5
32	12/20/72	23:59	46 40.99	119 34.43	6.70	1.1
33	06/17/73	15:45	46 39.86	119 35.22	0.57	1.5
34	03/07/74	04:59	46 38.77	119 37.45	2.39	0.4
35	06/21/74	13:53	46 38.70	119 37.29	1.98	0.8
36	07/22/74	00:21	46 38.22	119 29.56	3.00	0.7
37	03/15/76	12:10	46 38.86	119 37.93	3.50	1.5
38	03/16/76	03:47	46 38.99	119 37.95	0.33	1.5
39	03/16/76	06:10	46 39.00	119 38.24	5.13	1.2
40	03/17/76	08:36	46 38.84	119 37.84	6.17	0.7
41	03/19/76	11:16	46 38.79	119 37.84	1.15	1.4
42	03/23/76	04:22	46 38.81	119 37.75	0.64	1.8
43	03/30/76	08:17	46 39.11	119 38.11	1.39	1.5
44	04/20/76	07:38	46 39.22	119 37.75	3.00	1.3
45	04/20/76	07:08	46 38.86	119 37.79	0.95	1.8
46	01/23/77	20:20	46 42.09	119 30.37	1.50	1.0
47	02/25/77	00:20	46 39.72	119 38.09	2.00	1.5
48	02/26/77	04:15	46 39.63	119 37.47	6.90	1.1
49	04/10/77	23:44	46 42.72	119 32.66	2.50	0.2
50	07/03/77	11:52	46 42.70	119 31.53	0.05	0.7
51	07/14/77	05:57	46 42.45	119 31.09	7.13	0.3
52	07/20/77	21:60	46 38.97	119 37.74	7.90	1.0
53	08/07/77	08:43	46 42.63	119 31.40	3.95	0.4
54	08/18/77	04:52	46 39.06	119 37.59	0.75	1.2
55	08/19/77	20:32	46 42.40	119 30.88	3.00	0.9
56	08/23/77	01:25	46 42.33	119 31.50	4.82	0.2
57	08/24/77	12:39	46 42.18	119 31.28	0.16	1.0
58	09/09/77	14:15	46 42.15	119 32.27	3.00	0.0
59	09/11/77	04:16	46 38.47	119 37.72	1.50	2.7
60	09/11/77	04:26	46 38.84	119 37.77	3.00	-0.1

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Table 1.4-8. Seismicity in the Coyote Rapids swarm area (sheet 3 of 3)

Event	Date	Time (GMT)	Latitude (North)	Longitude (West)	Depth (km)	Magnitude
61	09/11/77	05:06	46 38.95	119 38.08	0.80	-0.3
62	09/16/77	00:32	46 42.54	119 31.81	6.86	0.3
63	01/11/78	20:18	46 43.00	119 29.86	7.08	0.8
64	01/12/78	14:05	46 42.43	119 29.81	4.00	0.9
65	01/13/78	02:35	46 42.52	119 29.76	5.10	1.8
66	01/13/78	03:15	46 42.08	119 29.81	5.40	0.7
67	01/14/78	00:01	46 42.22	119 29.78	3.80	1.0
68	01/14/78	22:38	46 42.40	119 29.89	1.50	1.2
69	02/19/78	20:52	46 38.58	119 37.99	4.60	0.9
70	02/23/78	06:36	46 38.81	119 38.43	5.40	0.4
71	03/01/78	20:55	46 39.11	119 37.95	5.50	0.4
72	03/21/78	06:21	46 38.97	119 37.88	1.00	0.5
73	06/21/78	05:41	46 39.47	119 37.90	3.00	0.9
74	12/09/78	00:41	46 39.31	119 37.36	0.23	1.2
75	01/31/794	05:54	46 39.43	119 38.38	4.51	1.8
76	04/24/79	13:52	46 39.40	119 38.61	1.50	1.5
77	08/03/80	16:72	46 39.60	119 83.81	6.49	0.1
78	08/05/80	15:36	46 39.16	119 38.47	3.11	0.7
79	08/08/80	22:60	46 39.16	119 38.13	4.29	0.6
80	08/13/80	22:62	46 39.09	119 38.32	7.50	0.6
81	09/25/81	02:26	46 38.76	119 38.30	4.11	0.2
82	03/27/83	15:56	46 40.79	119 34.90	5.59	1.4
83	10/20/83	07:25	46 42.58	119 35.07	0.05	2.3
84	10/20/83	08:74	46 42.72	119 34.51	0.87	2.1
85	10/20/83	08:17	46 42.42	119 35.09	1.40	1.3
85	10/20/83	09:58	46 43.02	119 35.04	1.86	3.4
87	10/24/83	22:36	46 42.85	119 35.20	0.05	1.1
88	11/01/83	02:24	46 42.81	119 35.72	1.10	1.2
89	07/10/84	12:55	46 42.75	119 31.44	0.02	1.1
90	08/24/84	08:39	46 42.92	119 33.71	0.45	1.1
91	01/13/85	15:37	46 42.62	119 34.86	0.03	1.9

NOTE: To convert kilometers to miles, multiply by 0.6214.

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have occurred in the basalt or below. These four events occur along a generally north-south trend across the reference repository location:

- Coda-length magnitude 2.2 at 10.3 km (6.4 mi) depth ± 1.2 km (0.75 mi).
- Coda-length magnitude 1.6 at 7.5 km (4.7 mi) depth ± 6.6 km (4.1 mi); poor depth control.
- Coda-length magnitude 1.4 at 6.6 km (4.1 mi) depth ± 1.8 km (1.1 mi).
- Coda-length magnitude 1.3 at 3.0 km (1.9 mi) depth ± 0.4 km (0.25 mi); depth fixed to locate this event, actual depth unknown.

These events will be relocated using a new velocity model, and reinspection of the first arrivals of phases will be done, before attempting to interpret the structural significance of these events (see Section 8.3.1.2.4.3.3.2).

The second period of deep earthquake activity occurred between March and September 1971. The following six events were centered in a small area near the central northern border of the reference repository location (see Fig. 1.4-17):

- Coda-length magnitude 0.8 at 7.1 km (4.4 mi) depth ± 0.4 km (0.25 mi).
- Coda-length magnitude 0.6 at 7.2 km (4.4 mi) depth ± 0.3 km (0.19 mi).
- Coda-length magnitude 0.4 at 7.4 km (4.6 mi) depth ± 0.9 km (0.56 mi).
- Coda-length magnitude 1.0 at 6.5 km (4.0 mi) depth ± 0.8 km (0.5 mi).
- Coda-length magnitude 0.8 at 7.3 km (4.5 mi) depth ± 1.2 km (0.75 mi).
- Coda-length magnitude 1.1 at 8.0 km (5 mi) depth ± 1.6 km (1 mi).

The characteristics and generating mechanisms of the few microearthquakes that have been detected below the Columbia River basalt are not well understood; therefore, the significance of any particular event or series of events to the reference repository location is uncertain (see Section 8.3.1.2.4.3.3.5).

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1.4.2.2 Vibratory ground motion at site resulting from potential earthquakes in the area

A probabilistic seismic exposure analysis for the Washington Public Power Supply System site was used to determine an annual probability of 1×10^{-4} for exceedence of 0.25 g (WPPSS, 1981, Amendment 18, p. 2.5K-62 to 2.5K-63 and Fig. 2.5K-68). For the Washington Public Power Supply System site, potential earthquakes associated with Gable Mountain southeast anticline segment dominated the exceedence probability calculations compared to other potential sources that were considered.

Other potential sources included in the analysis are closer to the reference repository location than the Washington Public Power Supply System site, especially the Rattlesnake Mountain segment of the Rattlesnake-Wallula alignment, Yakima Ridge, and other segments of the Umtanum Ridge-Gable Mountain structural trend. Of these sources, the Rattlesnake Mountain segment probably has the potential for producing the largest ground accelerations at the reference repository location site.

Preliminary ground motion estimates at surface and subsurface locations used in conceptual design are discussed in Section 6.3.7. These estimates are based on the final safety evaluation report for the Washington Public Power Supply System WNP-2 (NRC 1982, pp. 2-29 to 2-30), and assume a maximum surface-wave magnitude 6.5 earthquake on Rattlesnake Mountain at approximately 10 km (6 mi) from the Exploratory Shaft Facility.

Three ground motion attenuation relations were applied to this hypothetical event to derive estimates of peak acceleration (Equations 3 and 5 of Campbell, 1981; Equation 4 of Joyner and Boore, 1981; and Equations 2.5K-A6 and -A8 of WPPSS, (1981, App. 2.5K). The data regressed for these three attenuation relationships are different; in particular, Campbell had more data in the distance range appropriate for the postulated maximum event (10 km (6 mi)) than did either Joyner and Boore, or the Washington Public Power Supply System.

Campbell's relations yield median (50% chance of exceedence) horizontal acceleration values of 0.25 and 0.27 g. At the median plus one standard deviation level (16% chance of exceedence), these same relations yield horizontal accelerations of 0.36 and 0.39 g.

Application of Joyner and Boore's (1981) equations gives 50% and 16% exceedence values of 0.30 and 0.54 g probabilities, respectively, for the maximum horizontal peak acceleration, while at the same exceedence levels, the relationships of WPPSS (1981, App. 2.5K) yield values of 0.32 and 0.46 g, respectively. These accelerations exceed those derived from Campbell (1981).

Estimates derived from Campbell are adopted for this site characterization plan because they are based on epicentral distances that are appropriate to this study. Nominal values of 0.25 and 0.40 g are suggested as preliminary peak horizontal acceleration values at the 50% and 16% exceedence levels for use in preliminary design estimates (Section 6.3.7).

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Other potential earthquake sources include the Umtanum Ridge-Gable Mountain structural trend and Yakima Ridge. For the southeast segment of Gable Mountain, which passes as close as 5 km (3 mi) to the reference repository location, the NRC (1982, pp. 2-27 to 2-29) estimated a maximum surface-wave magnitude of 5.0 with an uncertainty of ±0.5 magnitude units. The predicted ground motions for a magnitude 5.5 earthquake at 5 km (3 mi) are less than those predicted for the magnitude 6.5 earthquake on Rattlesnake Mountain at a distance of 10 km (6 mi). Since the duration of ground motion would be less for the smaller earthquake, the larger earthquake appears to be the most important potential earthquake source. Using the logic that the NRC applied to licensing the Washington Public Power Supply System sites, a surface-wave magnitude 5 3/4, floating tectonic province earthquake (NRC, 1982, pp. 2-32) is not considered to occur any nearer than the postulated Rattlesnake Mountain earthquake; the latter should therefore have a greater impact on the site.

A number of significant factors have not yet been considered in these ground motion estimates. The attenuation relationships can be modified by the type of faulting, the direction of fault propagation, and the seismic velocity and thickness of surficial sediments. Furthermore, although the direct shear wave from an earthquake generally produces the peak accelerations, the ground motion of other phases may be comparable because of resonant amplification at particular frequencies. Also, near-surface site effects, including those of the free surface and of impedance contrasts, can amplify ground motions by more than a factor of two, the usual free-surface correction. The nominal subsurface ground motion estimates in Section 6.3.7 and Table 6.1-5 include only the free-surface correction.

Further analysis of site effects and ground motion in the subsurface is required to facilitate more realistic ground motion estimates, including evaluation of subsurface motion at locations away from the Exploratory Shaft Facility.

Earthquake swarms, estimated to have a maximum Richter magnitude of 4.0 by the NRC (1982), must be further evaluated for potential effects and recurrence at the reference repository location. The reasons for earthquake swarms to occur where they do are poorly understood. However, there is a possible correlation between their occurrence (see Fig. 1.4-9) and (1) thinning of basalt flows (see Fig. 1.3-41); (2) steepening of the dip of the top of basement (see Fig. 1.3-37); (3) folding and associated faulting (see Fig. 1.3-12); and (4) raising of the unconfined water table due to irrigation (see Section 1.4.1.3). The potential for future swarm occurrences in the vicinity of the reference repository location will be studied further (see Sections 8.3.1.2.4.3.5 and 8.3.1.2.4.3.6).

The seismic risk assessment for the repository site will be guided by a Woodward-Clyde Consultants report (WCC, 1985, pp. 4-1 to 4-29), which recommends specific approaches to the assessment (see Section 8.3.1.2.4.3.3.6). Their report makes a fundamental distinction between tectonic earthquakes, which occur on specific geologic structures, and basalt earthquakes, which

occur in the basalt and are dominated by swarm activity. Their recommendations for tectonic earthquakes are given below.

- Maximum magnitude estimates should be based on the results of previous licensing studies near the repository site, which are discussed briefly in Section 1.4.1.3.
- Ground motion estimates should be based on empirical relationships derived from selected strong-motion observations and, possibly, analytical models.
- Subsurface ground motion estimates should be based on the observed depth dependence of strong-motion data and on analytical wave propagation techniques.

Their recommendations for basalt earthquakes are as follows:

- The location of such earthquakes should be assumed to be within or adjacent to the repository.
- General source and recurrence characteristics of the earthquakes should be those observed in the Columbia Plateau and, possibly, in similar tectonic environments.
- Detailed source characteristics should be obtained from the analysis of the BWIP seismic data and studies of the small-scale fault features, such as tectonic fractures, indigenous to the Columbia Plateau.
- A study of the influence of faulting and ground shaking on the hydraulic conductivity of the rock should be considered.

Plans for these studies are described in Section 8.3.1.2.4.3.3.6.

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1.4.2.3 Characteristics of seismic-wave transmission at site

No site-specific data are available to describe the characteristics of seismic wave transmission at the reference repository location. The preliminary estimates for vibratory ground motion that have been prepared for preconceptual design purposes have used data from other areas. The development of a model for the attenuation of seismic energy between seismic sources and the reference repository location is a major part of the site characterization activities that are planned in the area of seismology (Section 8.3.1.2.4.3.3.3).

1.4.2.4 Potential for induced seismicity affecting the site

The data base presently available for use as a baseline to identify induced seismicity consists of instrumental locations of events magnitude 1.5 or larger from 1969 through 1980. In 1980, the BWIP installed a special four-station array around the reference repository location that permitted the location of all events coda-length magnitude 1.0 or larger in the reference repository location. An eight-station shallow borehole array was installed in 1984 to locate all events in the reference repository location of coda-length magnitude 0.0 or larger. Any seismic activity observed during or after construction can be compared to this preconstruction baseline to help identify possible induced seismicity.

Using existing instrumental data, it can be shown that discharge of liquid waste in the ground and local mounding of the groundwater table in the 200 Areas of the Hanford Site are not correlated with increased seismicity. Although some rock bursts are expected during the initial underground construction of repository tunnels and shafts (see Section 2.7.1), there is no reason to suspect that human activity during the preclosure period (i.e., approximately 100 yr) would induce seismicity. However, recordings of any induced earthquakes will be monitored after initial construction studies (Section 8.3.1.2.5.4.3.3.5).

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1.5 LONG-TERM REGIONAL STABILITY WITH RESPECT TO TECTONIC AND GEOLOGIC PROCESSES

This section presents an assessment of geologic stability of the candidate site that emphasizes the next 10,000 yr. It is based on the information presented in the previous sections of this chapter with the understanding that the data base is incomplete and, as such, is only a preliminary assessment. The emphasis of this assessment is on the uncertainties and constraints on the tectonic and geologic processes that have occurred during the Tertiary and Quaternary and on those processes operating today.

1.5.1 TECTONISM

The principal elements of the tectonic setting are described in Section 1.3. This description focuses on the development of the features observed in the region and in the vicinity of the candidate site and the likelihood of their continued development or the development of new geologic structures during the preclosure and postclosure periods of a repository. This last aspect, the development of new geologic structures, can only be speculated on at present.

The phrase "tectonic model" will be used to refer to conceptual representations of various aspects of the tectonic setting presented either in narrative or graphic form. These models are essentially hypotheses that will be continuously tested by new field observations. As confidence in a working hypothesis or set of hypotheses grows, they can be used to deduce future conditions with greater levels of confidence. The methods by which this will be carried out are described in Section 8.3.1.2.4.3.3.

1.5.1.1 Tectonic setting

Numerous hypotheses have been proposed to explain the structural development of features in the Pacific Northwest and Columbia Plateau. Regional models for the Pacific Northwest can be generalized into eight different classes, while those for the Columbia Plateau can be grouped into four classes (Duncan, 1983). The Pacific Northwest regional models are as follows:

1. Accretion of allochthonous terranes.
2. Active subduction.
3. Subducted spreading center.
4. Back-arc regime.

5. Mantle plume, diapir, or hot spot.

6. Shear between plates.

7. Mantle diapir and interplate shear.

8. Microplate rotations.

The Columbia Plateau models are the following:

1. Decollement between basalt and sub-basalt layers or within sub-basalt layers.

2. Coupled basalt/sub-basalt layers with transcurrent displacement.

3. Coupled basalt/sub-basalt layers with horizontal contraction.

4. Coupled basalt/sub-basalt layers with vertical displacement.

The following paragraphs summarize the literature that is available to describe the tectonic development of the Pacific Northwest, with special emphasis on structural features in the basalts of the Columbia Plateau. For further information refer to the original papers provided in Table 1.5-1.

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1.5.1.1.1 Pacific Northwest and Columbia Plateau

At least forty different models have been proposed in the literature as interpretations for the tectonic evolution of the Pacific Northwest. This literature has been reviewed and summarized previously by Duncan (1983, Table 7-1). The principal geographic regions and geologic features that are referred to in the following discussion are shown in Figure 1.5-1, and an updated version of Duncan's review is presented in Table 1.5-1.

The guidelines that will be adopted to decide whether a tectonic model that has been proposed in the literature is significant for a geologic stability assessment (see Section 8.3.1.2.4.3.3) are given below:

- The model must address the Cenozoic, and in particular, the late Tertiary and Quaternary.

- The characteristics of tectonic activity must have affected the site or have a potential effect on the site, and there must be a possibility of those characteristics continuing into the future.

Table 1.5-1. Pacific Northwest regional tectonic models[a] (sheet 1 of 10)

Source	Area modeled; time	Geologic observations or tectonic relationships	Rate of deformation	Tectonic pattern or driving force	Current status and possible impact on reference repository location[b]
I Accretion of allochthonous terranes					
Ben-Avraham et al. (1981)	Western North America; Phanerozoic	Modern analog of many accreted terranes are oceanic plateaus that are embedded in moving oceanic plates	Not given	Collision between terranes and western North America may be driving force behind major orogenic events	Probable minor impact on site. Possible suture between terranes accreted more than 17 m.y.B.P. may be present beneath Columbia Plateau; however, if true, suture appears to be aseismic.
Jones et al. (1982)	Western North America; Phanerozoic	Abrupt juxaposition and discontinuities in lithology, paleontology, and paleomagnetics across major fault zones	Not given	Collision and accretion of terranes by subduction processes to western North America	
II Active subduction					
Ando and Balazs (1979)	Western Washington; present	Regional eastward tilt of western Washington	Uplift of +3 mm/yr (0.1 in./yr) at western Olympic Peninsula and subsidence of -3 mm/yr (0.1 in./yr) at western base of Cascades define regional eastward tilt	Juan de Fuca plate is continuously aseismically underthrusting the North American plate	Subduction is probably continuing at about 40 mm/(1.6 in./yr) and will likely continue to do so for at least another 10,000 yr. Will generate moderate to large subduction zone earthquake(s) every few tens to hundreds of years, but ground motion would probably attenuate to levels lower than those from sources nearer to site as evidenced by isoseismal maps of larger Puget Sound area earthquakes. Contribution to preclosure seismic design will be evaluated during site characterization. May account for or contribute to extant stress regime in all or parts of Columbia Plateau. Continued subduction will mean continued periodic eruption of Cascade Range volcanoes, which may deposit airfall ash that could affect preclosure
Carson et al. (1974)	Washington offshore; Pleistocene to present	Anticline formation and landward thrusting of marine sediments at base of continental slope	Not given	Active subduction off Washington coast	
Hyndman (1976)	Southwestern British Columbia; recent	A zone of low heat flow from the coast to approximately 200 km (124 mi) inland is paralleled further inland by a zone of high heat flow	Not given	Subduction of the Juan de Fuca plate beneath the North American plate is active at present (or recently north of 51° N. latitude)	
Keen and Hyndman (1979)	Southwestern Canada; 10 m.y.B.P. to present	Seismic data indicate that motion on Nootka transform fault (perpendicular to coast offshore from Vancouver Island) is sinistral	Perpendicular convergence between North American and Juan de Fuca plates is approximately 40 mm/yr (1.6 in./yr)	Active subduction of Juan de Fuca plate	
Riddihough (1979)	British Columbia and Washington; present	Gravity high-low pair in arc-trench gap	Not given	Active subduction along margin of British Columbia and Washington	

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Table 1.5-1. Pacific Northwest regional tectonic models[a] (sheet 2 of 10)

Source	Area modeled; time	Geologic observations or tectonic relationships	Rate of deformation	Tectonic pattern or driving force	Current status and possible impact on reference repository location[b]
II Active subduction (cont.)					
Langston (1981)	Vancouver Island, western Washington and Oregon; present	Seismic analysis suggests 10° to 20° dip for subducting crust from the coastline to 140 km (86 mi) inland where it plunges under the Cascades at a dip of about 50°	Not given	Active subduction of Juan de Fuca plate	ventilation operations and could result in damming of Columbia River where it flows through Cascade Range by high-volume lava flows, especially during postclosure.
Weaver and Smith (1983)	Southwestern Washington; present	Focal mechanism solutions for earthquakes along the Mount St. Helens seismic zone suggest maximum compression is northeast, parallel with the direction of plate convergence and interpreted as evidence of locked subduction	Not given	Subduction of the Juan de Fuca plate	
Heaton and Kanamori (1984)	Pacific Northwest; present	Strong seismic coupling and present-day low level of seismicity associated with Juan de Fuca subduction zone	Present-day plate convergence of 3 to 4 cm/yr (1.2 to 1.6 in./yr) across Juan de Fuca subduction zone	Plate convergence/subduction	
Tabor and Smith (1985)	Olympic Peninsula, Washington; present	Data from an expanded seismic network provides further evidence of active subduction. However, rate of seismicity is presently lower than typical rates at other convergent margins	Not given	Plate convergence and subduction	
III Subducted spreading center					
McKee (1971)	Great Basin; Tertiary	Widespread Basin and Range faulting accompanied initiation of extensive basaltic magmatism (including Columbia River basalts) at approximately 16 m.y.B.P.	Not given	The Farallon-Pacific spreading center was subducted beneath the North American plate and caused crustal expansion and basaltic eruptions	Insignificant for reference repository location. Spreading centers probably destroyed during subduction so the concept appears to be no longer valid.

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Table 1.5-1. Pacific Northwest regional tectonic models[a] (sheet 3 of 10)

Source	Area modeled; time	Geologic observations or tectonic relationships	Rate of deformation	Tectonic pattern or driving force	Current status and possible impact on reference repository location[b]
IV Back-arc regime					
Davis (1977)	Pacific Northwest and Columbia Plateau; late Cenozoic	Alternation of regional maximum stress from north-south to east-west, and back to north-south allowed north-south diking and east-west folding to develop since approximately 20 m.y.B.P. Columbia Plateau tectonic block is separated from Basin and Range terrane by a major fault zone	Subduction of Juan de Fuca plate proceeds at 40 mm/yr (1.6 in./yr)	Subduction of Juan de Fuca plate creates back-arc regime. Juan de Fuca and North American plates are uncoupled, accounting for lack of east-west compressional features in Columbia Plateau. Right-lateral transform occurs at plate boundary	Probably insignificant for reference repository location. May have operated in pre-Miocene time. However, the east-west extension appears to have ended in Miocene with cessation of Columbia River basalt volcanism from linear vent systems. Low heat flow, absence of Quaternary volcanism in the central plateau, and structures in the central plateau developed from north-south compression for the last 15 m.y. suggest minor influence of back-arc processes, if any, during Neogene.
Dickinson (1976)	Western North America; middle Miocene to present	Incipient crustal separation in back arc (Columbia Plateau) possibly related to ductility induced by thermal effects of Oligocene arc magmatism	Not given	Continuing subduction of Farallon plate west of Cascades creates back arc terrane	
Eaton (1979)	Western United States; late Cenozoic	Back-arc extension in Columbia Plateau began at 16 to 17 m.y.B.P. and was oriented northeast-southwest. In the Basin and Range between 11 and 7 m.y.B.P., spreading turned to east-west, and after 7 m.y.B.P. changed to west-northwest-east-southeast. Spreading apparently ceased in the Columbia Plateau after 11 m.y.B.P.	Not given	Hydrodynamic convection in asthenosphere drags the lithosphere apart, causing tension and eventual failure	
Eaton et al. (1978)	Western Cordillera; Cenozoic	Early Cenozoic northeast-southwest spreading in southern Washington to southern Nevada. Late Cenozoic east-west spreading, initiated between 9 and 7 m.y.B.P., overprinted earlier spreading regime and accelerated in rate	Not given	Rise and divergent flow of asthenosphere accompanying mantle upwelling caused spreading	

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Table 1.5-1. Pacific Northwest regional tectonic models[a] (sheet 4 of 10)

Source	Area modeled; time	Geologic observations or tectonic relationships	Rate of deformation	Tectonic pattern or driving force	Current status and possible impact on reference repository location[b]
IV Back-arc regime (cont.)					
Stewart (1978)	Basin and Range and Columbia Plateau; middle and late Cenozoic	Basin and Range Province characterized by low crustal seismic velocities, thin crust, high heat flow, uplift and extension, previous deformational history, and inland position relative to transform plate boundary	Not given	Back-arc spreading in Basin and Range and probably Columbia Plateau	
V Mantle plume, diapir, or hot spot					
Armstrong (1978)	Northwestern United States; Cenozoic	On the Columbia Plateau rapid basalt extrusion from 16 to 13 m.y.B.P. (Columbia episode) was followed by waning magmatism. Dissection, subsidence, and deformation of the plateau followed	Not given	Subduction on continental margin and crustal disruption from the Yellowstone hot spot account for tectonism since the Columbia episode. Origin of the Columbia episode is unexplained	Probably minor effect on reference repository location, but will be assessed further. May have operated during Miocene, but no consistent eastward migratory trend of mapped Columbia River basalt linear vent systems observed.
Smith and Sbar (1974)	Western United States; present	Fault plane solutions from the Intermountain Seismic Belt suggest the Northern Rocky Mountain subplate (north of the Snake River Plain) is moving northward away from the Great Basin subplate and westward away from the remainder of the North American plate	Juan de Fuca plate is subducting to the east-northeast at 28 mm/yr (1.1 in./yr)	Lithospheric rifting along the Snake River Plain is caused by westward migration of North American plate over a mantle plume (Yellowstone). Extension occurs to west of Intermountain Seismic Belt, owing to radial stress away from Yellowstone plume	Basalts of eastern Snake River Plain where model appears to work well are chemically distinct from Columbia River basalt. No clear evidence of high-temperature alteration of Columbia River basalts in post-Miocene time. Quaternary volcanism to west and south of Columbia Plateau not in accord with model.
Suppe et al. (1975)	Western United States; late Cenozoic (10 m.y.B.P.) to present	Fanning pattern of Yakima fold and thrusts indicates that the Western United States subplate (to the south) has been moving north and west against northeastern Oregon and Washington. The Columbia Plateau clockwise sense of rotation is related to distributed extension to the south	1 to 10 mm/yr (0.04 to 0.4 in./yr) extension between Western United States and North American plates	Western United States subplate is rotating counterclockwise about a center in southern California. Rising asthenosphere at plate boundary or heating of lithosphere from below or some combination of processes may be the cause of regional uplift and extension	

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Table 1.5-1. Pacific Northwest regional tectonic models[a] (sheet 5 of 10)

Source	Area modeled; time	Geologic observations or tectonic relationships	Rate of deformation	Tectonic pattern or driving force	Current status and possible impact on reference repository location[b]
V Mantle plume, diapir, or hot spot (cont.)					
Thompson (1977)	Western United States (Columbia-Snake River-Yellowstone Province); Cenozoic	The volume and rate of magmatism in the Columbia Plateau and western Snake River Plain greatly exceed the eastern Snake River Plain. This is evidence against the Yellowstone deep mantle plume producing province-wide magmatism	Rate of magmatism: Columbia River Plateau, 100,000 km^3/m.y (24,000 mi^3/m.y.).; western Snake River Plain, 31,000 km^3/m.y. (7,400 mi^3/m.y.); eastern Snake River Plain, 3.3 km^3/m.y. (0.8 mi^3/m.y.)	Tectonic and magmatic features produced by shallow diapiric mantle upwelling in both the Basin and Range and the Columbia Plateau. Constriction of Columbia Plateau diapir by shallowly subducting Farallon plate led to "run-away" mantle fusion and massive basaltic magmatism	
Duncan (1982)	Pacific Northwest; Cenozoic	Radiometric age determinations for early Tertiary basalts of the Coast Range and Olympic Mountains show a progressive pattern of decreasing age, from both the north and the south, toward the Columbia River. Geochemical evidence suggests these basalts were produced by ridge-centered hot spot volcanism	Not given	Generation of sea mounts and oceanic islands by spreading ridge-centered hot spot that were accreted to the Pacific Northwest by lock-up and westward jump of the subduction zone. Continued westward movement of the North American plate over the hot spot produced the Columbia River basalt, Snake River Plains, and Yellowstone volcanism	
VI Shear between plates					
Atwater (1970)	Western North America; late Cenozoic	Pacific Northwest undergoing slight east-west compression and regional dextral shear on northwestern-trending zones	Oblique motion of 60 mm/yr (2.3 in./yr)	Subduction of Juan de Fuca plate and transform of Pacific plate relative to North American plate	Effects on site to be determined during site characterization. May account for north-south compression in central plateau and wrench faulting in southwestern Columbia Plateau. Transition from prevalent strike-slip faults accompanying folding and thrust faulting in western plateau to minmal strike-slip faulting accompanying folding and
Beck (1976, 1980)	Western edge of North America; Cenozoic	Northwestward translation and clockwise rotation of crustal blocks on western margin of North America. Oregon-Washington Coast Range Province rotated as independent microplate. Columbia Plateau basalts unrotated	15 mm/yr (0.6 in./yr) of relative northward movement in early and middle Tertiary for western Washington and Oregon	Transform faulting, oblique subduction, or oblique rifting between Pacific or Farallon plates and North American plate	

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Table 1.5-1. Pacific Northwest regional tectonic models[a] (sheet 6 of 10)

Source	Area modeled; time	Geologic observations or tectonic relationships	Rate of deformation	Tectonic pattern or driving force	Current status and possible impact on reference repository location[b]
VI Shear between plates (cont.)					
Christiansen and McKee (1978)	Great Basin and Columbia Intermontane regions; late Cenozoic	Extension of a few kilometers north of High Lava Plains accompanied by basaltic magmatism, increased heat flow, lowered lithospheric rigidity, and regional uplift	Extension inactive since 14 m.y.B.P.	Partial coupling of transform between Pacific and North American plates caused east-west extension	thrust faulting in central plateau not well understood, but may relate to eastward limits of transmission of interplate shear to western North American Plate. Possible transition from active subduction of Juan de Fuca Plate to transform faulting of Pacific and North American Plates may affect magnitude of compressional stress in future. Available gravity, magnetotelluric, and seismic refraction data do not support a northwest-trending zone along the Rattlesnake-Wallula alignment that juxtaposes rocks of contrasting properties as might be expected along a continental-oceanic crustal boundary.
Coney (1978)	North American Cordillera; early Miocene to present	East-west extension and cessation of subduction related to wide transform zone in thermally weakened Basin and Range Province	Not given	Subduction of Farallon plate virtually ceases; transform of Pacific plate predominates	
Crosson (1972)	Puget Sound region; present	North-south compression determined for contemporary earthquakes	Not given	Subduction recently ceased and transitional tectonics are active	
Ewing (1980)	Pacific Northwest; Paleogene	Eocene right-lateral motion on major strike-slip faults, by grabens and reset terranes (e.g., metamorphic core complexes) suggest that a large, concealed extensional area exists beneath the Columbia Plateau	Not given	Transcurrent fault system resulting from oblique subduction or an on-land transform margin. The second model is preferred	
Ingersoll (1982)	Western United States; late Cenozoic	Crustal extension in western United States not related to back-arc spreading. Northwestward migration of Mendocino triple junction has caused clockwise rotation and regional extension	Not given	Unstable Mendocino triple junction; geometry of plate motions	
Livaccari (1979)	Western United States, late Cenozoic	Northwest-trending dextral faulting in Oregon, California, and Nevada; no similar faulting in British Columbia. Dextral faulting minimal in Washington	Not given	San Andreas transform is not buttressed to north, so dextral slip occurs. Queen Charlotte transform is buttressed, so no slip occurs. No transform exists to west of Washington, so driving force for dextral shear is absent in Washington	

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Table 1.5-1. Pacific Northwest regional tectonic models[a] (sheet 7 of 10)

Source	Area modeled; time	Geologic observations or tectonic relationships	Rate of deformation	Tectonic pattern or driving force	Current status and possible impact on reference repository location[b]
VI Shear between plates (cont.)					
Magill et al. (1982)	Southern Washington, 12 m.y.B.P. to present	Pomona Member basalts rotated clockwise approximately 16° to the west of Cascades, but are essentially undisturbed on the Columbia Plateau	Not given	Southwest Washington rotated as a rigid block, while Columbia Plateau remained unrotated but possibly sheared on northwest-trending faults. A distinct zone of unspecified nature (the Cascades) separates the tectonic domains. Cause of rotation is possibly shear on North American plate imposed by the Pacific plate, or unbuttressed sliding off of the Great Basin asthenospheric high (to the north this would cause north-south compression of Columbia Plateau)	
Robyn and Hoover (1982)	Eastern Oregon; 36 m.y.B.P. to present	Recognize three main periods of compressional deformation: 36 to 17 m.y.B.P., 17 to 10 m.y.B.P., and 10 to 6 m.y.B.P. Type of deformation and attendant volcanism changed between periods.	Not given	Deformation developed from interaction between a rigid lithospheric block and northwest movement of lithosphere along right-lateral strike-slip zones (microplates)	
Sbar (1982)	Western North America; present	Six seismotectonic domains delineated on basis of crustal stress and regional seismicity. Pacific Northwest domain has stress field similar to San Andreas, east-central California, and Mendocino Triple Junction domains	Not given	Four domains listed are generated by shear between Pacific and North American plates. Transform connection between San Andreas and Queen Charlotte Island fault systems may be initiating	
Wise (1963)	North American Cordillera; Paleozoic to present	East-west extension and north-south compression for Columbia Plateau. Regional northwest-trending dextral shear	Not given	Not given	

CONSULTATION DRAFT

Table 1.5-1. Pacific Northwest regional tectonic models[a] (sheet 8 of 10)

Source	Area modeled; time	Geologic observations or tectonic relationships	Rate of deformation	Tectonic pattern or driving force	Current status and possible impact on reference repository location[b]
VII Mantle diapir and interplate shear					
Smith (1977, 1978)	Western North America; Cenozoic	Western United States is composed of subplates, each with its own motion in overall regime of northwest-southeast extension. General northwest movement of all subplates is accomplished by right-lateral oblique shear and extensional faulting. North-south compres-sion in Columbia Plateau is possibly due to buttressing against the rigid North American plate to the north	Not given	Obliquely convergent plate interaction, extension over a mantle diapir, and stress relaxation following end of subduction account for features observed	Possible effect on reference repository location (see V and VI). Hypothesis of three major periods of deformation under shifting compressive stress axes is speculative and not strongly supported by evidence in central plateau where deformation appears to be a continuum from Miocene to present under north-south compression.
Barrash and Venkatakrishnan (1982)	Western North America; late Cenozoic	Tectonic and magmatic events began, changed intensity, or ceased at approximately 16, 10, and 5 m.y.B.P. Magmatism at 16 m.y.B.P., shift of maximum compressive stress 25° clockwise to north-south at 10 m.y.B.P., and cessation of folding at 5 m.y.B.P. affected the Columbia Plateau	Not given	16-m.y.B.P. events were related to mantle diapir; 10-m.y.B.P. events were related to rotation of Pacific plate spreading direction; 5-m.y.B.P. events were related to oceanic plate reorganiza-tions. Farallon plate was uncoupled since 16 m.y.B.P., so continental tectonic forces were derived from Pacific plate	
Barrash et al. (1983)	Columbia Plateau; 17 m.y.B.P. to present	Same as above.	Not given	Same as above.	
VIII Microplate rotations					
Bates et al. (1981)	Western Washington; Oligocene to present	Paleomagnetic data for Washington Coast Range and southern Cascades show similar clockwise rotations of approximately 34°	1.5°/m.y. from early Eocene to early Miocene	Oregon and Washington Coast ranges rotated together since late Eocene, owing to no specific driving mechanism	Probably not significant for reference repository loca-tion. Paleomagnetic data suggest rotation of crustal blocks and accreted

CONSULTATION DRAFT

Table 1.5-1. Pacific Northwest regional tectonic models[a] (sheet 9 of 10)

Source	Area modeled; time	Geologic observations or tectonic relationships	Rate of deformation	Tectonic pattern or driving force	Current status and possible impact on reference repository location[b]
VIII Microplate rotations (cont.)					
Hammond (1979)	Pacific Northwest; Cenozoic	Coast Range and Cascade arc blocks rotated clockwise from Olympic-Wallowa lineament about Olympic Peninsula center. Blue-Ochoco Mountains dragged behind along northwest-trending dextral faults. Mesozoic rocks below Columbia Plateau are thinned tectonically. Yakima folds superimposed on northern Cascades are from 12 to 5 m.y. (This is essentially the second model of Simpson and Cox, 1977)	Rotation apparently ceased by 20 m.y.B.P.	Rotation of subduction zone (Juan de Fuca) and related arc and back-arc extention remain unexplained	terranes west of Cascades. Some evidence of rotation of small, local blocks in anticlinal hinge areas in Columbia Plateau that may relate to folding. No evidence of rotation found in synclinal areas such as Cold Creek syncline. Paleomagnetic analyses will continue to look for evidence of rotation during site characterization.
Heptonstall (1977)	Western Cordillera; middle Tertiary (30 m.y.B.P.) to present	Three oroclines between Vancouver, British Columbia, and northern California, including one located near the Oregon-Washington-Idaho border disrupt the linearity of the Cordilleran orogenic belt	14° rotation from 29 to 4 m.y.B.P.; inactive after 4 m.y.B.P.	Cordillera north of Vancouver, British Columbia remained fixed as Cordillera south of the Klamath Mountains moved northwest with the Pacific plate. Two segments linked by Oregon-Washington-Idaho orocline acted as fragmented segments linking the major plates	
Magill et al. (1981)	Oregon Coast Range; 44 m.y.B.P. to present	Paleomagnetic data show clockwise rotations of approximately 46° of the entire Oregon Coast Range block. The Washington coast is characterized by smaller discrete blocks of variable clockwise rotation	Two phases: Eocene, 40° to 50°/5 to 6 m.y. (6°/m.y.) and Miocene to present, 30°/20 m.y. (1-1/2°/m.y.)	Fragmentation of Farallon plate results in Eocene rotation and accretion of Coast ranges to North America. Eocene phase involves southern pivot linked to northern Klamath Mountains. Initiation of Basin-Range extension caused Miocene phase rotation about northern pivot. Northwest-trending strike-slip faulting and microplate adjustments cause north-south compressive strain in relatively stable Columbia Plateau of Washington	

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Table 1.5-1. Pacific Northwest regional tectonic models[a] (sheet 10 of 10)

Source	Area modeled; time	Geologic observations or tectonic relationships	Rate of deformation	Tectonic pattern or driving force	Current status and possible impact on reference repository location[b]
VIII Microplate rotations (cont.)					
Simpson and Cox (1977)	Pacific Northwest; Eocene to present	Rotation of Oregon Coast Range clockwise into alignment with present coastline with either southern or northern pivot. Northern pivot requires rifting and extension in back-arc regime east of Coast Ranges, along Olympic-Wallowa lineament, with extension increasing southward	50° to 75° of rotation since Eocene; 28° since Oligocene	Rotating oceanic plates during subduction or back-arc extension causes rotation of Coast Range block	
Watkins and Baksi (1974)	Oregon, Washington, Idaho; 16 to 13 m.y.B.P.	Paleomagnetic data show an orocline extending across southeastern Washington, western Idaho, and eastern Oregon. Magnetic poles for contemporaneous lava sections indicate a clockwise rotation of at least 15° of the southern sections relative to the northern sections. Compression in central Washington and Oregon is required	Average rotation rate of 1°/m.y.	Not given	

[a]Modified from Duncan (1983), pp. 7-2 to 7-6; updated to 1985.
[b]Comments apply to entire section, not to individual references within the section.

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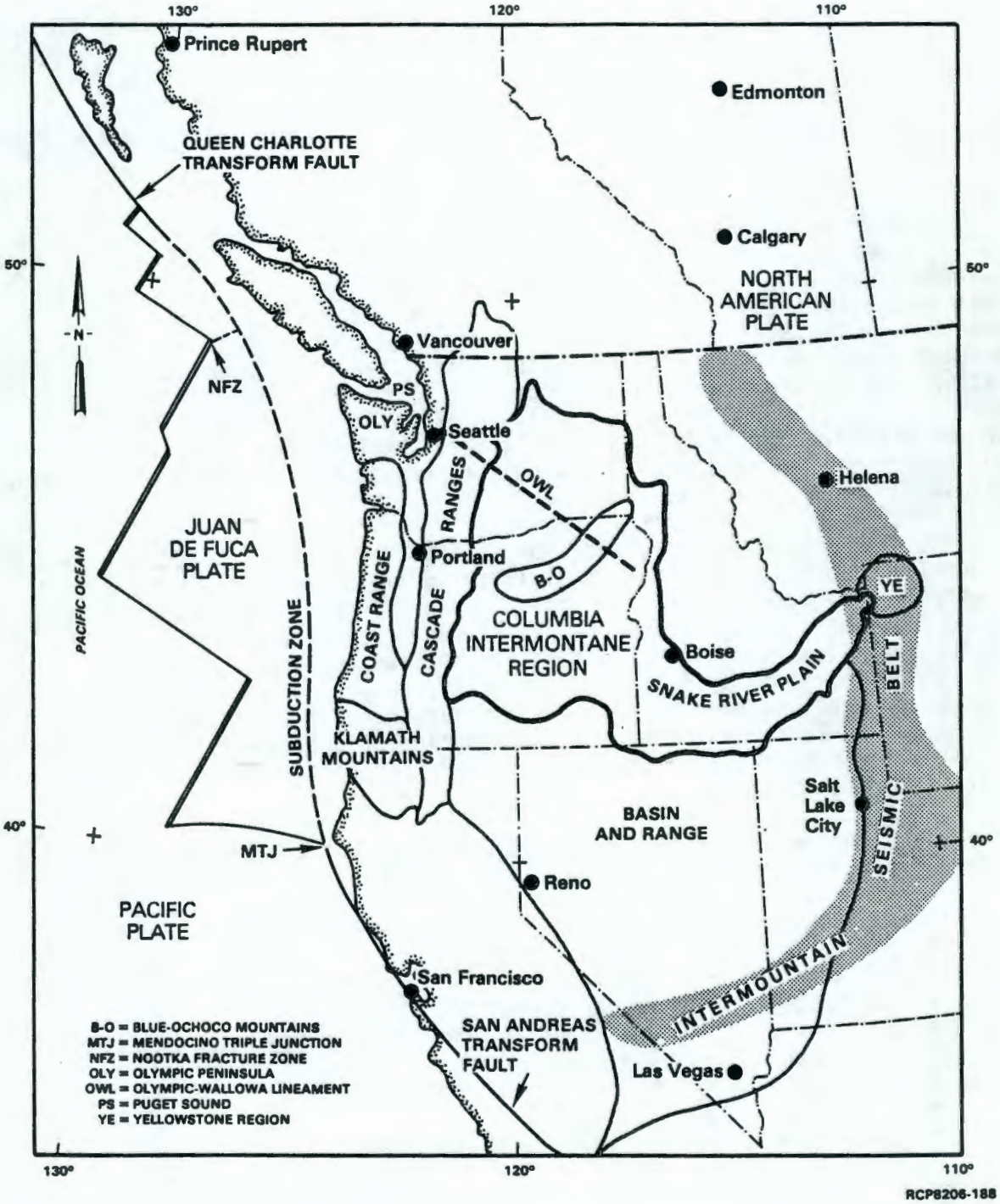

Figure 1.5-1. Location map for geologic and geographic features.

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Few models have specifically treated the tectonic development of the Columbia Plateau. None completely explains the sequential development of the (1) intermontane basin in which the Columbia River flood basalts lie and the previous geologic record of the basin, (2) origin of the linear vent systems through which the basalt was extruded, (3) petrogenesis of the basalts, (4) deformation of the basalt sequence into asymmetrical folds, and (5) relationship between basalt structures and structures beyond the margins of the basalt flows.

The features within the Columbia Plateau that have been addressed in previous modeling efforts include the Yakima folds and wrench (strike-slip) faults in the western plateau, the Blue Mountain structures in the southeastern plateau, and the comparatively minor deformation of the Palouse Slope in the northeastern plateau (see Section 1.3.2.2.1). Also, several studies have focused on the Olympic-Wallowa lineament, a major northwest-trending topographic feature that extends from the Olympic Mountains of western Washington to the Wallowa Mountains of northeastern Oregon (see Section 1.3.2.2.1.3). Tectonic models for the Yakima Fold Belt structural subprovince have considered geologic features such as east-west-trending folds and reverse faults, northwest-trending strike-slip faults, and the Cle Elum-Wallula alignment or "disturbed zone."

The reference repository location is situated within the eastern part of the Yakima Fold Belt, where folds diminish in amplitude and merge with the relatively undeformed Palouse structural subprovince. This transition zone is also coincident with changes in trends of the Horse Heaven Hills and Rattlesnake Hills. The probable location and rate of future tectonic deformation, the extent of involvement of pre-basalt rocks, and the timing of folding and faulting must be addressed in hypotheses that explain the tectonic setting. A model for the timing and kinematics of deformation will help form the basis for predicting the stability of the reference repository location during the next 10,000 yr.

Models that describe the tectonic development of the setting for the candidate area during the late Cenozoic portray the region as being influenced by the following:

- Subduction of an oceanic plate.
- Accretion of microplates.
- Construction of a volcanic arc.
- Rotation of the Coast Range and central Oregon blocks.
- Extension in a back-arc environment.
- Production of voluminous flood basalts.
- North-south crustal shortening.
- Northwest-trending transcurrent faulting.

The early Tertiary extension of the back-arc region apparently has not had a dominant effect on the Columbia Plateau in the the post-Miocene, as evidenced by the lack of continued basaltic volcanism from linear vent systems and the predominance of compressional structures in the basalt strata. Rotation of the coastal ranges may be continuing, but large-scale rotation of

the Columbia Plateau is not apparent. The influence of the subducting Juan de Fuca plate on tectonic activity in central Washington is not completely understood; however, potential seismic activity associated with subduction is likely to be less intense in central Washington than in western Oregon and Washington (Heaton and Hartzell, 1987, pp. 162-168).

1.5.1.1.2 Pasco Basin

The Pasco Basin is the principal structural unit that contains the candidate site (Section 1.3). An understanding of its relationship to the larger crustal features in the region, and of the tectonic processes acting to change that relationship, are important parts of the stability assessment. The most detailed data collection and modeling work will focus on this structural unit (see Sections 8.3.1.2.3 and 8.3.1.2.4).

1.5.1.1.2.1 Structural configuration of the Pasco Basin and surrounding area

The structural configuration of the Pasco Basin is shown by an east-west cross section and a north-south cross section in Figure 1.5-2. These sections include the Columbia River Basalt Group, sub-basalt sedimentary strata, and crystalline basement. They have been drawn from data derived from surface mapping and geophysical surveys that are described in Section 1.3.2.2.2.

Several features are apparent in the east-west cross section. First is the eastern plateau paleoslope (Palouse Slope) and the increase in westward tilt along the eastern margin of the Pasco Basin. A second, but less obvious feature is associated with the Hog Ranch-Naneum Ridge anticline. This structure cannot be resolved using existing geophysical data, and has been interpreted from surface exposures and the information given in Campbell (1985). A third observation is the increase in thickness from east to west of the suprabasalt sediments, Columbia River basalt, and underlying units.

The data summarized in the east-west cross section in Figure 1.5-2 can be interpreted to suggest that the Pasco Basin was a subsiding basin during the emplacement of the Columbia River basalt (Reidel et al., 1981, 1983) and probably prior to the Columbia River basalt volcanic episode; subsidence probably continued to the present (Reidel, 1984, pp. 974-975), but the cause of subsidence is unclear. Also, data are insufficient to determine if subsidence occurs on basement faults or along simple flexures as suggested in Figure 1.5-1. Also unclear is the relationship between the margin of the basin and the Ice Harbor dike swarm and a series of low-amplitude, long-wavelength folds (Swanson et al., 1980) that parallel the Ice Harbor dikes farther east on the Palouse Slope. The basin margin and the Ice Harbor dike swarm mark the eastern edge of the Yakima Fold Belt suggesting a possible relationship between fold development and the edge of the basin. Reidel (1984, pp. 974-975) suggests that this may be somehow related to decreased sediment thickness to the east between the basalt and basement.

The north-south cross section (see Fig. 1.5-2) shows several additional structural features of the Pasco Basin. There is a general thickening of the basalt from north to south, but it is not as dramatic as the thickening from east to west. The principal feature is the Yakima folds superimposed on a much larger structural basin of which the Pasco Basin is only a small surficial feature.

Purposefully omitted from this cross section are the continuations at depth of the faults associated with the Yakima folds. This is the principal uncertainty associated with this cross section. Yakima folds are sharp, narrow anticlines superimposed on this broad, generally low-relief synclinal basin. The amplitudes of these folds are small relative to the overall thickness of the basalt and the basins at the surface, such as the Pasco Basin, are small minor features between the anticlines. Field data are inconclusive as to whether the faults extend into the units underlying the basalt, or if the faults flatten out into detachment faults. Magnetotelluric data across Rattlesnake Mountain (Berkman et al., 1986) suggest that the entire basalt sequence thins over the anticline, which is consistent with similar patterns in surface flows (Reidel et al., 1981; Reidel, 1984).

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1.5.1.1.2.2 Structural development of the Pasco Basin: Current concepts

The structural characteristics of the Pasco Basin have been described in Section 1.3.2.2.2. Structural models for the development of the Pasco Basin and adjacent Yakima Fold Belt are divided into two groups of thought: the first considers deformation of the basalt to occur independently of sub-basalt rocks, thus involving detachment faulting and a major decollement; the second requires coupling between the basalts and sub-basalt rocks. Models can be further subdivided within these groups on the basis of the sense of motion involved in producing the observed structures.

In Figure 1.5-3, a summary is provided of current ideas for the development of the Yakima folds and some of the features observed in the Pasco Basin. It is important to note that the same surface structures have been interpreted at depth in many different ways. The data that are presently available do not support a unique interpretation for the development of the structural setting, but rather suggest several equally plausible modes of origin. Additional data are required before any models can be chosen with confidence. In the following sections data that are available are used to constrain some aspects of these models and the uncertainties in models with respect to available data.

Yakima folds

Yakima folds are generally asymmetric in cross section and are typically segmented along their axes. Cross-sectional geometry and vergence along the fold commonly change at locations where structures cut across the main axes of the folds. Examples of this segmentation can be observed on Gable Mountain and along the Saddle Mountains. Northwest-trending transcurrent or cross

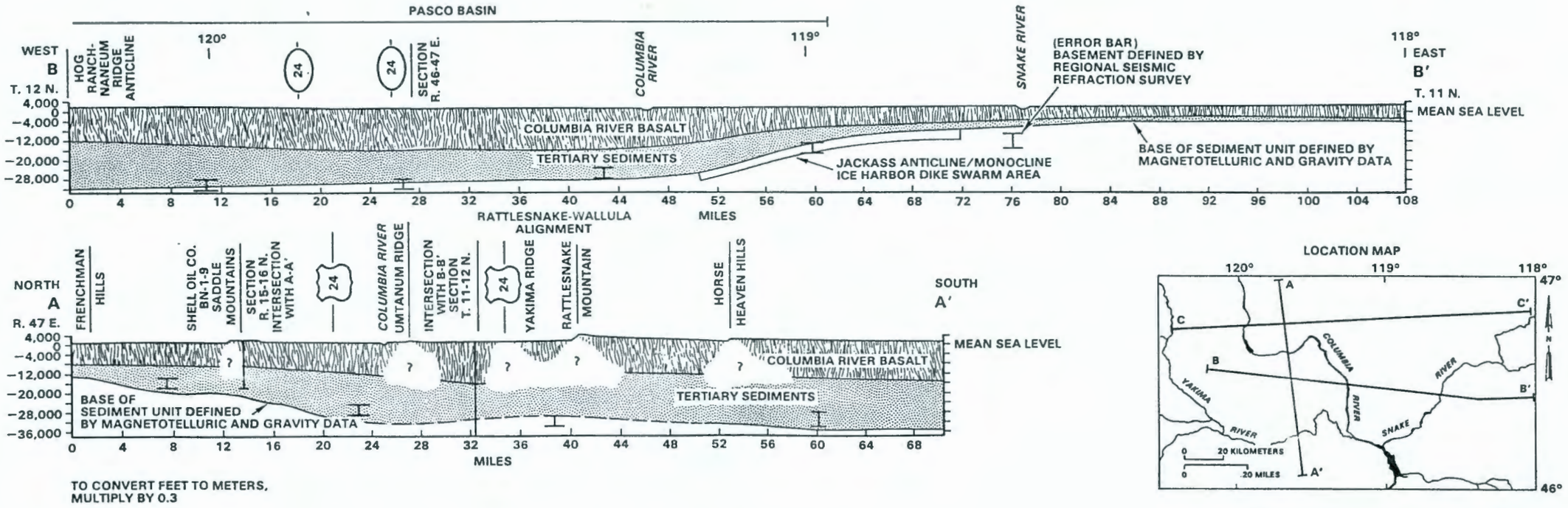

Figure 1.5-2. Summary of current ideas for structural models of the Pasco Basin.

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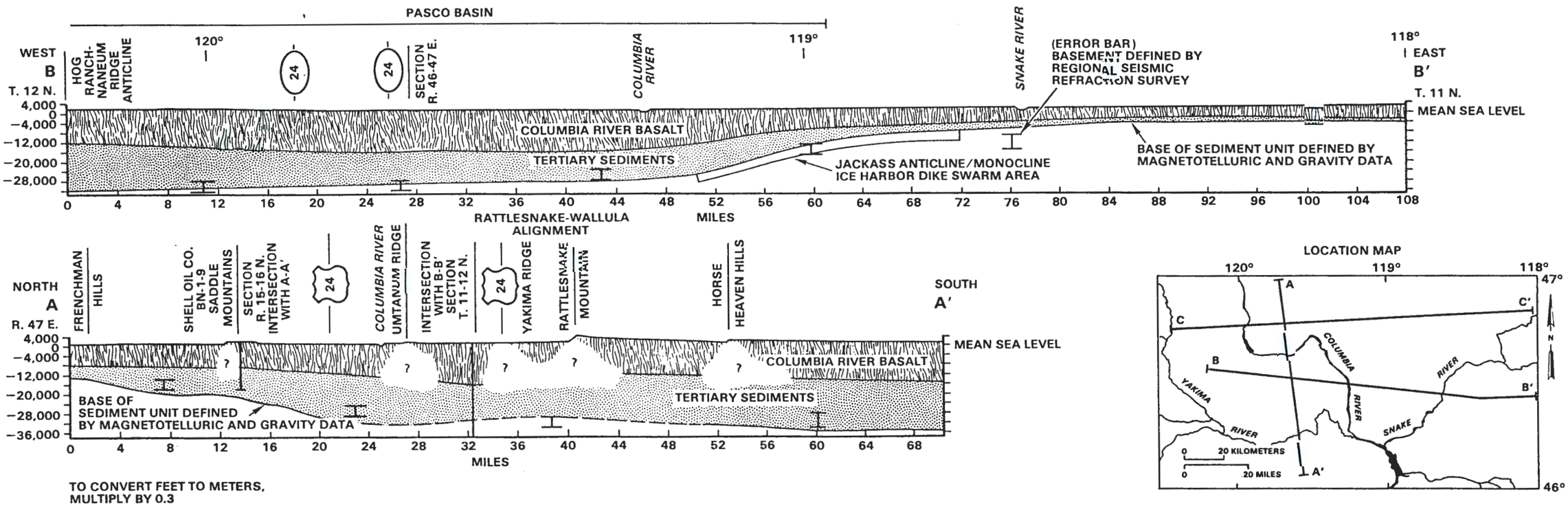

Figure 1.5-2. Summary of current ideas for structural models of the Pasco Basin.

SOURCE	MODEL DESCRIPTION	COMMENTS
DECOLLEMENT		
LAUBSCHER (1981)	KINK-BANK FOLDING DUE TO LOCALIZED DECOLLEMENT AT THE BASE OF THE COLUMBIA RIVER BASALT. THESE LOCAL DECOLLEMENTS ARE PART OF A REGIONAL NORTH-MIGRATING DECOLLEMENT (YAKIMA BLOCK) THAT OCCURS AT THE CRUST/MANTLE BOUNDARY.	FOCAL MECHANISM SOLUTIONS, HYPOCENTER DISTRIBUTION, AND MAGNETOTELLURIC DATA DO NOT SUPPORT THE EXISTENCE OF A DECOLLEMENT OR LARGE CRUSTAL BLOCKS. FRACTURE ANALYSIS OF PRICE (1982) DOES NOT SUPPORT MODEL. DIRECT SUBSURFACE INFORMATION IS NOT AVAILABLE.
BRUHN (1981)	FAULT RAMP-FLEXURE MODEL WITH DECOLLEMENT OR GROUP OF LOCALIZED DETACHMENTS OF 3 TO 5 km (1.9 TO 3.1 mi) DEPTH (i.e., WITHIN THE BASALT, OR AT BASE).	FRACTURE ANALYSIS OF PRICE (1982) DOES NOT SUPPORT MODEL. DIRECT SUBSURFACE INFORMATION IS NOT AVAILABLE.
BENTLEY (1982) CAMPBELL AND BENTLEY (1981)	ANTICLINAL RIDGES-REFLECTION OF DRAG ON RAMPS FROM SUB-BASALT AND INTERBASALT DECOLLEMENTS. DECOLLEMENT SURFACES CAN HAVE VARIABLE SLIP DIRECTIONS.	EVIDENCE CITED DOES NOT SUPPORT INTERPRETATION OF DEEP STRUCTURE. FOCAL MECHANISM SOLUTIONS, HYPOCENTER DISTRIBUTION, AND MAGNETOTELLURIC DATA DO NOT SUPPORT THE EXISTENCE OF A MAJOR DECOLLEMENT. DIRECT SUBSURFACE INFORMATION IS NOT AVAILABLE.
COUPLED COLUMBIA RIVER BASALT/SUB-BASALT LAYERS WITH TRANSCURRENT DISPLACEMENT		
BENTLEY AND FAROOQUI (1979) BENTLEY et al. (1980)	RIDGES REPRESENTATION OF MOBILE ZONES THAT CONSIST OF DEEP-SEATED, SINISTRAL, STRIKE-SLIP FAULT ZONES FORMED UNDER A NORTH-SOUTH COMPRESSIONAL REGIME.	INCONSISTENT WITH PALEOMAGNETIC DATA COLLECTED FROM PASCO BASIN THAT WOULD SUPPORT DEXTRAL MOTION. DIRECT SUBSURFACE INFORMATION IS NOT AVAILABLE.
COUPLED COLUMBIA RIVER BASALT/SUB-BASALT LAYERS WITH HORIZONTAL CONTRACTION		
PRICE (1981) DAVIS (1981) COWAN (1981)	BUCKLE/KINK-BANK-TYPE FOLDING, WITH LATE-STAGE FAULTING, WITHIN THE BASALT LAYER. SUB-BASALT LAYERS SHORTENED DUCTILLY, WITH LOCAL DETACHMENTS UNDER EACH CONCENTRIC ANTICLINE.	CONSISTENT WITH AVAILABLE SURFACE DATA. DIRECT SUBSURFACE INFORMATION IS NOT AVAILABLE.
COUPLED COLUMBIA RIVER BASALT/SUB-BASALT LAYERS WITH VERTICAL DISPLACEMENT		
BENTLEY (1977)	FAULTED DRAPE FOLD MODEL-ANTICLINAL RIDGES IN THE COLUMBIA RIVER BASALT FORMED OVER VERTICALLY ROTATED, NORMAL FAULTED, BASEMENT BLOCKS.	INCONSISTENT WITH SURFACE GEOMETRIES OF FOLDS. DIRECT SUBSURFACE INFORMATION IS NOT AVAILABLE.
REIDEL (1984)	PREEXISTING, HIGH-ANGLE, REVERSE FAULT-FOLDING THAT PROBABLY BEGAN PRIOR TO OR SIMULTANEOUSLY WITH THE EMPLACEMENT OF THE OLDEST COLUMBIA RIVER BASALT GROUP FLOWS, FAULTING PROPAGATES UPWARD FROM CORE OF FOLD ONCE LAYERS CAN NO LONGER DEFORM BY FOLDING.	CONSISTENT WITH SURFACE GEOMETRIES AND EXPOSURES OF FAULTS BELOW FOLDS IN FRENCHMAN HILLS (GROLIER AND BINGHAM, 1978) AND ROCK CREEK IN COLUMBIA HILLS (ANDERSON IN SWANSON et al., 1979a). DIRECT SUBSURFACE INFORMATION IS NOT AVAILABLE.

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Figure 1.5-3. Summary of current ideas for development of Yakima folds.

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faults that have a strike-slip component have been mapped at a number of segment boundaries. The total length of each of these faults is uncertain and may be related to the development of the fold.

Bentley et al. (1980) suggest that northwest-trending cross faults on Toppenish Ridge extend considerable distances into flanking synclinal basins, using the interpretation of such features on aerial photographs as evidence. Toppenish Ridge is in an area of the western plateau where long strike-slip faults have been mapped (see Anderson and Bentley in Swanson et al., 1979a), in contrast to the Pasco Basin where the evidence for northwest-trending strike-slip faults extending beyond the margins of anticlinal folds is more speculative (see Section 1.3.2.2.6).

The involvement of or lack of involvement of the basement in the development of the folds is uncertain. Many studies have addressed this problem (see Fig. 1.5-3), but there is no clear consensus in interpretation (e.g., Duncan (1983, pp. 7-18)).

Although there is a general similarity among the various Yakima folds (Reidel, 1984, Fig. 3), there are occasional structures that are atypical or unique. For example, Snively Basin, a structurally complex area within the Rattlesnake Hills, is an atypical feature for most Yakima folds. A better understanding of its origin may provide important clues to understanding the development of other folds. A related problem is the geometry of secondary structures and cross structures, such as the Gable Mountain and Gable Butte anticlines (Fecht, 1978, Plate I), and how these features develop in relation to the primary structures.

Many Yakima folds are crossed by regional cross structures. The intersections of the north-south trending Hog Ranch-Naneum Ridge anticline with the east-west trending Saddle Mountains, Yakima Ridge, and Umtanum Ridge are an example. Another example is the intersection of the Saddle Mountains uplift with the cross-cutting Smyrna anticline near Smyrna Bench (Reidel, 1984, pp. 952-955). Knowledge of the structural relationship between the Rattlesnake-Wallula alignment where it intersects various Yakima folds is also important information for understanding the tectonic setting. Both the Horse Heaven Hills and the Rattlesnake Hills change structural trends along the Rattlesnake-Wallula alignment, but the Umtanum and Yakima Ridges appear to be unaffected. The present evidence for north-south compression, when combined with the current understanding of the development of the folds from surface mapping and strain analysis from paleomagnetic data, does not indicate that the change in trends results from a change in strain directions during growth of the folds (i.e., the tectonic scheme of Barrash et al. (1983)). Planned study of the intersection of these oblique-trending cross structures and intersecting with the main structures will provide insight on the timing of deformation, controlling stresses, and structural characteristics in the subsurface (see Section 8.3.1.2.4.3.1).

The development of many crosscutting structural trends is in itself not conclusive evidence of basement control. However, many of the Yakima folds, or fold trends such as the Horse Heaven Hills and the Cle Elum-Wallula

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disturbed zone, can be recognized beyond the basalt margin. This suggests involvement or control between the basalt section and sub-basalt rocks. In other areas such as in the Yakima area, however, such relationships have not been observed (Campbell, 1987). Presently there are conflicting data for the involvement of sub-basalt structure in the development of the Yakima folds. Additional evidence will be collected during site characterization to resolve this question (see Section 8.3.1.2.3.3.4).

The Rattlesnake-Wallula alignment is one of the most prominent geologic features in the Pasco Basin. The limited data available to describe it leave a high degree of uncertainty in its characteristics. The N. 50° W. trend of the structures that comprise the alignment crosses the east-west trend of other Yakima folds, yet the folds along it are similar to other Yakima folds. Previous mapping by Bond et al. (1978b) suggests that the Rattlesnake-Wallula alignment does not continue beyond the Snively Basin area. These data do not indicate if a buried fault in the basalt or the sub-basalt sediment continues beyond Snively Basin, however.

Whether or not sub-basalt structures are associated with the Rattlesnake-Wallula trend is unclear. No major basement involvement is indicated by the most recent geophysical data (Berkman et al., 1986). These data suggest up to 1-km (0.6-mi) of structural relief at the base of the basalt (Berkman et al., 1986). This suggests steep faults extend through the basalt, but this neither precludes basement structure control of surface structures nor does it preclude detachment faulting at the base of basalt or within the sub-basalt sediments.

In addition to the uncertainties in the interpretation of these large-scale features, questions also remain regarding minor features. A better understanding of the nature of secondary folding and faulting will help in creating a more defensible model for the kinematic development of the Yakima folds. These questions will be addressed in studies described in Section 8.3.1.2.4.3.1.

Age of deformation

Studies on the growth of the folds indicate that those structures that have been studied in detail were growing during the eruption and emplacement of the basalt and probably continued to grow, perhaps even to the present time (see Sections 1.3.2.2.2 and 1.3.2.4.1). This implies that models involving different periods of growth on the folds (e.g., Laubscher, 1981; Barrash et al., 1983), or a short period of active growth following emplacement, are probably incorrect. Models must account for continuous growth given the resolution of data (Reidel, 1984, pp. 969-972).

Current stress regime

Focal mechanisms support the geologic constraints placed on tectonic models for the Columbia Plateau, adding further support to the idea that the stress regime responsible for the Yakima folds persists today (Malone, 1979; Rohay and Davis, 1983; Caggiano, 1983; see Section 1.4.1.2.3). Focal

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mechanism solutions and the distribution of hypocenters do not suggest the existence of a major fault zone within the Pasco Basin, nor do they provide evidence that the Rattlesnake-Wallula alignment is a northwest-trending zone of right-lateral strike-slip displacement.

Earthquakes, including swarms of microearthquakes that are common along the margins of the Pasco Basin, have not been clearly correlated with causative structures (see Section 1.4.1.2). Swarms of instrumentally recorded microearthquakes have been recorded on the north and south flanks of the Saddle Mountains uplift, but not on a mapped fault or fold that comprises the structure. This suggests the possibility of some structural association. However, other swarms occur in areas where no geologic structures have been mapped, such as the Wooded Island swarm area. The microearthquakes that are being recorded are indicative of rupture along reverse faults having small displacements.

Distribution of strain features

Results described in Section 1.3.2.2.2 indicate that the bulk of the strain is concentrated in the anticlines, whereas the synclines are deformed to a lesser degree. This constrains kinematic models for the growth of the anticlinal ridges and adds one additional constraint to the tectonic models for the Columbia Plateau. At the present stage of research on the Columbia Plateau, tectonic models have not progressed to detailed kinematic models. The present kinematic models are based on the strain analyses of Price (1982), Reidel et al. (1982), Reidel (1984), and Barsotti (1986). Additional studies to address these questions are described in Section 8.3.1.2.4.3.1.

1.5.1.2 Strategy to select preferred tectonic models

The plans for arriving at a preferred model for the tectonic setting of the candidate site are described in Section 8.3.1.2.4.3.3. The steps that are being taken to lead to a preferred model or group of models are given below:

1. Review the available literature regarding the stratigraphy, structural geology, and tectonics for western North America, the Pacific Northwest, and the Columbia Plateau. Prepare a compilation of this information.

2. Compare the models proposed to explain the tectonic setting with available geologic, geophysical, seismologic, and geodetic data for the candidate area.

3. Identify models or elements of models that have the potential to affect the geologic stability of the candidate site.

4. Evaluate the potential impacts on the candidate site and repository of future tectonic activity that is suggested by models.

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Step 1 was essentially completed (Caggiano and Duncan, 1983; Tolan, 1986), with the exception of updating the compilation with new ideas that are proposed in the literature or developed in this program. In Table 1.5-1, the current compilation of models, and also a preliminary assessment of the impact that various classes of models might have on the stability of the reference repository location are presented.

Step 2 is well under way as part of the initial stages of the site-selection process. The progress in making these comparisons is reflected in the interpretations of the origin of structures described in Section 1.3.2.2.2. Reevaluation of current models will continue throughout the site-characterization period as new data become available to test hypotheses. Indeed, it will continue throughout subsequent licensing activities if the site is selected for the first geologic repository.

Step 3 will be accomplished at several geographic scales and levels of detail. The screening of models for further use in evaluating the geologic stability of the site, and assessing the impacts to waste isolation, will consider the rates at which deformation is occurring, the distances from the site at which events are likely to occur, and the magnitude of structural changes that are possible.

Step 4 will consider the impact that various aspects of future tectonic activity might have on the geologic stability of the candidate site. This is a two-step process in itself, since it will consist of identifying potential changes to the physical characterisitics of the site and assessing the potential influence of those changes on the capability of the repository to isolate radioactive wastes.

A summary of the progress made in identifying the impact that various aspects of tectonic activity might have on the geologic stability of the site can be found in the Environmental Assessment (DOE, 1986, pp. 6-158 to 6-172). Some discussion of the impact on waste isolation capabilities is also presented, although most conclusions are deferred until the results of analyses to be performed during site characterization become available.

The plans to further define future tectonic activity that could change the physical characteristics of the site are described in Section 8.3.1.2.4. Part of this work will be to assign probabilities to the occurrence of particular events so that a semiquantifiable risk assessment can be made regarding the release and dispersion of radioactivity.

1.5.1.3 Status of tectonic stability assessment

Possible geologic structures that might be present in the reference repository location, as suggested by known geologic structures and present tectonic models, include (1) a deep, vertical dip-slip or oblique slip fault, (2) a thrust/decollement fault, and (3) a relatively short dip-slip cross fault emanating from the core of an anticlinal fold. These structures are

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postulated from explanations for the development of anticlines adjacent to the controlled area study zone in the Yakima Fold Belt. A better understanding of the tectonic setting may also indicate the type of faulting that is possible at the reference repository location, and thus aid in planning studies to characterize such faults.

Strike-slip faults have been found in the western Columbia Plateau, where they are typically subparallel to anticlines in an interpreted wrench-tectonic regime. Such faults have not been mapped in the immediate vicinity of the Pasco Basin. Local transcurrent or cross faults, with a component of strike-slip displacement, have segmented Yakima folds into sections with different cross-sectional geometries. However, these faults appear to be limited in length to the approximate width of anticlines. In synclinal areas, the absence of focal mechanism solutions that show a strike-slip component is in agreement with the absence of mapped strike-slip displacement.

Microearthquakes in and below the basalt suggest the presence of reverse faults of limited area and extent that have not been geologically mapped. These structural features are given in Figure 1.5-3. Shear zones with limited areal extent and displacement and orientations similar to those given above may occur in the reference repository location. Some tectonic breccias have been found in boreholes in the Cold Creek syncline, but they are of narrow apparent width, unknown extent and orientation, and volumetrically represent a small percentage of the core taken from such holes (see Section 1.3.2.2.2.6). The presence of such features was suggested by Price (1982) from detailed analysis of strain features in Yakima folds in the central plateau.

The reference repository location in the Cold Creek syncline contains gently dipping strata, generally less than five degrees, in a structural setting where strain has occurred primarily on adjacent anticlines (Caggiano, 1983, pp. 8-1 through 8-5; Section 1.3.2.2.2). Deformation has been occurring at low average rates since at least the mid-Miocene, and these rates are expected to continue in a similar fashion for at least the next 10,000 yr. The principal geologic features that are associated with this deformation have been identified, and future deformation is expected to occur on these structures.

The extent of faulting and folding in the sub-basalt rocks under the Yakima folds would contribute to predicting the style of future deformation. For example, the areal extent of the faults underlying the Yakima folds varies considerably depending on which possible tectonic model is assumed to be correct. At present, there is insufficient information to identify a preferred model that can satisfactorily be used to address tectonic issues associated with site selection. The planned work described in Sections 8.3.1.2.3 and 8.3.1.2.4 is keyed to the collection and interpretation of additional geologic, seismologic, and geophysical data to support testing alternative models and to identify a preferred tectonic model for the geologic setting.

In summary, numerous tectonic models have been proposed to explain limited sets of data, but no single model satisfactorily explains all of the current data and interpretations.

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The style, rates, and mechanisms of deformation that have lead to the formation of the Yakima folds are expected to continue during the next 10,000 yr in a manner similar to the way in which they have occurred since the mid-Miocene (i.e., during at least the last 17 m.y.). However, large uncertainties are associated with the rates of occurrence of various types of deformation, significance of tectonic activity involving sub-basalt strata, implications of tectonic breccia observed in some Pasco Basin boreholes, and stress regime that causes microearthquake swarms in synclinal areas.

1.5.2 VOLCANISM

The volcanism that has affected the candidate area in the geologic past is of two types: (1) continental flood basalt volcanism, which has produced the Columbia Plateau; and (2) back-arc volcanism associated with the Cascade Range. Several volcanoes in the High Cascades are presently considered to be active, but activity associated with flood basalt volcanism has ceased. A description of the volcanic activity that has occurred in the geologic setting is presented in Section 1.3.2.1. The following discussion focuses on the possibilities of renewed or continued volcanic activity and the type of products that result.

1.5.2.1 Renewed flood basalt volcanism

The flood basalt volcanism that produced the Columbia River Basalt Group of rocks occurred between approximately 17 and 6 m.y.B.P., with the bulk of the lavas being extruded during the first 2 to 1/2 m.y. of the episode (see Sections 1.2.1.2 and 1.3.2.1.1, Table 1.3-1). Volcanic activity has not recurred during the last 6 m.y. to suggest a continuation of the tectonic processes that created the episode, nor a renewal of flood volcanism.

Most evidence suggests that the Pasco Basin has experienced north-south crustal shortening during at least the late Tertiary and presently exists in a dominantly compressive stress regime that has its principal axis oriented north-south (see Sections 1.3.2.3 and 1.4.1.2.3). While this stress regime permits extension in an east-west direction, which is consistent with the opening of linear vent systems that are oriented north-south, the mechanisms for producing great volumes of magma at crust-mantle boundary depths are thought to have ceased operating (see Section 1.3.2.5.2.1).

1.5.2.2 Cascade Range volcanic activity

Volcanism of the Cascade Range is divided into two episodes. The older period occurred between approximately 38 and 5 m.y.B.P., and involved the western part of the Cascade Range. Since 5 m.y.B.P. to the present, volcanic activity has been confined to the High Cascades, which are represented by

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young composite volcanoes (Section 1.3.2.1; Table 1.3-1; Fig. 1.3-6). Volcanic activity in the western Cascade Range has ceased and is not considered further in the geologic stability assessment.

Stratovolcanoes of the High Cascade Range have been active during the Quaternary and most have been active during the Holocene. Lassen Peak, Mount Shasta, Mount Rainier, Mount Hood, Mount Baker, and Mount St. Helens have been active during historic time (Shipley and Sarna-Wojcicki, 1983; Crandell and Mullineaux, 1978; Mullineaux and Crandell, 1981). The primary products of eruption from these vents have been ash and lava flows and various forms of pyroclastic ejecta. Mudslides, landslides, and debris flows are also commonly associated with these eruptions.

The proportion and composition of lava, ejecta, and gases varies with each source and each eruption. High Cascade Range stratovolcanoes erupt lavas of calc-alkaline affinity. Mafic sources (e.g., the Indian Heaven Fissure Zone) are also present in the Cascade Range and have erupted basaltic lavas during the Quaternary and Holocene.

The hazard posed by any particular Cascade volcano to the candidate site is dependent on the probability of renewed eruptive activity. Shipley and Sarna-Wojcicki (1983) have estimated an annual probability of 10^{-4} to 10^{-5} for eruption of some Cascade Range volcanoes based on the frequency of occurrence of various ejecta during a given interval of geologic time. Some of the volcanoes, such as Mount St. Helens, are known to erupt more frequently than this, and the stratigraphic record may not provide complete information on the frequency of eruptions, but rather only reflect the relatively large eruptive episodes.

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1.5.2.3 Status of volcanic stability assessment

The only volcanic activity that could potentially affect the site directly during the next 10,000 yr is recurrent volcanism in the High Cascades (see Sections 1.1.3.2 and 1.3.2.1). Neither renewed flood volcanism nor eruptive activity in the Western Cascades is likely to recur. The most likely product of volcanism to reach the site is airfall tephra, and its greatest impact would be on surface facilities. Other types of activity associated with Cascades eruptions may affect the site indirectly--mostly through changes to the geomorphic processes acting on the site (see Section 1.5.3).

A preliminary assessment of the effects of volcanism on the reference repository location was made just prior to the 1980 eruption of Mount St. Helens (Johnpeer et al., 1981). This study was done in addition to the volcanic hazards study by the Washington Public Power Supply System (WPPSS, 1981) for the WNP-2 at the Hanford Site and by Pacific Gas and Electric for the Pebble Springs nuclear powerplant site (Shannon and Wilson, 1978). The assessment was based on limited data, and the conclusions are to be reassessed using new data obtained during studies of the Mount St. Helens' eruption (see Section 8.3.1.2.4.3.3). Reliable conclusions are not yet available from

statistical analysis of the temporal and spatial characterisitics of eruptions, and estimates for the probabilities of future eruptions and the volumes of their products are highly uncertain.

1.5.3 GEOMORPHIC PROCESSES

The stability of the site relative to geomorphic processes is a function of tectonic activity, volcanism, and climate changes. Tectonic movements modify topography and create zones of weakness in rock. These changes may affect rates of erosion and deposition, as well as change drainage patterns and alter base level. Volcanic activity may alter or block drainages, and supply large quantities of airborne ejecta to the site. Climatic changes influence rates of weathering and erosion. The ice age cycle and climate changes are closely related, and glaciation has a profound effect on the geomorphic characteristics of a region.

1.5.3.1 Influence of tectonism

Tectonic activity may alter topography and change the base level for a drainage basin, thus modifying the basin's erosion characteristics. The changes in topography that are caused by folding and faulting, and the resulting modifications to drainage patterns may affect areas of recharge and discharge of groundwater. Regional uplift or subsidence will also affect the volume and locations for recharge and discharge. The present state of knowledge concerning the rates at which folds develop, the activity levels of known faults, and the rates of uplift and subsidence associated with the Pasco Basin and vicinity suggest that changes to the geomorphic characteristics of the site due to these processes will be negligable during the life of a repository.

The reference repository location is in an area of apparent long-term subsidence relative to the stable Palouse Slope and the uplifted anticlines of the Yakima folds, such as the Saddle Mountains and Rattlesnake Hills (Reidel et al., 1983). Most erosion and incision by streams occurs on anticlinal ridges, while deposition prevails in the intervening synclinal valleys and basins. Evidence suggests that subsidence in the basins will continue into the future (see Section 1.3.2.4.1). Therefore, the potential for incision to repository depths, as a result of tectonic uplift, appears to be minimal. The results from site characterization activities designed to provide more complete information on the style and rate of deformation in the Pasco Basin will improve the confidence in this assessment (see Section 8.3.1.2.4.3.1).

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1.5.3.2 Influence of volcanism

There is no evidence of lava flows, ash flows, or mudflows from Cascade Range volcanoes having reached the Pasco Basin during the Quaternary. The nearest Cascade Range volcano is more than 100 km (62 mi) from the reference repository location. With the exception of mudflows and airborne ejecta, most eruption products remain within 50 km (31 mi) of Cascade volcanoes. At increasing distances from the eruptive vent, flows of lava, debris, and mud tend to become more confined to existing drainage channels. Because no streams flow directly from the Cascade Range volcanoes to the reference repository location, this type of volcanic product is not considered likely at the candidate site during the life of a repository.

Lava flows from Cascade eruptions could conceivably block the Columbia River at its gorge along the axis of the range. Source areas for the most recent lavas in this area are the Indian Heaven Fissure Zone and Mount Hood, both of which have produced lava flows during the Holocene (Bela, 1982). Some of these flows are known to have created dams that blocked the Columbia River near Hood River, Oregon (Waters, 1973). The duration of the dams is uncertain, and there is no evidence to suggest that the upstream extent of their impoundments resulted in flooding of the Pasco Basin.

To dam the Columbia River, large volume of highly fluid lava would be required. To create an impoundment of water large enough to flood the Pasco Basin would require a dam with a height of approximately 120 m (400 ft) in the present gorge. Cascade volcanoes have typically produced relatively small flows of highly viscous, calc-alkaline lavas. Therefore, the possibility of a lava dam at the gorge creating a lake that floods the Pasco Basin, is considered to be remote.

Mudflows and other volcanic debris slides from eruptions of Mount Hood, Mount Adams, or other Cascade Range vent areas could reach the Columbia River. However, such slides are small in volume and easily eroded by the river, so they pose little threat to damming the Columbia River. Even the large landslides at Cascade Locks in the gorge, which were not caused by volcanic eruptions, did not impound water as far upstream as the Pasco Basin, nor did they create long-lasting impoundments (Allen, 1979, pp. 52-57).

Tephra deposits from eruptions of Mount St. Helens, Glacier Peak, and Mount Mazama (Crater Lake, Oregon), as well as from several unidentified sources, are interbedded in Quaternary sediments in the Pasco Basin (see Section 1.1.3.2). Tephra deposits are also present in pre-Quaternary sediments such as the Ringold and Ellensburg Formations. Most, if not all, of these tephras were derived from Cascade Range sources, although individual vents cannot be identified for each of these pre-Quaternary deposits.

The stratigraphic record of tephras in the Pasco Basin suggests that the only primary product of Cascade Range volcanism that may be expected to reach the Pasco Basin during the next 10,000 yr is airfall tephra. The U.S. Geological Survey made a similar assessment for the Washington Public Power Supply System Project WNP-2 nuclear powerplant site (NRC, 1982).

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The amount of airfall tephra that may reach the site depends on the volume of material erupted, the tephra characteristics, and the distance of the site from the source. Dispersal patterns of ejecta from eruptions are determined by the wind direction and velocity, and the altitude to which the ash cloud rises.

Varying amounts of ash were deposited across the Columbia Plateau during the May 18, 1980 eruption of Mount St. Helens. Approximately 8 mm (0.3 in) of ash was deposited at the Hanford Site meteorological tower, which is located in the reference repository location. In the first 9 h following the eruption, approximately 1 mm (0.04 in) of uncompacted ash was recorded at the Washington Public Power Supply System Project WNP-2 meteorological station, which is about 25 km (15 mi) south-southeast of the reference repository location (WPPSS, 1981, p. 2.5-103). The Pasco Basin was not in the main path of the ash cloud, and received only a fraction of ash compared with locations to the north that were located directly in the path of dispersing winds (Sarna-Wojcicki et al., 1981).

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1.5.3.3 Effects of changes in climate

Climate exerts a strong influence on geomorphic processes. In particular, temperature and precipitation control the type and severity of weathering, the growth of stabilizing vegetation, the recharge of aquifers, and the volume of runoff. These parameters in turn influence rates of erosion and deposition, and the development of drainage patterns. While the surficial characteristics of the region may change significantly in response to climate changes that occur on a time scale measured in tens of years, these changes may be ephemeral, and of little consequence to a deep repository.

Of potentially greater significance are climate changes that occur on a much longer scale ($>10^4$ yr), such as those associated with glacial cycles. The probability of renewed glaciation in the vicinity of the site is very low during the next 10,000 yr, although it is relatively high during the next 100,000 yr (see Section 5.2.1.2.4). Glaciation can have a profound impact on the geomorphology of a region as a result of ice movements, radical changes in runoff and drainage patterns, and changing patterns of erosion and deposition. The cataclysmic floods that occurred at the end of the last glacial advance, approximately 13,000 yr ago, modified the land surface by scouring out steep-walled canyons, or "coulees". The floods also removed large quantities of sediment from some areas and deposited them elsewhere as bedforms (see Section 1.1.3.3). Periodic lakes formed during these floods that undoubtedly altered the recharge and discharge characteristics of regional aquifers and the groundwater flow system (see Section 3.7.4).

A potential impact on a repository could occur if flood waters remained long enough to produce changes in the recharge of both the unconfined and confined aquifers in the hydrologic setting. Such changes might alter hydraulic heads, gradients, and groundwater travel paths and travel times. Increased recharge could also lead to increased discharge from the unconfined

and confined aquifer systems, into the Columbia River and tributary streams. Erosion during cataclysmic flooding might expose more area of an aquifer and lead to changes in recharge and discharge.

Renewed glaciation in the geologic setting could also result in isostatic adjustments of the crust because of the added overburden of ice sheets and large surface water impoundments. The magnitude of these effects is not known. It has been suggested that isostatic loading under a thick, continental ice sheet may produce a crustal bulge in front of the ice sheet (Morner, 1980). This stress on the underlying rocks could result in fracturing and perhaps induce seismicity. The present understanding of this potential phenomenon is limited, and large uncertainties are associated with estimates of the distance from the ice sheet that bulging might occur, the amplitude of the bulge, the characteristics of fracturing, and the severity of induced seismicity.

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1.5.3.4 Status of geomorphic stability assessment

The potential to breach a repository at a 1,000-m (3,000-ft) depth by erosion during the next 100,000 yr, based on the present tectonic setting, climate, and expected future conditions is very low. Some denudation will occur during the preclosure and postclosure periods, but will probably be minor relative to similar topographic settings in areas with a more humid climate. Erosion and deposition along the floodplain of Cold Creek, due to both fluvial and eolian action, is not expected to change the elevation of the floodplain by more than a few meters during the next 10,000 yr.

Denudation in the hydrogeologic setting under the present rates of weathering, mass wasting, and erosion could potentially expose new areas to groundwater recharge, thereby altering the groundwater flow regime. The impacts of this on aquifers within the Pasco Basin at repository depths are uncertain, and will be addressed along with other potential changes to the groundwater flow regime during site characterization (see Section 8.3.1.3). Eolian activity is restricted to reworking the uppermost land surface and is unlikely to influence the performance of a deep repository.

Geomorphic changes related to renewed glacial activity are changes that are most likely to alter site characterisitics (see Section 1.1.3.3). The potential changes in site characteristics brought about by climatic change or glaciation are not completely understood. Possible changes could involve groundwater recharge, the volume of surface runoff, and drainage patterns. These changes could subsequently alter the deep groundwater flow system. Loading and unloading of an ice sheet could induce fracturing and possible microseismic activity, and the effect on the site would be dependent on the distance between the site and the ice sheet.

1.5.4 DISSOLUTION AND DIAPIRISM

Evaporite units are not known to be interbedded with or to underlie Columbia River Basalt in the central Columbia Plateau. Because dissolution and diapirism leading to major changes in elevation of the ground and subsurface units occur principally where such rock types are present, and because such rock types are not known or suspected to be present beneath the reference repository location, evaporite dissolution and diapirism are of no concern to a BWIP repository and are not expected (DOE, 1987c).

Dissolution of basaltic glass along cooling joints by hydrothermal alteration has resulted in precipitation of secondary minerals. Only a small percentage of rock is expected to undergo such changes over 10,000 yr, and no major changes in rock strength or permeability are envisioned because of such minor changes (DOE, 1987c, p. 6-156). Dissolution of basaltic glass is discussed in Section 4.1.1.3.2.

1.5.5 STATUS OF DISRUPTIVE SCENARIO DEVELOPMENT

Since the inception of the BWIP, volcanic and tectonic processes have been recognized as being potentially disruptive to a possible nuclear waste repository in Columbia River basalt in the reference repository location at the Hanford Site. Programmatic concerns of the BWIP for disruptive natural events and processes were subsequently reflected in regulations promulgated by the EPA, NRC, and DOE. As stated in these regulations, the reasons for characterizing the site are (1) to conceptually understand the geologic and hydrologic systems sufficiently to construct computer models that can replicate these natural systems and their recent evolution; (2) to identify potentially disruptive natural events (or processes) that could possibly lead to the modification of the travel paths or travel times of groundwater and, thus, radionuclides; and (3) to characterize and analyze these disruptive scenarios to determine if they can affect the ability of the repository to isolate high-level nuclear waste for the required 10,000-plus yr.

1.5.5.1 Previous work

Scenarios involving faulting and volcanism for a repository in Columbia River basalt at the Hanford Site have been proposed by a number of people (see Arnett et al., 1980; Davis et al., 1983; Hunter, 1983; Lee et al., 1978; DOE, 1987c). Some of these are illustrated in Table 1.5-2. Preliminary scenario analyses were conducted as part of the process used to nominate the three sites for site characterization. Of 14 potentially significant scenarios used by the DOE to compare sites, five scenarios involved faulting of different size and different locations relative to a hypothetical repository at the candidate site. Values of various parameters relating to faulting were assigned using expert opinion and supplied to those conducting the analyses. Three scenarios analyzed for site comparison involved volcanic events for initiation.

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Table 1.5-2. Possible types of disruptive scenarios for a repository in the reference repository location

Potentially disruptive event/process	Location	Scenario	Likely distance to site	Geologic history of event/process		Subjective estimate of probability	Issue for		Comments
				Quaternary	Neogene		Pre-closure	Post-closure	
Volcanism - Columbia River Basalt Group	Pasco Basin	Lava flow on site	0 km	No	Yes	Unlikely	Yes	No	Youngest flow at reference repository location is 10.5-m.y.-old Elephant Mountain flow
		Dike instrusion into repository	0 km	No	No	Very unlikely	Yes	Yes	No dikes known in Pasco Basin
		Dike instrusion close to repository	0.5-35 km	No	Yes	Unlikely	Yes?	Yes	Youngest dikes are 6-m.y.-old Monumental Member
	Beyond Pasco Basin	Change in transmissivity	>35 km	No	Yes	Very likely			
Cascades volcanism	High Cascade Range	Lava flow on site	0 km	No	No	Very unlikely	Yes	Yes	Lava and (or) mudflows from Cascade volcanoes have not reached site or Hanford Basin during Neogene or Quaternary time
		Lava flow close to site	5 km	No	No	Very unlikely	Yes	No	
		Lava flow that dams Columbia River in gorge	275 km	No	Yes[a]	Very unlikely	Yes	Yes	Gorge blocked by lava flows ephemerally during Columbia River Basalt time
		Ashfall on site	0 km	Yes	Yes	Very likely	Yes	No	Tephras interbedded in Hanford and Ringold Formations
Faulting	Through repository	Shear waste canister(s)	0 km	No[b]	No?	Unlikely	Yes	Yes	Small faults/shears may not be detected by preconstruction exploration
	Through controlled area	Shear and (or) displace host and (or) surrounding rock	0-5 km	No[b]	No?	Unlikely	Yes?	Yes	
	Beyond controlled area	Groundwater flow/ boundary conditions of groundwater flow model	5-?? km	Yes[c]	Yes	Likely	Yes?	Yes	Size and location of fault to be specified. Faults exhibit Neogene movement. Some show Quaternary movement. Location of fault and characteristics of gouge will influence effect on waste isolation.

NOTE: To convert kilometers to miles, multiply by 0.6214.

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[a]Ephemeral dams across Columbia created impoundments that did not reach Pasco Basin.
[b]Tectonic breccias in boreholes and microearthquakes suggest slip on unmapped faults.
[c]Geologic evidence of Quaternary slip on some faults.

CONSULTATION DRAFT

Methods of assessment of long-term performance of a repository subject to tectonic and volcanic processes and events include development of geologic simulation models (Foley et al., 1982) as well as analyses of the nominal case with possible subsequent perturbations by potentially disruptive tectonic and volcanic events. The role and timing of sensitivity studies, compared with disruptive scenario identification and analyses in performance assessment, vary with approaches to scenarios analyses and are discussed by Roberds et al. (1984). Conducting sensitivity studies relatively early in the assessment process may be useful in restricting the number of disruptive tectonic and volcanic scenarios that may have to be characterized and run during site characterization.

Tectonic events and processes to be evaluated in assessing long-term performance of a repository in the reference repository location include faulting within the vicinity of the repository that either shears waste canisters, the repository, or host rock in the vicinity of the repository; renewal of Columbia River basalt volcanism; and the effects of distal Cascade Range volcanoes on repository ventilation (ashfall) or possible flooding (damming the Columbia River Gorge). Following sensitivity studies and nominal case analyses, disruptive event scenarios involving these processes will be identified and characterized to determine their net effect on the repository system (see Sections 8.3.1.2.4.3.3 and 8.3.5).

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1.5.5.2 Possible effects of tectonic and (or) volcanic events

Tectonic and (or) volcanic events or processes could influence waste isolation capability after repository closure by affecting the travel paths or travel times of groundwater. Development of a new fault or renewed movement on an existing fault could possibly shorten or lengthen the travel paths and travel times of groundwater from the repository to the accessible environment. The effects that occur are a function of (1) the location extent, and spatial orientation of the fault; (2) the distance from the repository to the fault; (3) the time at which the fault displacement occurred in postclosure time; (4) the transmissivity of the material filling the fault zone; and (5) the hydrologic head relationships in the groundwater flow system.

Assuming the fault was more transmissive than surrounding basalt, displacement on a fault could have a negative influence on waste isolation, if it occurred shortly after repository closure and either sheared waste canisters or occurred within the controlled area just downgradient from the decommissioned repository. In such a case, fault displacement would likely reduce travel times and decrease travel path length to the accessible environment. Conversely, if such a fault occurred on the upgradient side of a repository, it might alter the course of groundwater flow such that it would reduce the volume and rate of groundwater flowing through the repository, thereby benefiting waste isolation. This example serves to illustrate that the size, characteristics, location, and timing of a fault displacement relative to a repository are important in assessing the possible effects of faulting on a

repository. Thus, it is essential to characterize the potential for faulting so as to predict, to the extent possible, the probability of fault displacement as well as the location, geometry, extent, and timing of any postulated fault movement.

Similarly, it is essential to assess the probability, frequency, location, and timing of volcanism relative to a waste repository after its closure. Renewal of Columbia River basalt volcanism is not anticipated from the geologic record. Possible effects of distant Cascade Range volcanism that can be anticipated during the postclosure 10,000 yr on repository performance also need to be assessed (see Section 8.3.1.2.4.3.3.2).

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1.6 DRILLING AND MINING

In this section, the location and characteristics of drill holes and excavations at or near the site are tabulated. Information on location, depth, diameter, drilling method, casing, and condition is provided for about 200 boreholes that penetrate through the first basalt flow. Information references are given for approximately 2,000 additional shallower boreholes used for groundwater and waste management monitoring. The effects of the boreholes on principal hydrogeologic units is evaluated in Chapter 3.

1.6.1 DRILLING

Information contained in this section is based on examination of available borehole records. Borehole records used were driller's logs, borehole drilling histories, and test records on file with the Washington State Department of Ecology, U.S. Geological Survey, U.S. Bureau of Reclamation, U.S. Army Corps of Engineers, Pacific Northwest Laboratory, and Westinghouse Hanford Company. The records also include geophysical logs on file with the Washington State Department of Ecology, Westinghouse Hanford Company, and Washington State University, and survey records on file with Kaiser Engineers Hanford.

Publications that document the approximately 2,200 boreholes drilled on the Hanford Site and adjacent areas include Jenkins (1922), Walters and Grolier (1960), Newcomb et al. (1972), Summers and Schwab (1977, 1978), Summers and Weber (1978a, 1978b), Summers et al. (1978), Fecht and Lillie (1982), and McGhan et al. (1985). Data from these sources and from information presented in Moak (1981, Table A-2), Bjornstad (1984), Landon (1983, 1985), Ledgerwood (1986), and Crowley and Ledgerwood (1987) were used to construct a summary chart that shows the stratigraphic levels penetrated by boreholes within the Hanford Site boundaries and immediate vicinity (Fig. 1.6-1).

Detailed information from those boreholes that penetrate through the first basalt flow, or have provided hydrologic or stratigraphic data used by the BWIP, is contained in Crowley and Ledgerwood (1987) and summarized in Table 1.6-1 and Figure 1.6-2. McGhan et al. (1985) provides detailed location, size, and status information for the 200 Area and Hanford Site monitoring and waste management boreholes. Cross and Fairchild (1985) and Landon (1983) provide tabulated thickness, correlation, and intraflow structure data for deep boreholes, along with graphic stratigraphic interpretations, within and adjacent to the Hanford Site. Figure 1.6-3 is an example of a data display for borehole RRL-2 showing flow correlations, summarized lithology, examples of geophysical logs, and whole-rock geochemical data (Cross and Fairchild, 1985, sheet 10).

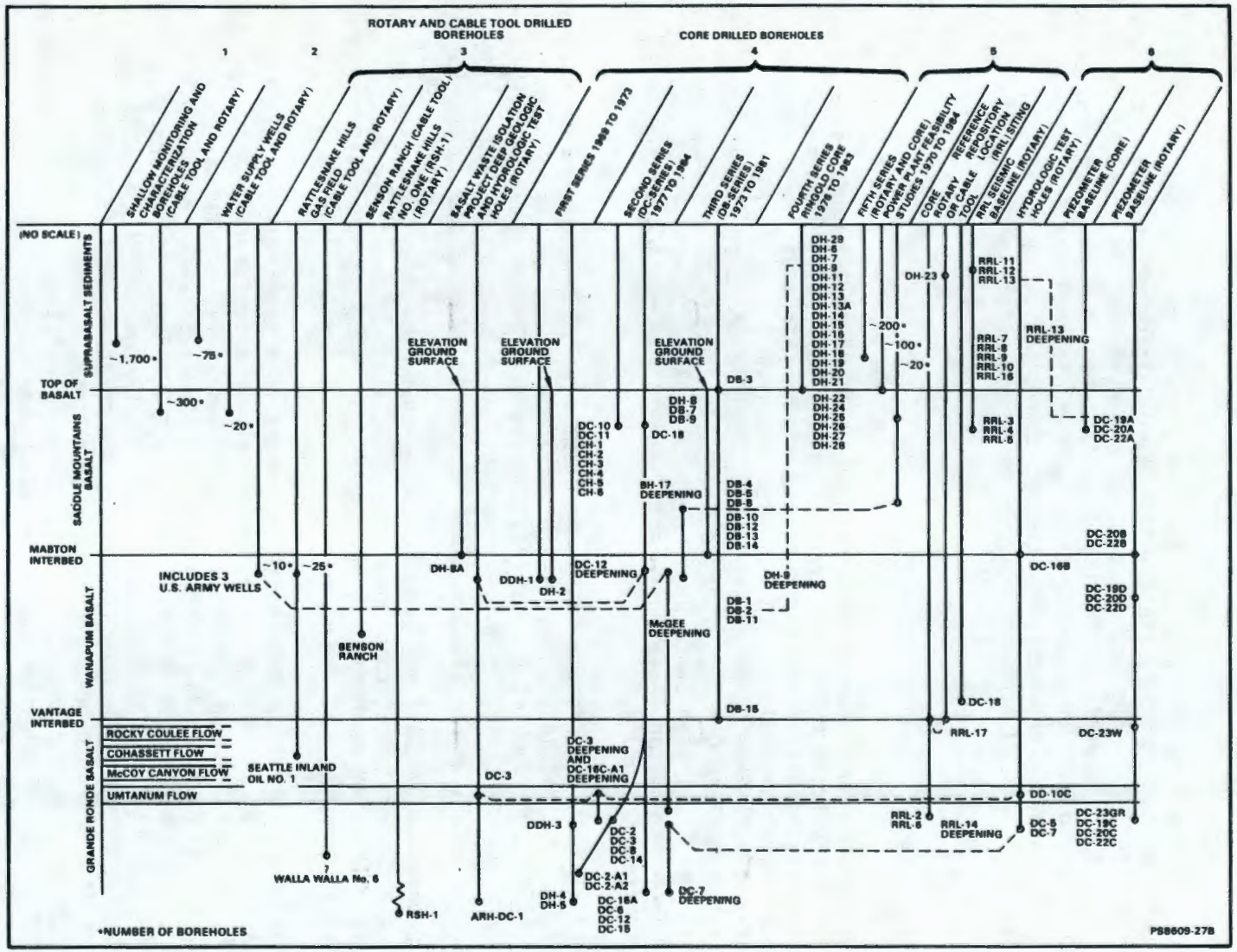

Figure 1.6-1. Stratigraphic levels penetrated by boreholes on the Hanford Site.

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Table 1.6-1. Inventory of boreholes that penetrate the uppermost basalt unit on the Hanford Site (sheet 1 of 16)

Borehole/ agency[a]	Washington State coordinates[b] (township, range, section)[c]	Depth[d] (ft)	Hole diameter[e] (in.)	Primary drilling method	Original drilling purpose	Date drilling stopped	Status	Test method
Enyeart	454397N 2183843E (T. 13 N., R. 24 E., sec. 36D1)	1,092.0	5	Cable tool	Water well	1922	Cased to 960 ft, open below, monitors Priest Rapids	--
Brown	457000N 2178192E (T. 13 N., R. 26 E., sec. 26M1)	668.0	16	Cable tool	Water well	1918	Casing status indeterminate	--
O'Brian	454404N 2183767E (T. 13 N., R. 24 E., sec. 26G1)	707.0	11	Cable tool	Water well	1922	Cased to 597 ft, obstructed at 585 ft, monitors Priest Rapids	--
Ford	458008N 2183787E (T. 13 N., R. 24 E., sec. 25E1)	777.0	10	Cable tool	Water well	1925	Cased to 622 ft, open below	--
McGee	457773N 2191774E (T. 13 N., R. 25 E., sec. 30G)	3,123.0	3 (NQ core)	Cable tool	Water well	1927, deepened 1983	Cased to 1,942 ft, open below, deepened from 978 ft	Hydrologically tested while deepening
Benson Ranch	424939N 2212931E (T. 12 N., R. 25 E., sec. 26M1)	2,000.0	12	Cable tool	Water well/ oil-gas exploration	1929	Cased to 1,315 ft, plugged at about 455 ft	--
Lemcke	457253N 2177237E (T. 13 N., R. 24 E., sec. 27K1)	625.0	8	Cable tool	Water well	1921	Cased to bottom 625 ft	--
Haynes	459347N 2258380E (T. 13 N., R. 27 E., sec. 30A2)	870.0	6	Cable tool	Water well	1923	Cased to 834 ft	--
Goodwin No. 1	396959N 2239749E (T. 11 N., R. 26 E., sec. 27D1)	2,212.0	8	Cable tool	Gas production	1920	Plugged at 1,238 ft (also known as Seattle Inland Oil No. 1)	--
Walla Walla No. 1	397843N 2233344E (T. 11 N., R. 26 E., sec. 20R1)	1,234.0	8	Cable tool	Gas production	1913	Open, casing pulled (also known as "Discovery Well")	--
Walla Walla No. 2	398900N 2233360E (T. 11 N., R. 26 E., sec. 21M2)	800.0	8	Cable tool	Gas production	1921		--
Walla Walla No. 3	401980N 2228133E (T. 11 N., R. 26 E., sec. 19A1)	1,507.0	8	Cable tool	Gas production	1921	Open, plugged at 785 ft	--
Walla Walla No. 4	401156N 2238535E (T. 11 N., R. 26 E., sec. 21G1)	640.0	8	Cable tool	Gas production	1922	Open, casing status indeterminate	--

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Table 1.6-1. Inventory of boreholes that penetrate the uppermost basalt unit on the Hanford Site (sheet 2 of 16)

Borehole/ agency[a]	Washington State coordinates[b] (township, range, section)[c]	Depth[d] (ft)	Hole diameter[e] (in.)	Primary drilling method	Original drilling purpose	Date drilling stopped	Status	Test method
Walla Walla No. 5	398636N 2230542E (T. 11 N., R. 26 E., sec. 20J1)	780.0	8	Cable tool	Gas production	1922	Open, casing status indeterminate	--
Walla Walla No. 6	396198W 2232122E (T. 11 N., R. 26 E., sec. 29B1)	3,660.0	8	Cable tool	Gas production exploration	1926-1939	Cased to 776 ft, open below, tools stuck in hole	--
Walla Walla No. 7	396208N 2231152E (T. 11 N., R. 26 E., sec. 29B2)	763.0	8	Cable tool	Gas production	1928	Open, casing status indeterminate	--
Walla Walla No. 8	395343N 2233270E (T. 11 N., R. 26 E., sec. 29B2)	784.0	8	Cable tool	Gas production	1931	Open, casing status indeterminate	--
Walla Walla No. 9	397045N 2234296E (T. 11 N., R. 26 E., sec. 21L1)	700.0	8	Cable tool	Gas production	1930	Open, casing status indeterminate	--
Northwest Natural Gas No. 1	396400N 2233700E (T. 11 N., R. 26 E., sec. 28D1)	712.0	8	Cable tool	Gas production	1930	Open, casing status indeterminate	--
Northwest Natural Gas No. 2	391945N 2234159E (T. 11 N., R. 26 E., sec. 281)	1,281.0	8	Cable tool	Gas production	1930	Open, casing status indeterminate	--
Northwest Natural Gas No. 3	394648N 2235302E (T. 11 N., R. 26 E., sec. 28F1)	757.0	8	Cable tool	Gas production	1931	Open, casing status indeterminate	--
Northwest Natural Gas No. 4	388380N 2239668E (T. 11 N., R. 26 E., sec. 34M1)	980.0	8	Cable tool	Gas production	1931	Open, casing status indeterminate	--
Northwest Natural Gas No. 5	393589N 2235885E (T. 11 N., R. 26 E., sec. 28L1)	980.0	8	Cable tool	Gas production	1931	Open, casing status indeterminate	--
Horseshoe No. 1	382200N 227500E (T. 10 N., R. 25 E., sec. 3N1)	935.0	8	Cable tool	Water well	1940	Status inderminate	--
North Pacific Gas No. 1	390642N 2233112E (T. 11 N., R. 26 E., sec. 32A)	100.0	8	Cable tool	Gas			--
Consolidated Oil and Gas	396564N 2241547E (T. 11 N., R. 26 E., sec. 27G1)	806.0	8	Cable tool	Gas production	1922	Open, casing status indeterminate	--
Yellowhawk No. 1	398987N 2231241E (T. 11 N., R. 26 E., sec. 20K1)	715.0	8	Cable tool	Gas production	1922	Open, casing status indeterminate	--
Blue Hen No. 1	398644N 2233742E (T. 11 N., R. 26 E., sec. 21M1)	800.0	8	Cable tool	Gas production	1917	Open, casing status indeterminate	--

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Table 1.6-1. Inventory of boreholes that penetrate the uppermost basalt unit on the Hanford Site (sheet 3 of 16)

Borehole/ agency[a]	Washington State coordinates[b] (township, range, section)[c]	Depth[d] (ft)	Hole diameter[e] (in.)	Primary drilling method	Original drilling purpose	Date drilling stopped	Status	Test method
Westcoast No. 1	397843N 2233344E (T. 11 N., R. 26 E., sec. 21M3)	705.0	8	Cable tool	Gas production	1930	Open, casing status indeterminate	--
Westcoast No. 2	396126N 2230678E (T. 11 N., R. 26 E., sec. 29C)	850.0	8	Cable tool	Gas production	1931	Open, casing status indeterminate	--
Big Bend No. 1	395182N 2229301E (T. 11 N., R. 26 E., sec. 20E1)	670.0	8	Cable tool	Gas production	1922	Open, casing status indeterminate	--
Colfax No. 1	402746N 2234431E (T. 11 N., R. 26 E., sec. 16N1)	740.0	8	Cable tool	Gas production	1922	Open, casing status indeterminate (also known as Rattlesnake Gas No. 10)	--
Hodges Well	380671N0 2244388E (T. 10 N., R. 26 E., sec. 11D1)	420.0	8	Cable tool	Water well	Unknown, early 1900s	Casing status indeterminate	--
Rattlesnake Gas No. 6	403730N 2228136E (T. 11 N., R. 26 E., sec. 18J1)	205.0	8	Cable tool	Gas exploration	1922	Open, casing status indeterminate	--
Rattlesnake Gas No. 11	415500N 2196500E (T. 11 N., R. 25 E., sec. 5E1)	1,003.0	8	Cable tool	Gas production	1922	Status indeterminate	--
S18-51/AEC	387171N0 2244371E (T. 11 N., R. 26 E., sec. 34R)	1,000.0	16	Cable tool	Water well	1958	Emergency Relocation Center water supply	--
B3-2/AEC	476851N 2216323E (T. 11 N., R. 28 E., sec. 27J1)	790.0	8	Cable tool	Groundwater monitoring	1953	Cased to below 645 ft	--
92-14/Army	497266N 2281088E (T. 14 N., R. 27 E., sec. 24C1)	1,396.0	12	Cable tool	Army camp water supply	1953	Cased to total depth, obstructed	--
112-37/Army	516945N 2258469E (T. 15 N., R. 27 E., sec. 32D)	1,140.0	12	Cable tool	Army camp water supply	1954	Cased to 1,123 ft, obstructed with debris	--
115-61/Army	519779N 2234474E (T. 15 N., R. 26 E., sec. 28Q1)	892.0	12	Cable tool	Army camp water supply	1953	Cased to total depth, obstructed with debris	--
699-47-50/DOE	452441N 2245696E (T. 13 N., R. 26 E., sec. 35K1)	295.0	6	Cable tool	Groundwater monitoring	1980	Screened 260 to 295 ft	--
699-50-45/DOE	455336N 2250204E (T. 13 N., R. 26 E., sec. 25P1)	178.0	6	Cable tool	Groundwater monitoring	1980	Screened 133 to 178 ft	--
699-50-48/DOE	455160N 2247639E (T. 13 N., R. 26 E., sec. 35A2)	250.0	6	Cable tool	Groundwater monitoring	1980	Screened 213 to 250 ft	--

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Table 1.6-1. Inventory of boreholes that penetrate the uppermost basalt unit on the Hanford Site (sheet 4 of 16)

Borehole/ agency[a]	Washington State coordinates[b] (township, range, section)[c]	Depth[d] (ft)	Hole diameter[e] (in.)	Primary drilling method	Original drilling purpose	Date drilling stopped	Status	Test method
699-52-46/DOE	457380N 2249485E (T. 13 N., R. 26 E., sec. 25L1)	225.0	6	Cable tool	Groundwater monitoring	1980	Screened 170 to 225 ft	--
699-52-48/DOE	456734N 2247116E (T. 13 N., R. 26 E., sec. 25J1)	197.0	6	Cable tool	Groundwater monitoring	1980	Screened 145 to 195 ft	--
699-53-50/DOE	458392N 2244993E (T. 13 N., R. 26 E., sec. 25F1)	194.0	6	Cable tool	Groundwater monitoring	1980	Screened 145 to 194 ft	--
399-5-2/AEC	378842N 2304802E (T. 10 N., R. 28 E., sec. 10K)	424.0	8	Cable tool	Groundwater monitoring	1954	Cased to basalt at 194 ft, open below	--
RSH-1/NA	401988N 2179682E (T. 11 N., R. 24 E., sec. 15R1)	10,655.0	9	Rotary	Resource exploration	1957-1958	Cased to 603 ft, plugged at 2,860 ft	--
FFTF No. 3/ERDA	404590N 2287447E (T. 11 N., R. 28 E., sec. 18M8)	1,964.0	9.6	Rotary	Water supply	1977	Cased to 1,300 ft, open to 1,835 ft	--
ARH-DC-1/AEC	453178N 2247000E (T. 13 N., R. 26 E., sec. 35H)	5,661.0	9.6	Rotary	Site feasibility	1969, re-entered 1972	Five piezometers installed	Drillstem tests
DB-1/DOE	406971N 2308893E (T. 11 N., R. 28 E., sec. 14D1)	1,139.0	3 (NX core)	Rotary/core	Waste management	1973, deepened 1981	Cased to 1,030 ft, open below	Water samples, hydrologic tests
DB-2/DOE	420657N 2308000E (T. 12 N., R. 28 E., sec. 34J1)	1,273.0	3 (NX core)	Rotary/core	Waste management	1974, deepened 1981	Cased to 957 ft, open below	Water samples, hydrologic tests
DB-3/DOE	407313N 2314243E (T. 11 N., R. 28 E., sec. 13D1)	288.0	7	Rotary	Starter hole for coring	1973	Cased to 273 ft, open below, coring canceled	--
DB-4/DOE	439903N 2267800E (T. 12 N., R. 27 E., sec. 10E1)	1,403.0	3 (NX core)	Rotary/core	Waste management	1974	Cased to 1,278 ft, open below	Water samples
DB-5/DOE	457054N 2242814E (T. 13 N., R. 26 E., sec. 26M1)	908.0	3 (NX core)	Rotary/core	Waste management	1974	Cased to 288 ft, open below	Water samples
DB-6/DOE	406709N 2277622E (T. 11 N., R. 27 E., sec. 14C1)	350.0	8	Cable tool	Groundwater monitoring	1958	Entry hole for coring was not to basalt	--
DB-7/DOE	388963N 2271833E (T. 11 N., R. 27 E., sec. 34M1)	812.0	3 (NX core)	Core	Waste management	1974	Cased to 597 ft, open below	Water samples
DB-8/DOE	447198N 2253205E (T. 12 N., R. 26 E., sec. 1J1)	1,092.0	3 (NX core)	Cable tool/ core	Waste management	1956, deepened 1977	Cased to 937 ft, partially cemented below	Water samples

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Table 1.6-1. Inventory of boreholes that penetrate the uppermost basalt unit on the Hanford Site (sheet 5 of 16)

Borehole/ agency[a]	Washington State coordinates[b] (township, range, section)[c]	Depth[d] (ft)	Hole diameter[e] (in.)	Primary drilling method	Original drilling purpose	Date drilling stopped	Status	Test method
DB-9/DOE	466565N 2237886E (T. 13 N., R. 26 E., sec. 15P)	589.0	3 (NX core)	Core	Waste management	1977	Cased to 461 ft, open below, screened 490-589 ft	Water samples
DB-10/DOE	456445N 2259309E (T. 13 N., R. 27 E., sec. 29M1)	893.0	3 (NX core)	Cable tool/core	Waste management	1975, deepened 1977	Cased to 794 ft, open below, screened 843-893 ft	--
DB-11/DOE	454471N 2194850E (T. 13 N., R. 25 E., sec. 32D1)	1,210.0	2.4 (BX core)	Cable tool/core	Waste management	1975, deepened 1977, 1982	Deepened monitoring hole as DH-9 to 429 ft, deepened DH-9 to 1,210 ft as DB-11	--
DB-12/DOE	468067N 2200144E (T. 13 N., R. 25 E., sec. 16E1)	707.0	3 (NX core)	Rotary/core	Waste management	1978, deepened 1980	Cased to 524 ft, open below	--
DB-13/DOE	422511N 2247964E T. 12 N., R. 26 E., sec. 35A1)	1,292.0	3 (NX core)	Cable tool/ core	Waste management	1959, deepened 1978	Cased to 1,069 ft, piezometer installed	--
DB-14/DOE	430190N 2215764E (T. 12 N., R. 25 E., sec. 23K1)	1,218.0	2.4 (BX core)	Cable tool/ core	Waste management	1948, deepened 1979 and 1981	Cased to 1,038 ft	--
DB-15/BWIP	452503N 2253430E (T. 13 N., R. 27 E., sec. 31M1)	1,971.0	3 (NX core)	Cable tool/ core	Waste management	1979	Cased to 858 ft, open below, monitors composite Wanapum Basalt	Hydrologic tests
DDH-1/AEC	454545N 2246851E (T. 13 N., R. 26 E., sec. 35A1)	1,165.0	3 (NX core)	Cable tool/ core	Site feasibility	1955, deepened 1969	Drill rods cemented in hole	--
DH-2/AEC	401903N 2179725E (T. 11 N., R. 24 E., sec. 15R2)	600.0	3 (NX core)	Core	Site feasibility	1969	Cased to 20 ft, open below	--
DDH-3/AEC	374957N 2309900E (T. 10 N., R. 28 E., sec. 14G3	3,540.0	2.4 (BX core)	Cable tool/ core	Site feasibility	1962, deepened 1970	Cased to 1,350 ft, rods cemented in hole to 2,870 ft, piezometer installed in lower Wanapum Basalt	--
DH-4/AEC	520713N 2287791E (T. 15 N., R. 28 E., sec. 30N1)	4,776.0	3 (NX core)	Rotary/core	Site feasibility	1971	Piezometer installed 4,508 - 4,710 ft, piezometer apparently plugged since installation	--

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Table 1.6-1. Inventory of boreholes that penetrate the uppermost basalt unit on the Hanford Site (sheet 6 of 16)

Borehole/agency[a]	Washington State coordinates[b] (township, range, section)[c]	Depth[d] (ft)	Hole diameter[e] (in.)	Primary drilling method	Original drilling purpose	Date drilling stopped	Status	Test method
DH-5/AEC	519087N 2167949E (T. 15 N., R. 24 E., sec. 28R1)	5,002.0	3 (NX core)	Rotary/core	Site feasibility	1972	Piezometer installed 4,654 - 5,002 ft, apparently now plugged	--
DH-6/DOE	448095N 2220256E (T. 12 N., R. 25 E., sec. 1B)	515.0	3 (NX core)	Cable tool/core	Waste management	1976	Cased to total depth	--
DH-7/DOE	442310N 2220230E (T. 12 N., R. 25 E., sec. 12G1)	573.0	3 (NX core)	Cable tool/core	Waste management	1976	Cased to 406 ft, open below	--
DH-8A/DOE	465878N 2239830E (T. 13 N., R. 26 E., sec. 15Q1)	249.0	3.8 (NC core)	Core	Waste management	1976	Uncased, plugged at 234 ft	--
DH-8B/DOE	465884N 2239883E (T. 13 N., R. 26 E., sec. 15Q2)	327.0	8 (nom)	Rotary/cable tool	Waste management	1976, deepened 1980	Uncased	--
DH-9/DOE	454471N 2194850E (T. 13 N., R. 25 E., sec. 32D1)	429.0	3.8 (NC core)	Cable tool/core	Waste management	1975 and 1976	Extended to 1,210 ft as DB-11	--
DH-9A/DOE	448309N 2253397E (T. 12 N., R. 26 E., sec. 1H1)	222.0	3.8 (NC core)	Cable tool/core	Groundwater monitoring	1966, deepened 1976	Cased to 154 ft, grouted back to casing	--
DH-9B/DOE	459365N 2277430E (T. 13 N., R. 27 E., sec. 26G3)	355.0	3.8/3 (NX core)	Rotary/core	Groundwater monitoring	1975 and 1976	Open, filled with drilling mud	--
DH-10/DOE	464437N 2239956E (T. 13 N., R. 26 E., sec. 22B1)	145.0	7 (nom)	Rotary	Groundwater monitoring	1976	Hole abandoned because of sand inflow	--
DH-11/DOE	445091N 2217134E (T. 12 N., R. 25 E., sec. 1N1)	581.0	3.8 (NC core)	Cable tool/core	Waste management	1976	Cased to total depth	--
DH-12/DOE	445112N 2220221E (T. 12 N., R. 25 E., sec. 1N2)	531.0	3.8 (NC core)	Cable tool/core	Waste management	1976 and 1977	Open	--
DH-13/DOE	445216N 2223428E (T. 12 N., R. 26 E., sec. 6P1)	723.6	3.8 (NC core)	Cable tool/core	Waste management	1976 and 1977	Drillstem cemented in hole, hole abandoned	--
DH-13A/DOE	445222N 2223434E (T. 12 N., R. 26 E., sec. 6P2)	563.0	3.8 (NC core)	Cable tool/core	Waste management	1976 and 1977	Cased to 478 ft, open below	--
DH-14/DOE	447161N 2239218E (T. 12 N., R. 26 E., sec. 3G1)	266.0	3.8 (NC core)	Cable tool/core	Waste management	1976 and 1977	Hole terminated and filled with mud due to deviation	--
DH-15/DOE	447299N 2243211E (T. 12 N., R. 26 E., sec. 2E1)	381.0	3.8 (NC core)	Cable tool/core	Waste management	1976 and 1977	Cased to total depth	--

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Table 1.6-1. Inventory of boreholes that penetrate the uppermost basalt unit on the Hanford Site (sheet 7 of 16)

Borehole/ agency[a]	Washington State coordinates[b] (township, range, section)[c]	Depth[d] (ft)	Hole diameter[e] (in.)	Primary drilling method	Original drilling purpose	Date drilling stopped	Status	Test method
DH-16/DOE	447334N 2247162E (T. 12 N., R. 26 E., sec. 2H1)	353.0	3.8 (NC core)	Cable tool/ core	Waste management	1976	Filled with cement	--
DH-17/DOE	443247N 2239203E (T. 12 N., R. 26 E., sec. 10C)	536.0	3.8 (NC core)	Cable tool/ core	Waste management	1957, deepened 1977	Filled with drilling mud	--
DH-18/BWIP	430926N 2280714E (T. 12 N., R. 27 E., sec. 24M3)	630.0	3.9 (NC core)	Cable tool/ core	Suprabasalt investigation	1980	Cased to total depth	--
DH-19/BWIP	475645N 2277825E (T. 13 N., R. 27 E., sec. 11B1)	776.0	3.9 (NC core)	Rotary/core	Suprabasalt investigation	1980	Cased to total depth	--
DH-20/BWIP	434345N 2211941E (T. 12 N., R. 25 E., sec. 15R1)	569.0	4 (HQ core)	Cable tool/ core	Suprabasalt investigation	1981	Cased to total depth	--
DH-21/BWIP	442206N 2211077E (T. 12 N., R. 25 E., sec. 10H1)	628.0	4 (HQ core)	Cable tool/ core	Suprabasalt investigation	1981	Cased to total depth	--
DH-22/BWIP	441644N 2203445E (T. 12 N., R. 25 E., sec. 9G1)	688.0	4 (HQ core)	Cable tool/ core	Suprabasalt investigation	1981	Cased to total depth	--
DH-23/BWIP	451576N 2210651E (T. 13 N., R. 25 E., sec. 35M1)	177.0	4 (HQ core)	Cable tool/ core	Suprabasalt investigation	1981	Drilling terminated, data obtained from RRL-7	--
DH-24/BWIP	448400N 2210873E (T. 12 N., R. 25 E., sec. 3A1)	577.0	4 (HQ core)	Cable tool/ core	Suprabasalt investigation	1982	Cased to 78 ft	--
DH-25/BWIP	445431N 2211075E (T. 12 N., R. 25 E., sec. 3R1)	620.5	4 (HQ core)	Cable tool/ core	Suprabasalt investigation	1982	Cased to 611 ft	--
DH-26/BWIP	430829N 2212013E (T. 12 N., R. 25 E., sec. 22J1)	363.0	4 (HQ core)	Cable tool/ core	Suprabasalt investigation	1982	Cased to total depth	--
DH-27/BWIP	454768N 2196455E (T. 13 N., R. 25 E., sec. 29P1)	732.6	3 (NQ core)	Cable tool/ core	Structural investigation	1983, deepened 1985	Cased to 517 ft, cemented back to 647 ft	--
DH-28/BWIP	454772N 2198774E (T. 13 N., R. 25 E., sec. 29Q1)	1,106.3	3 (NQ core)	Cable tool/ core	Structural investigation	1983, deepened 1984 and 1985	Cased to 748 ft, open below	--
DH-29/BWIP	454766N 2197274E (T. 13 N., R. 25 E., sec. 29R1)	100.0	4 (nom)	Cable tool	Structural investigation	1983	Entry hole for coring, not cored	--
DH-30/BWIP	438102N 2217241E (T. 12 N., R. 25 E., sec. 13D)	63.0	8	Cable tool	Suprabasalt investigation	1986	Entry hole for coring	--

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Table 1.6-1. Inventory of boreholes that penetrate the uppermost basalt unit on the Hanford Site (sheet 8 of 16)

Borehole/ agency[a]	Washington State coordinates[b] (township, range, section)[c]	Depth[d] (ft)	Hole diameter[e] (in.)	Primary drilling method	Original drilling purpose	Date drilling stopped	Status	Test method
DH-31/BWIP	431403N 2217958E (T. 12 N., R. 25 E., sec. 24E)	63.0	8	Cable tool	Suprabasalt investigation	1986	Entry hole for coring	--
DH-32/BWIP	437470N 2204792E (T. 12 N., R. 25 E., sec. 16G)	62.5	8	Cable tool	Suprabasalt investigation	1986	Entry hole for coring	--
DH-33/BWIP	438053N 2198441E (T. 12 N., R. 25 E., sec. 17G)	1,046.8	3 (HQ core)	Cable tool/ core	Suprabasalt investigation	1986	Cased to 732 ft, cement plug at 984 ft between Selah and Rattlesnake Ridge interbeds	--
DH-34/BWIP	454769N 2196798E (T. 13 N., R. 25 E., sec. 29Q1)	103.0	8	Cable tool	Suprabasalt investigation	1986	Entry hole for coring	--
DH-35/BWIP	454767N 2197898E (T. 13 N., R. 25 E., sec. 29R2)	101.0	8	Cable tool	Suprabasalt investigation	1986	Entry hole for coring	--
CH-1/BWIP	465166N 2242171E (T. 13 N., R. 26 E., sec. 22A1)	150.0	4 (NC core)	Core	Borehole sealing test	1980	Open, exact location indeterminate	--
CH-2/BWIP	465166N 2242171E (T. 13 N., R. 26 E., sec. 22A1)	160.0	4 (NC core)	Core	Borehole sealing test	1980	Open, exact location indeterminate	--
CH-3/BWIP	465166N 2242171E (T. 13 N., R. 26 E., sec. 22A1)	150.0	4 (NC core)	Core	Borehole sealing test	1980	Open, exact location indeterminate	--
CH-4/BWIP	465166N 2242171E (T. 13 N., R. 26 E., sec. 22A1)	160.0	4 (NC core)	Core	Borehole sealing test	1980	Open, exact location indeterminate	--
CH-5/BWIP	455166N 2242171E (T. 13 N., R. 26 E., sec. 22A5)	150.0	4 (NC core)	Core	Borehole sealing test	1980	Open, exact location indeterminate	--
CH-6/BWIP	455166N 2242171E (T. 14 N., R. 26 E., sec. 22A6)	290.0	4 (NC core)	Core	Borehole sealing test	1980	Open, exact location indeterminate	--
DC-2/BWIP	453144N 2246946E (T. 13 N., R. 26 E., sec. 35G1)	3,300.0	3 (NX core)	Cable tool/ core	Geohydrologic investigation	1977	Cased to 2,253 ft, packer lost in hole, grouted back to allow deviated drilling	Drillstem tested
DC-2-A1/BWIP	453144N 2246946E (T. 13 N., R. 26 E., sec. 35G1-A1)	2,370.0 - 3,348.0	3 (NX core)	Deviated core	Geohydrologic investigation	1978	Deviated from DC-2, plugged back to 2,185 ft	--
DC-2-A2/BWIP	453144N 2246946E (T. 13 N., R. 26 E., sec. 35G1-A2)	2,280.0 - 3,374.0	3 (NX core)	Deviated core	Geohydrologic investigation	1978	Deviated from DC-2, open	--

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Table 1.6-1. Inventory of boreholes that penetrate the uppermost basalt unit on the Hanford Site (sheet 9 of 16)

Borehole/ agency[a]	Washington State coordinates[b] (township, range, section)[c]	Depth[d] (ft)	Hole diameter[e] (in.)	Primary drilling method	Original drilling purpose	Date drilling stopped	Status	Test method
DC-3/BWIP	448925N 2225057E (T. 12 N., R. 26 E., sec. 6B1)	3,707.0	8 and 3 (NQ core)	Rotary/core	Geohydrologic investigation	1978, deepened 1982	Cased to 3,575 ft, open below	Seismic monitoring geophone installed
DC-4/BWIP	454467N 2209995E (T. 13 N., R. 25 E., sec. 34A2)	3,998.0	3 (NX core)	Cable tool/ core	Geohydrologic investigation	1978	Cased to 2,639 ft, open below	Cross hole seismic and hydrologic tests with DC-5
DC-5/BWIP	454536N 2210071E (T. 13 N., R. 25 E., sec. 34A1)	3,990.0	8.6	Rotary	Geohydrologic investigation	1978	Cased to 2,635 ft, open below	Cross hole seismic and hydrologic tests with DC-4
DC-6/BWIP	459382N 2277465E (T. 13 N., R. 27 E., sec. 26G4)	4,336.0	3 (NX core)	Cable tool/ core	Geohydrologic investigation	1978	Cased to 2,261 ft, open below	Post-completion hydrologic tests
DC-7/BWIP	420175N 2280448E (T. 12 N., R. 27 E., sec. 35J6)	5,008.0	8.6 and 3 (NQ core)	Rotary/core	Geohydrologic investigation	1977, deepened by coring 1980	Cased to 2,780 ft, open below	Post-completion hydrologic and tracer tests with DC-8
DC-8/BWIP	420221N 2280424E (T. 12 N., R. 27 E., sec. 35J7)	4,100.5	3 (NX core)	Cable tool/ core	Geohydrologic investigation	1978	Cased to 2,734 ft, open below	Post-completion hydrologic and tracer tests with DC-7
DC-9/NA	NA NA	NA	NA	Planned rotary	Geohydrologic investigation	NA	Planned near DC-6, never drilled	--
DC-10/BWIP	467633N 2241920E (T. 13 N., R. 26 E., sec. 15J1)	456.9	3 (NX core)	Core	NSTF[f] design	1977	Surface casing pulled, open. Deviated hole, 27 degrees	--
DC-11/BWIP	465859N 2242144E (T. 13 N., R. 26 E., sec. 15R1)	385.0	3 (NX core)	Core	NSTF design	1978	Open, uncase, vertical hole	--
DC-12/BWIP	412290N 2241612E (T. 11 N., R. 26 E., sec. 3G2)	4,455.0	3 (NX core)	Rotary/core	Geohydrologic investigation	1980	Cased to 2,260 ft, open below	Test-as-drilled and post-completion hydrologic tests
DC-13/NA	NA NA	NA	NA	Planned core	Geohydrologic investigation	NA	Planned N.W. corner of Hanford Site, never drilled	--
DC-14/BWIP	489704N 2261248E (T. 14 N., R. 27 E., sec. 29K1)	3,335.0	3 (NX core)	Cable tool/ core	Geohydrologic investigation	1981	Cased to 1,085 ft, open below. Flows artesian	Test-as-drilled and postcompletion hydrologic tests

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Table 1.6-1. Inventory of boreholes that penetrate the uppermost basalt unit on the Hanford Site (sheet 10 of 16)

Borehole/ agency[a]	Washington State coordinates[b] (township, range, section)[c]	Depth[d] (ft)	Hole diameter[e] (in.)	Primary drilling method	Original drilling purpose	Date drilling stopped	Status	Test method
DC-15/BWIP	389808N 2309775E (T. 11 N., R. 28 E., sec. 35L1)	4,243.0	3 (NX core)	Cable tool/ core	Geohydrologic investigation	1981	Cased to 2,198 ft, open below	Test-as-drilled and post-completion hydrologic tests
DC-16A/BWIP	436404N 2211518E (T. 12 N., R. 25 E., sec. 15J1)	4,398.0	4 (HQ core)	Cable tool/ core	Geohydrologic investigation	1981	Cased to 2,827 ft, open below	Test-as-drilled and post-completion hydrologic tests
DC-16B/BWIP	436353N 2211520E (T. 12 N., R. 25 E., sec. 15J2)	1,600.0	12.2	Rotary	Hydrologic investigation	1982	Cased to 1,368 ft, screened 1,410 - 1,570 ft across Mabton interbed	--
DC-16C/BWIP	436377N 2211009E (T. 12 N., R. 25 E., sec. 15J3)	3,854.0	8.9	Rotary	Hydrologic investigation	1982	Cased to 1,644 ft, open below	--
DC-16C-A1/ BWIP	436377N 2211009E (T. 12 N., R. 25 E., sec. 15J3A1)	3,746.0 - 3,899.0	2.9	Deviated core	Geologic investigation	1983	Deviated core from DC-16C at about 5°	--
DC-17/NA	NA NA	NA	NA	Planned core	Geologic investigation	NA	Planned west of reference repository location, drilling canceled	--
DC-18/BWIP	465150N 2236171E (T. 13 N., R. 26 E., sec. 21A1)	1,560.7	4 (HQ core)	Rotary/core	Geohydrologic investigation	1983 and 1986	Coring suspended, casing set to 681 ft	Hydrologic tests and hydrochemical sampling as-drilled
DC-19A/BWIP	433655N 2224918E (T. 12 N., R. 26 E., sec. 19B1)	804.2	5.2 (PQ core)	Cable tool/ core	RRL9 piezometer baseline	1984	Cored extension of borehole RRL-13, piezometers installed for basal Ringold and Rattlesnake Ridge interbed	--
DC-19C/BWIP	433933N 2225012E (T. 12 N., R. 26 E., sec, 19B3)	3,983.0	12.2	Cable tool/ rotary	RRL piezometer baseline	1983	Multilevel piezometers installed for Wanapum and Grande Ronde Basalts	--
DC-19D/BWIP	433845N 2225135E (T. 12 N., R. 26 E., sec. 19B3)	1,550.0	8.6	Cable tool/ rotary	RRL piezometer baseline	1983	Pizometer installed for Mabton interbed	--
DC-20A/BWIP	451803N 2215392E	755.7	5.2	Cable tool	RRL piezometer baseline	1983	Piezometers installed for basal Ringold and Rattlesnake Ridge interbed	--

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Table 1.6-1. Inventory of boreholes that penetrate the uppermost basalt unit on the Hanford Site (sheet 11 of 16)

Borehole/ agency[a]	Washington State coordinates[b] (township, range, section)[c]	Depth[d] (ft)	Hole diameter[e] (in.)	Primary drilling method	Original drilling purpose	Date drilling stopped	Status	Test method
DC-20B/BWIP	452009N 2215372E (T. 13 N., R. 25 E., sec. 35J2)	1,635.0	12.2	Cable tool/ rotary	RRL piezometer baseline	1983	Cased to 1,560 ft, open below	Planned pumping well for large-scale test
DC-20C/BWIP	451884N 2215288E (T. 13 N., R. 25 E., sec. 35J3)	3,781.0	12.2	Cable tool/ rotary	RRL piezometer baseline	1983	Cased to 1,581 ft, open below, multilevel piezometers installed for Wanapam and Grande Ronde Basalts	--
DC-20D/BWIP	452084N 2215170E (T. 13 N., R. 25 E., sec. 35J4)	1,495.0	8.6	Cable tool/ rotary	RRL piezometer baseline	1984	Cased to 1,250 ft, piezometer installed for Mabton interbed	--
DC-21/NA	NA NA	NA	NA	Planned core	Geohydrologic investigation	NA	Planned near 100N Area, data replaced by deepening of WPPSS BH-17	--
DC-22A/BWIP	448437N 2204438E (T. 12 N., R. 25 E., sec. 4A)	860.7	5.2 (PQ core)	Cable tool/ core	RRL piezometer baseline	1984	Cased to 656 ft, piezometers installed for basal Ringold and Rattlesnake Ridge interbed	--
DC-22B/BWIP	448519N 2204314E (T. 12 N., R. 25 E., sec. 4B)	1,805.0	12.2	Cable tool/ rotary	RRL piezo-meter baseline	1983	Cased to 1,718 ft, open below, pumping well for large- scale test	--
DC-22C/BWIP	448600N 2204188E (T. 12 N., R. 25 E., sec. 4C)	3,960.0	12.2	Cable tool/ rotary	RRL piezometer baseline	1983	Cased to 1,709 ft, multilevel piezometers installed for Wanapum and Grande Ronde Basalts	--
DC-22D/BWIP	448530N 2204074E (T. 12 N., R. 25 E., sec. 4D)	1,625.0	8.6	Cable tool/ rotary	RRL piezometer baseline	1984	Cased to 1,370 ft, monitors Mabton interbed	--
DC-23GR/BWIP	461889N 2212179E (T. 13 N., R. 25 E., sec. 23L3)	3,533.0	9.9	Rotary	Piezometric baseline	1986	Cased to 2,385 ft, piezometers installed for Grande Ronde Basalt	--

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Table 1.6-1. Inventory of boreholes that penetrate the uppermost basalt unit on the Hanford Site (sheet 12 of 16)

Borehole/ agency[a]	Washington State coordinates[b] (township, range, section)[c]	Depth[d] (ft)	Hole diameter[e] (in.)	Primary drilling method	Original drilling purpose	Date drilling stopped	Status	Test method
DC-23W/BWIP	462089N 2212189E (T. 13 N., R. 25 E., sec. 23L2)	2,395.0	9.9	Cable tool/ rotary	Piezometer baseline	1985	Cased to 1,300 ft, piezometers installed for Wanapum Basalt	--
DC-24CX/BWIP	431089N2 2212258E (T. 12 N., R. 25 E., sec. 23M1)	64.0	20	Cable tool	Piezometer baseline	1986	Entry hole for rotary drilling	--
DC-25CX/BWIP	424500N 2257500E (T. 12 N., R. 27 E., sec. 30Q1)	60.0	20	Cable tool	Piezometer baseline	1986	Entry hole for rotary drilling	--
FH-1/BWIP	444086N 2211225E (T. 12 N., R. 25 E., sec. 10A3)	151.0	6	Rotary	ES[h] foundation studies	1982	Drilled as B-1, filled in	--
FH-2/BWIP	444086N 2211225E (T. 12 N., R. 25 E., sec. 10A4)	30.0	6	Rotary	ES foundation studies	1982	Drilled as B-2, filled in	--
FH-3/BWIP	444086N 2211225E (T. 12 N., R. 25 E., sec. 10A5)	21.0	6	Rotary	ES foundation studies	1982	Drilled as B-3, filled in	--
FH-4/BWIP	444086N 2211225E (T. 12 N., R. 25 E., sec. 10A6)	21.0	6	Rotary	ES foundation studies	1982	Drilled as B-4, filled in	--
RRL-1/BWIP	438086N 2211240E (T. 12 N., R. 25 E., sec. 15A1)	242.0	8	Rotary	Geohydrologic investigation	1980	Bit lost in hole, casing pulled, cemented back to surface	--
39-84A/BWIP	444086N 2211275E (T. 12 N., R. 25 E., sec. 10A1)	213.0	8	Rotary	Geohydrologic investigation	1980	Drilled as RRL-2, bit lost in hole, casing pulled, cemented back to surface	--
RRL-2A/BWIP	444298N 2211184E (T. 12 N., R. 25 E., sec. 10B)	3,973.0	3 (NX core)	Cable tool/ core	ES-1 principal borehole	1982	Cased to 2,713 ft, open below. Principal borehole for ES-1	--
RRL-2B/BWIP	444795N 2211122E (T. 12 N., R. 25 E., sec. 3R)	2,858.0	12.2	Cable tool/ rotary	Large-scale pump test	1985	Cased to 2,776 ft, open below. Pumping well for large-scale pump test	--
RRL-2C/BWIP	444824N 2211376E (T. 12 N., R. 25 E., sec. 2N1)	3,404.0	12.2	Rotary	Large-scale pump test	1985	Cased to 2,775 ft, multilevel piezometers installed	--

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Table 1.6-1. Inventory of boreholes that penetrate the uppermost basalt unit on the Hanford Site (sheet 13 of 16)

Borehole/ agency[a]	Washington State coordinates[b] (township, range, section)[c]	Depth[d] (ft)	Hole diameter[e] (in.)	Primary drilling method	Original drilling purpose	Date drilling stopped	Status	Test method
RRL-3/BWIP	449676N 2216917E (T. 13 N., R. 25 E., sec. 36N1)	730.0	9.9	Cable tool/ rotary	Seismic baseline	1981	PVC cased to 730 ft, seismic monitoring geophone installed	--
RRL-4/BWIP	440599N 2216983E (T. 12 N., R. 25 E., sec. 12M1)	642.0	9.9	Cable tool/ rotary	Seismic baseline	1981	PVC cased to 638 ft, seismic monitoring geophone installed	--
RRL-5/BWIP	447389N 2206742E (T. 12 N., R. 25 E., sec. 3E1)	701.0	9.9	Cable tool/ rotary	Seismic baseline	1981	PVC cased to 701 ft, seismic monitoring geophone installed	--
34-89A/BWIP	438624N 2206489E (T. 13 N., R. 25 E., sec. 15D1)	441.0	8	Cable tool/ rotary	RRL site investigation	1981	Drilled as RRL-6A, completed as temporary water supply well	--
RRL-6/BWIP	438580N 2206423E (T. 13 N., R. 25 E., sec. 15D2)	4,040.0	3 (NX core)	Cable tool/ core	RRL site investigation	1981 and 1982	PVC cased to 2,841 ft, open below	--
RRL-7/BWIP	450804N 2210393E (T. 13 N., R. 25 E., sec. 34R1)	723.0	9.9	Cable tool/ rotary	Seismic baseline	1982	PVC cased to 723 ft, seismic monitoring geophone installed	--
RRL-8/BWIP	452477N 2203573E (T. 13 N., R. 25 E., sec. 33G1)	755.0	9.9	Cable tool/ rotary	Seismic baseline	1981	PVC cased to 755 ft, seismic monitoring geophone installed	--
RRL-9/BWIP	444762N 2215245E (T. 12 N., R. 25 E., sec. 2Q1)	559.0	9.9	Cable tool/ rotary	Seismic baseline	1982	PVC cased to 550 ft, seismic monitoring geophone installed	--
RRL-10/BWIP	442103N 2206591E (T. 12 N., R. 25 E., sec. 10E1)	668.0	9.9	Cable tool/ rotary	Seismic baseline	1981 and 1983	PVC cased to 668 ft, seismic monitoring geophone installed	--
RRL-11/BWIP	440306N 2200627E (T. 12 N., R. 25 E., sec. 28A1)	142.0	10	Cable tool	Seismic baseline	1982	Entry hole not deepened, cased to 122 ft, no geophone installed	--
RRL-12/BWIP	436598N 2211845E (T. 12 N., R. 25 E, sec. 18M1)	150.0	10	Cable tool	Seismic baseline	1982	Entry hole not required for seismic network, cased to 150 ft, no geophone installed	--

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Table 1.6-1. Inventory of boreholes that penetrate the uppermost basalt unit on the Hanford Site (sheet 14 of 16)

Borehole/ agency[a]	Washington State coordinates[b] (township, range, section)[c]	Depth[d] (ft)	Hole diameter[e] (in.)	Primary drilling method	Original drilling purpose	Date drilling stopped	Status	Test method
RRL-13/BWIP	433652N 2224913E (T. 12 N., R. 26 E., sec. 19B1)	150.0	10	Cable tool	Seismic baseline	1982	Drilled as seismic monitoring entry hole, deepened and now known as DC-19A	--
RRL-14/BWIP	446541N 2203992E (T. 12 N., R. 25 E., sec. 4K1)	4,000.0	4	Rotary/core	RRL site investigation	1982	Cased to 2,870 ft, open below	--
RRL-15/BWIP	NA NA	NA	NA	NA	RRL site investigation	NA	Planned near existing monitoring well 699-39-79, not drilled (State coordinates 444300N. 2216473E.)	--
RRL-16/BWIP	442091N 2213230E (T. 12 N., R. 25 E., sec. 11F1)	626.0	10	Cable tool/ rotary	Seismic baseline	1983	PVC cased to 626 ft, seismic monitoring geophone installed	--
RRL-17/BWIP	448349N 2213853E (T. 12 N., R. 25 E., sec. 2C1)	3,337.0	4	Rotary/core	RRL site investigation	1985 and 1986	Cased to 2,768 ft, open below	--
UC-1/BWIP	466247N 2193068E (T. 13 N., R. 25 E., sec. 17N1)	96.5	7.8	Core	Rock mechanics core	1981	Cased to 4.5 ft, open below	--
ES-1/BWIP	444169N 2210913E (T. 12 N., R. 25 E., sec. 10C)	100.0	172	Flight auger	RRL site characterization	1983	Cased to total depth	--
BH-1/WPPSS	4891420N 2232800E (T. 14 N., R. 26 E., sec. 28L1)	981.0	2.4	Rotary/core	Nuclear power	1973	Deviated hole plant siting	--
BH-16/WPPSS	4894740N 2235629E (T. 14 N., R. 26 E., sec. 27N1)	1,001.0	3.0	Rotary/core	Nuclear power	1973	Open plant siting	--
BH-17/WPPSS/ BWIP	485956N 2233046E (T. 14 N., R. 26 E., sec. 26K)	1,471.0	1.9	Rotary/core	Nuclear power plant siting	1973, deepened 1983	Cased to 1,331 ft, open below, deepened by BH-BWIP, 1983	--
BH-18/WPPSS	490917N 2231045E (T. 14 N., R. 26 E., sec. 29K1)	950.0	3.0	Rotary/core	Nuclear power	1973	Open plant siting	--
B-12/WPPSS	417059N 2294134E (T. 11 N., R. 28 E., sec. 5G)	846.1	3	Auger/ rotary/core	Nuclear power plant siting	1972	Cased to 565.5 ft	--
B-35/WPPSS	417822N 2293448E (T. 11 N., R. 28 E., sec. 5C)	874.5	3	Rotary/core	Nuclear power plant siting	1972	Status indeterminate	--

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Table 1.6-1. Inventory of boreholes that penetrate the uppermost basalt unit on the Hanford Site (sheet 15 of 16)

Borehole/ agency[a]	Washington State coordinates[b] (township, range, section)[c]	Depth[d] (ft)	Hole diameter[e] (in.)	Primary drilling method	Original drilling purpose	Date drilling stopped	Status	Test method
B-36/WPPSS	415290N 2291833E (T. 11 N., R. 28 E., sec. 5M)	946.9	3	Rotary/core	Nuclear power plant siting	1972	Status indeterminate	--
BH-137/WPPSS	410797N 2293310E (T. 11 N., R. 28 E., sec. 8F)	916.0	3	Rotary/core	Nuclear power plant siting	1974	Cased to 464 ft	--
BH-138/WPPSS	414439N 2290181E (T. 11 N., R. 28 E., sec. 6R)	886.0	3	Rotary/core	Nuclear power plant siting	1974	Cased to 446 ft, hole deviated 11°, true vertical depth 878 ft	--
BH-139A/ WPPSS	420981N 2298865E (T. 11 N., R. 28 E., sec. 33L)	706.0	3	Rotary/core	Nuclear power plant siting	1974	Cased to 384 ft	--
BH-140/WPPSS	415811N 2298798E (T. 11 N., R. 28 E., sec. 4L)	656.0	3	Rotary/core	Nuclear power plant siting	1974	Cased to 436 ft	--
BH-141/WPPSS	425649N 2297750E (T. 12 N., R. 28 E., sec. 28N)	701.0	3	Rotary/core	Nuclear power plant siting	1974	Cased to 470 ft	--
BH-142/WPPSS	418812N 2297792E (T. 11 N., R. 28 E., sec. 4D)	629.0	3	Rotary/core	Nuclear power plant siting	1974	Cased to 409 ft	--
BH-143/WPPSS	415886N 2303177E (T. 11 N., R. 28 E., sec. 3M)	567.0	3	Rotary/core	Nuclear power plant siting	1974	Cased to 371 ft	--
DH-92/S/HNP	453750N 2262027E (T. 13 N., R. 27 E., sec. 32G)	356.0	8	Rotary	Nuclear power plant siting	1980	Plugged at 206 ft	--
DH-93/S/HNP	453847N 2264528E (T. 13 N., R. 27 E., sec. 32H)	675.0	8	Rotary	Nuclear power plant siting	1980	Status indeterminate	--
DH-96/S/HNP	453702N 2260433E (T. 13 N., R. 27 E., sec. 32F)	455.0	8	Rotary	Nuclear power plant siting	1980	Status indeterminate	--
DH-97/S/HNP	453790N 2263334E (T. 13 N., R. 27 E., sec. 32H)	339.0	8	Rotary	Nuclear power plant siting	1980	Status indeterminate	--
DH-125/S/HNP	444382N 2288370E (T. 12 N., R. 28 E., sec. 7C)	451.6	8	Rotary	Nuclear power plant siting	1981	Status indeterminate	--
S-1/S/HNP	426503N 2265442E (T. 12 N., R. 27 E., sec. 28E)	975.0	8	Rotary	Nuclear power plant siting	1981	Status indeterminate	--
S-5/S/HNP	424503N 2272289E (T. 12 N., R. 27 E., sec. 34C)	942.0	8	Rotary	Nuclear power plant siting	1981	Status indeterminate	--

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Table 1.6-1. Inventory of boreholes that penetrate the uppermost basalt unit on the Hanford Site (sheet 16 of 16)

Borehole/ agency[a]	Washington State coordinates[b] (township, range, section)[c]	Depth[d] (ft)	Hole diameter[e] (in.)	Primary drilling method	Original drilling purpose	Date drilling stopped	Status	Test method
S-6/S/HNP	430424N 2264275E (T. 12 N., R. 27 E., sec. 20R)	816.0	8	Rotary	Nuclear power plant siting	1981	Status indeterminate	--
S-7/S/HNP	433100N 2265443E (T. 12 N., R. 27 E., sec. 21L)	957.0	8	Rotary	Nuclear power plant siting	1981	Status indeterminate	--
S-22/S/HNP	429837N 2275531E (T. 12 N., R. 27 E., sec. 23N)	992.0	8	Rotary	Nuclear power plant siting	1981	Status indeterminate	--
S-24/S/HNP	415133N 2264836E (T. 11 N., R. 27 E., sec. 5J)	780.0	8	Rotary	Nuclear power plant siting	1981	Status indeterminate	--
MJ-1/S/HNP	451449N 2264631E (T. 13 N., R. 27 E., sec. 33M)	573.0	8	Rotary	Nuclear power plant siting	1982	Status indeterminate	--
MJ-2/S/HNP	451413N 2263630E (T. 13 N., R. 27 E., sec. 32R)	425.0	8	Rotary	Nuclear power plant siting	1982	Status indeterminate	--

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NOTE: All borehole data is recorded in the English System of feet and inches.
NA = Not applicable.
To convert feet to meters, multiply by 0.3048.
To convert inches to centimeters, multiply by 2.54.

[a]Agency denotes the agency or organization responsible for drilling the borehole. Abbreviations used:
AEC = U.S. Atomic Energy Commission
Army = U.S. Army
BWIP = Basalt Waste Isolation Project
DOE = U.S. Department of Energy
ERDA = U.S. Energy Research and Development Administration
S/HNP = Skagit Hanford Nuclear Project
WPPSS = Washington Public Power Supply System

[b]Washington State coordinates are given in feet from the Washington State Grid System based on a Lambert Conformal Conic projection.
[c]Township/Range-Section are equivalent locations based on the Congressional Land Grid System used by the U.S. Geological Survey.
[d]Final drilled depth in feet below ground surface, uncorrected for deviation.
[e]Diameter in inches of the deepest portion of the borehole.
[f]NSTF = Near-Surface Test Facility.
[g]RRL = Reference repository location.
[h]ES = Exploratory shaft.

CONSULTATION DRAFT

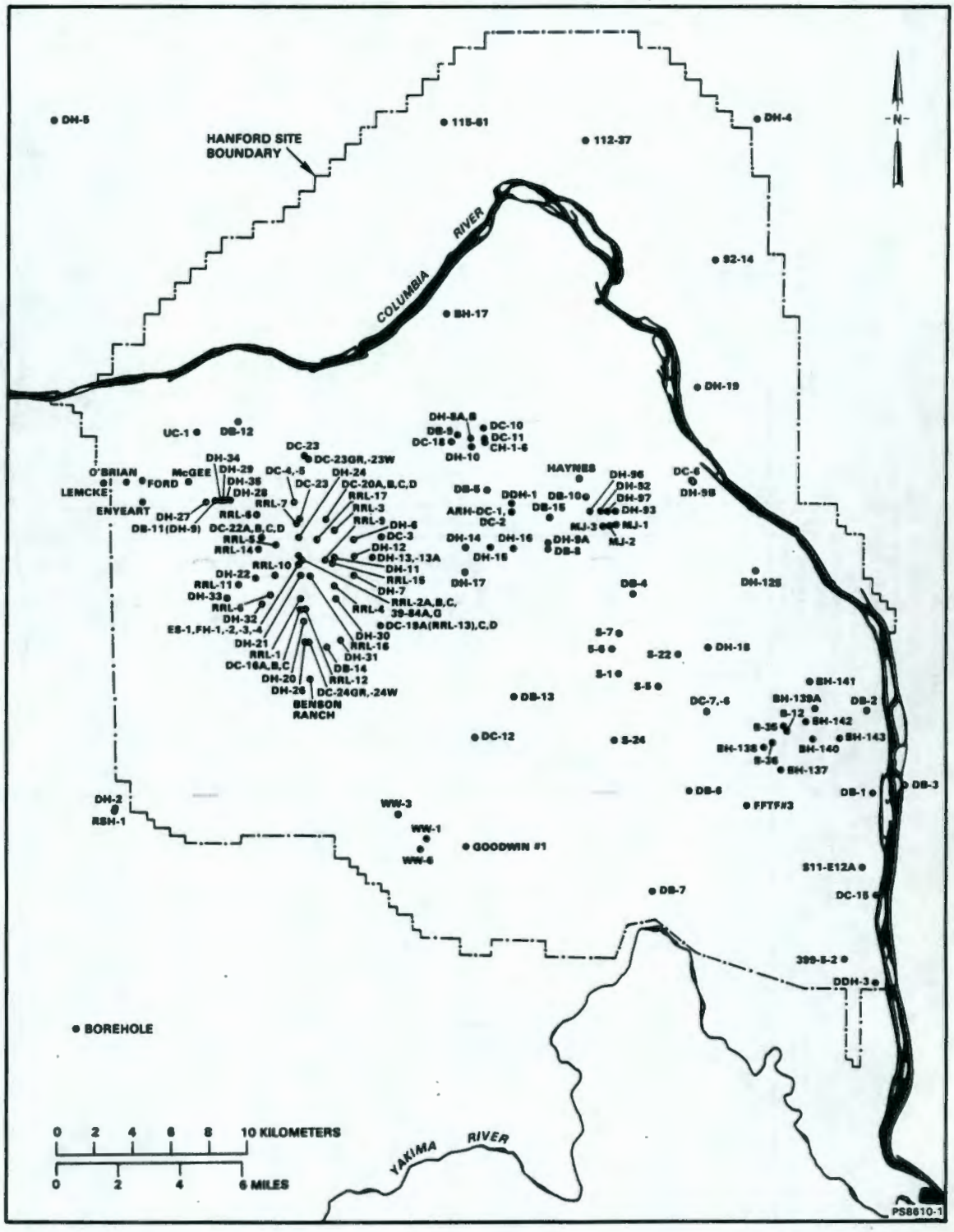

Figure 1.6-2. Location map for boreholes used in Basalt Waste Isolation Project studies.

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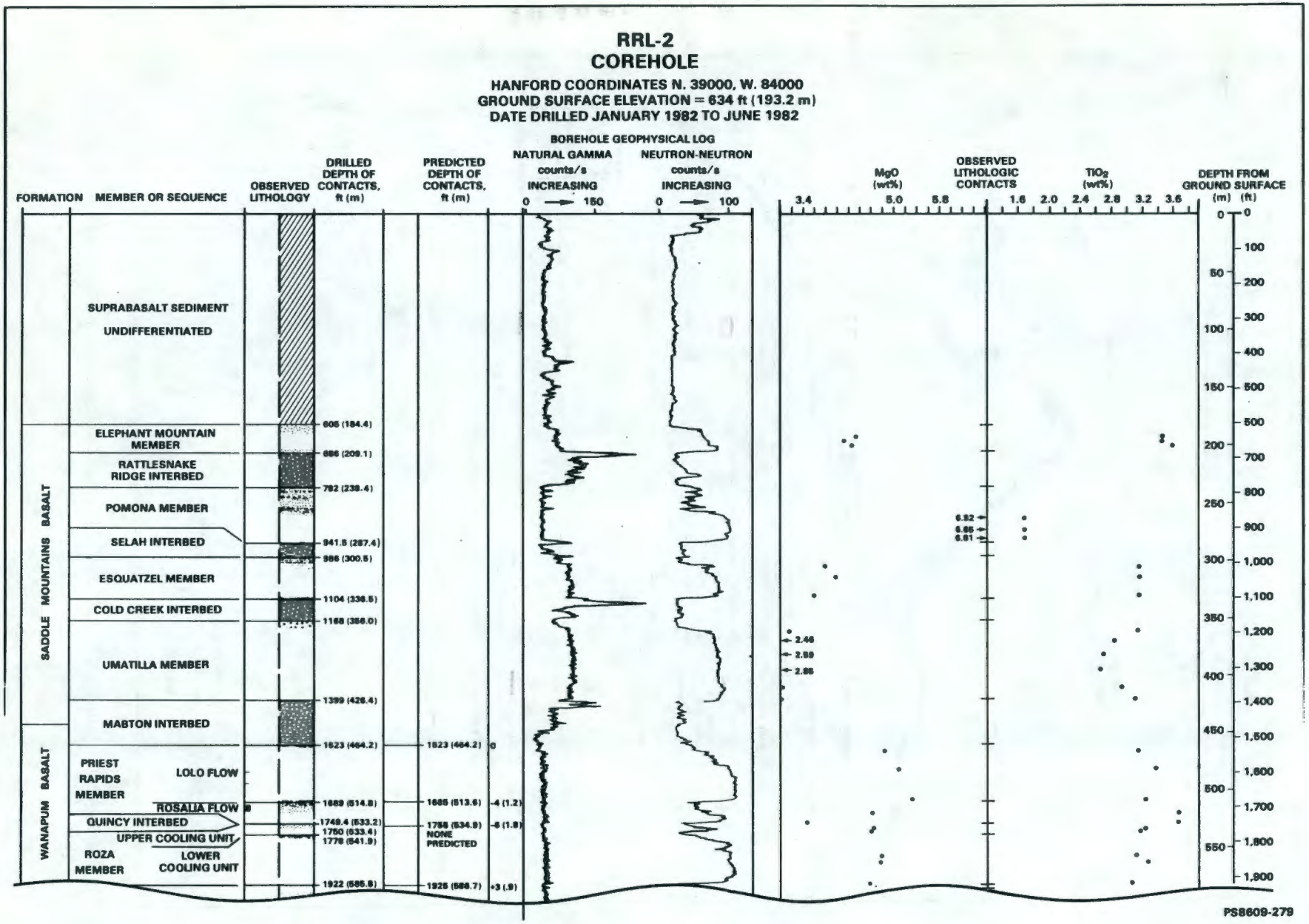

Figure 1.6-3. Example of deep borehole stratigraphic correlation.

CONSULTATION DRAFT

Boreholes are grouped into two categories for discussion and location map presentation: those within and adjacent to the Hanford Site and those specifically within or near the reference repository location.

1.6.1.1 Boreholes within and adjacent to the Hanford Site

The area described in this section is the Hanford Site and adjacent geohydrologically related areas of the Pasco Basin (e.g., the upper Cold Creek Valley). The description of boreholes that have been drilled within this area are grouped into six categories: (1) water supply, (2) oil-gas exploration and production (Section 1.7), (3) surveillance and waste management, (4) nuclear powerplant siting, (5) repository feasibility and siting, and (6) injection. These six categories are not mutually exclusive in all cases, because some of the boreholes serve more than one function. However, for this discussion, the boreholes are categorized according to the primary function for which they were drilled.

1.6.1.1.1 Water supply

This category includes approximately 200 water-supply wells that were hand dug into suprabasalt sediments along the Columbia River by turn-of-the-century homesteaders. The earliest recorded boreholes into basalt include approximately seven water-supply wells that were drilled between 1918 and 1927, all to depths of less than approximately 300 m (1,000 ft). The boreholes nearest the reference repository location include the Brown, Enyeart, Ford, O'Brian, Lemcke, and McGee Cold Creek artesian wells 5 to 10 km (3 to 6 mi) northwest of the reference repository location, and the Haynes well, a 295-m- (970-ft-) deep well located approximately 7 km (4 mi) to the northeast (see Fig. 1.6-2). A series of about nine army water-supply wells were drilled on the Hanford Site north of the Columbia River in 1952 and 1953. The deepest was 426-m (1,396-ft) deep into Wanapum Basalt. A borehole drilled in 1977 to a depth of 599 m (1,964 ft) into lower Wanapum Basalt is located about 25 km (15 mi) southeast of the reference repository location (see Fig. 1.6-2) and provides an emergency water supply at the Fast Flux Test Facility. Wells drilled into Saddle Mountains Basalt were used for water supply during nuclear power reactor construction by the Washington Public Power Supply System.

Several of these boreholes, both on and off the Hanford Site, are routinely sampled and monitored (Section 3.6). Groundwater-bearing geologic units that have been penetrated by water-supply boreholes include unconfined to semiconfined aquifers in the Hanford and Ringold Formations, and confined aquifers in the basalt section that consists mostly of interbeds (Ellensburg

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Formation) and interflow contacts (Saddle Mountains and Wanapum Basalts; see Section 3.8). No known water-supply well within the Hanford Site penetrates Grande Ronde Basalt.

1.6.1.1.2 Oil-gas exploration and production

Resource exploration and production boreholes include wells drilled into basalt between 1917 and 1931 in a small gas field located on the northern limb of Rattlesnake Mountain, approximately 10 km (6 mi) south of the reference repository location (see Section 1.7 and Fig. 1.3-12 for location of Rattlesnake Mountain). Hammer (1934) and McFarland (1979) discuss this gas field and the 26 boreholes associated with it. Only seven of these boreholes were drilled deeper than approximately 300 m (1,000 ft), the deepest being Walla Walla No. 6 (see WW-6, Fig. 1.6-2), which was drilled to a depth of 1,116 m (3,660 ft). The original driller's log (Hammer, 1934) and geologic cross sections and interpretations (Moak, 1981, Table A-2) indicate that Walla Walla No. 6 penetrated into Grande Ronde Basalt, probably as deep as the Umtanum flow. The next deepest hole is the Seattle Inland Oil Goodwin No. 1, which is 670-m (2,200-ft) deep, and probably penetrates to a depth near the Rocky Coulee flow. An oil-gas exploration borehole, the Benson Ranch Well, is located 2.5 km (1.6 mi) south of the reference repository location (see Fig. 1.6-2). It was drilled in 1929 to a depth of 610 m (2,000 ft) and penetrates rock units that are stratigraphically equivalent to the lower Wanapum Basalt.

The only oil-gas exploration well that has been drilled since 1942 near the reference repository location is Rattlesnake Hills Well No. 1, which is located approximately 13 km (8 mi) southwest of the reference repository location near the crest of Rattlesnake Mountain (see Fig. 1.3-12 and 1.6-2).

The well was drilled between 1956 and 1957 to a depth of 3,248 m (10,655 ft) (Raymond and Tillson, 1968) into lower Grande Ronde Basalt (Reidel et al., 1981). The final depth was 2,383 m (7,820 ft) below the Umtanum flow. Other more recently drilled resource investigation boreholes in the vicinity of the Pasco Basin, including the BN 1-9 Saddle Mountains Well, are discussed in Section 1.7.2.2.

1.6.1.1.3 Surveillance and waste management

Approximately 2,000 boreholes were drilled in conjunction with the production and reprocessing of nuclear materials at the Hanford Site. These include dry wells to characterize and monitor waste-disposal facilities, emergency water-supply wells, and deeper boreholes to monitor potential groundwater contamination. The majority of these boreholes end within sediments overlying basalt, although about 450 penetrate the top of basalt (Fecht et al., 1986). More than half are located within the 200 East and

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200 West Separations Areas of the Hanford Site (McGhan et al., 1985). Included are 29 boreholes drilled for the purpose of characterization and surveillance of confined aquifers in the Saddle Mountains Basalt. Fifteen of these are core holes (prefaced by DB in Fig. 1.6-2) that average approximately 300 m (1,000 ft) in depth and generally penetrate into or through the Mabton interbed that separates the Saddle Mountains and Wanapum Basalts (Moak, 1981, pp. A-7 through A-9; Crowley and Ledgerwood, 1987); another series of 14 boreholes is discussed in Graham et al. (1984).

1.6.1.1.4 Nuclear powerplant siting

Two series of boreholes were drilled to support the siting and construction of nuclear powerplants at the Hanford Site. These boreholes include about 100 core and rotary boreholes drilled since 1968 by the Washington Public Power Supply System (WPPSS, 1981) and an additional 175 boreholes drilled by Northwest Energy Services Company (PSPL, 1982). Of these boreholes, only 42 penetrate into or through the uppermost confined aquifer (i.e., the Rattlesnake Ridge interbed).

1.6.1.1.5 Repository feasibility and siting

The first boreholes drilled as part of assessing the feasibility of a nuclear waste repository in basalt were drilled between 1969 and 1973. Data from five core holes (DDH-1, DDH-3, DH-2, DH-4, and DH-5) and one rotary borehole (ARH DC-1) (Fig. 1.6-2 and 1.6-4) were used to establish a stratigraphic framework for the basalt underlying the Hanford Site and to identify potential repository host-rock horizons (Isaacson, 1968, pp. 1-5; Myers, 1973, pp. 96-115; Myers and Brown, 1973; ARHCO, 1976). Two core holes, DC-10 and DC-11, were drilled during siting of the Near-Surface Test Facility.

Between 1977 and 1982, additional boreholes (ranging from 550- to 1,525-m (1,800- to 5,000-ft) deep) were drilled within the Hanford Site to further evaluate geohydrologic properties of potential repository host rock and to support site identification. Eight core holes (DC-2, DC-4, DC-6, DC-8, DC-12, DC-14, DC-15, and DC-16A (see Fig. 1.6-2 and 1.6-4)) and two rotary boreholes (DC-5 and DC-7) were drilled to depths below the Umtanum flow, which was at that time the deepest horizon being considered for a repository (Long and WCC, 1984). Rotary borehole DC-7 was later deepened 275 m (900 ft) by continuous coring into lower Grande Ronde Basalt. Two rotary boreholes (DC-3 and DC-16C) (see Fig. 1.6-2 and 1.6-4) were also drilled to penetrate into the Umtanum flow; continuous coring was later used to advance these boreholes to depths below the Umtanum flow. One existing water-supply borehole, the McGee well, was also deepened through the Umtanum flow by continuous coring. Core hole DC-18 is being drilled at a location between Gable Mountain and Gable Butte (see Fig. 1.6-2) to a planned depth of approximately 1,070 m (3,500 ft) for tectonic and hydrochemical investigations (see Sections 8.3.1.2.5 and 8.3.1.4.1).

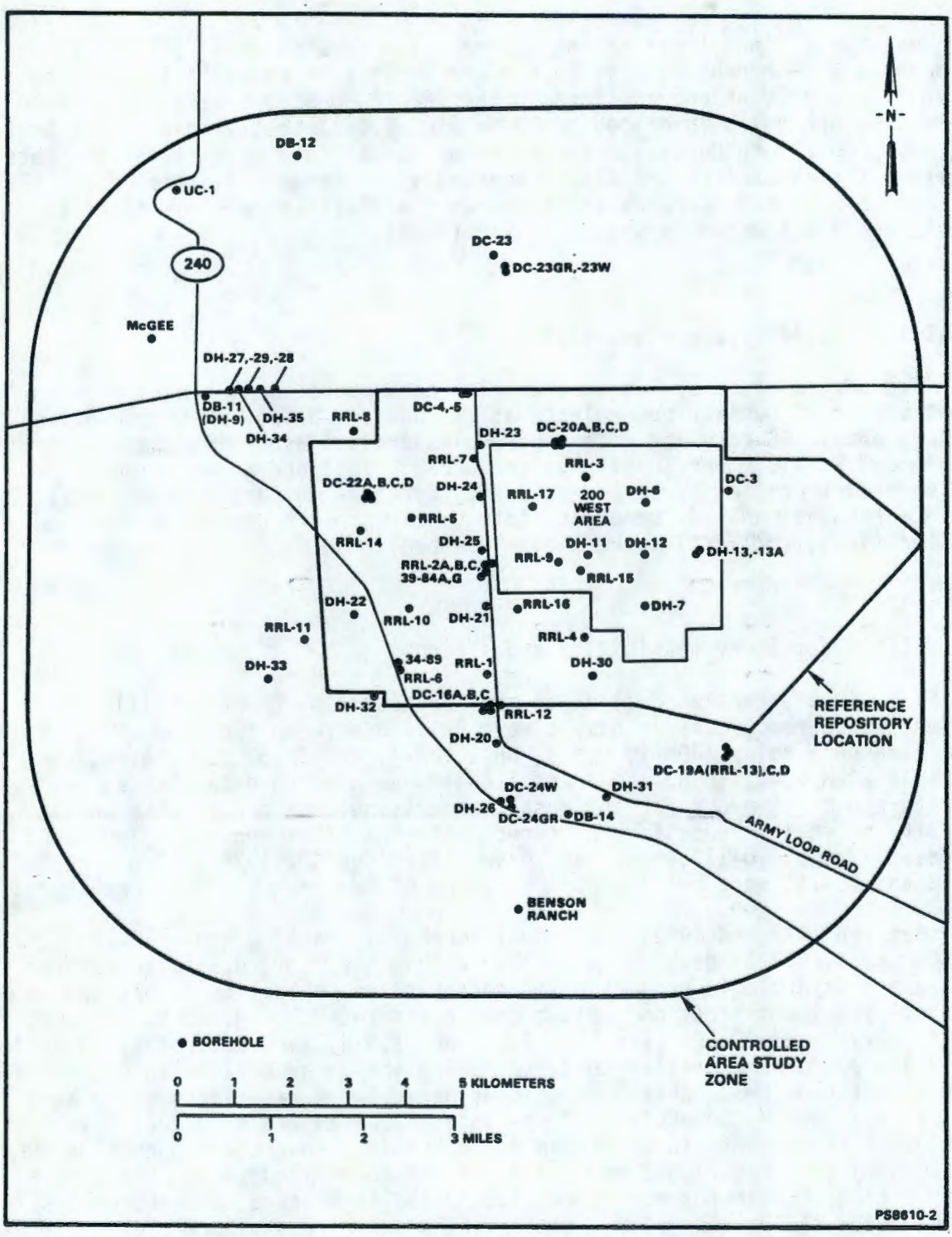

Figure 1.6-4. Location map for boreholes located within the reference repository location and controlled area study zone.

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With only four exceptions, all of the boreholes at the Hanford Site that penetrate the top of the Saddle Mountains Basalt have been vertical boreholes (see Fig. 1.6-1). The exceptions are two slant core holes (DC-2-A1 and DC-2-A2) that were drilled from borehole DC-2 through the Umtanum flow at angles of approximately 25° from vertical; a shallow borehole (DC-10) approximately 140-m (450-ft) deep, drilled at an angle of approximately 27° on Gable Mountain; and one side-tracked core hole (DC-16C-A1), drilled at a slight angle from the vertical (less than a 5° deviation) to extend borehole DC-16C to a depth below the Umtanum flow. Of the repository feasibility and siting boreholes drilled to date, two boreholes (DC-2 and DC-2-A1) are no longer accessible because they were partially backfilled with cement grout to allow slant-hole drilling.

Twenty DH-series core holes (see Fig. 1.6-2 and 1.6-4) were drilled primarily to develop the subsurface stratigraphy of the Ringold Formation. The results of analyses of samples from this suprabasalt sedimentary sequence are discussed in Tallman et al. (1981) and Bjornstad (1984) and are summarized in Section 1.2.2.2. Two additional DH-series core holes (DH-27 and DH-28) were drilled into the top of basalt to assess tectonic deformation across the Yakima Barricade geophysical anomaly (see Section 1.3.2.2.1). At least six additional DH boreholes (DH-30 through DH-35; see Fig. 1.6-4) are planned to further define tectonic features within the reference repository location (Section 8.3.1.2.5).

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1.6.1.1.6 Injection

No known boreholes into basalt within the Hanford Site were used for waste injection, aquifer recharge, or gas reservoir stimulation. Some wells above the vadose zone have been used for defense waste management at the Hanford Site (ERDA, 1975, pp. II-1-C-12 and C-16).

1.6.1.2 Boreholes within or near the reference repository location

Approximately 41 boreholes that penetrate basalt have been drilled within or adjacent to the reference repository location (see Fig. 1.6-4). A number of boreholes drilled since 1982 are specifically for hydrologic testing and installation of piezometers or pumps, as part of geohydrologic investigations of the site (DC-16B, DC-16C, DC-19A, DC-19C, DC-19D, DC-20A, DC-20B, DC-20C, DC-20D, DC-22A, DC-22B, DC-22C, and DC-22D). Also shown in Figure 1.6-4 are the locations of most of the DH-series core holes drilled to near the top of basalt to characterize the suprabasalt stratigraphy (Bjornstad, 1984). Detailed maps of the nearly 200 shallow-surveillance boreholes located in the 200 West Area are presented in McGhan et al. (1985) and Tallman et al. (1979, Plate 2); therefore, the locations of these boreholes are not included in Figure 1.6-4. Other boreholes not included on Figure 1.6-4 are 18 pre-BWIP groundwater-monitoring boreholes within the area that is now the reference

repository location. These boreholes were drilled to or above the top of basalt. Driller's logs and locations of these borings are presented in Fecht and Lillie (1982).

Only 17 boreholes in the reference repository location extend below the top of basalt and penetrate the upper confined aquifer system (Rattlesnake Ridge interbed) within the Saddle Mountains Basalt. All other boreholes in the reference repository location end within the suprabasalt sediments or within the uppermost basalt flow.

Eight boreholes within the reference repository location boreholes (RRL-3, RRL-4, RRL-5, RRL-7, RRL-8, RRL-9, RRL-10, and RRL-16) were designed and constructed solely to obtain geologic data and (or) provide access holes for the installation of a shallow seismic array (see Section 1.4). All of these boreholes penetrate the uppermost Saddle Mountains Basalt; boreholes RRL-3, RRL-4, and RRL-5 bottom within the Saddle Mountains Basalt. Other RRL-series boreholes include boreholes RRL-2, RRL-6, and RRL-14, which were drilled through the Umtanum flow; boreholes RRL-17, which was drilled through the Cohassett flow; and boreholes RRL-11, RRL-12, and RRL-13 (borehole RRL-13 was subsequently deepened as borehole DC-19a), which end within the suprabasalt sediments. Borehole RRL-2, termed the "principal borehole" was used as the design hole for the exploratory shaft. A starter hole for the exploratory shaft, located approximately 100 m (330 ft) southwest of borehole RRL-2 (see Fig. 1.6-3) was drilled through sediments to a depth of approximately 30 m (100 ft).

Locations of the six series of existing and planned piezometric monitoring and large-scale test holes RRL-2B and RRL-2C were shown in Figure 1.6-4. The piezometric monitoring network boreholes were drilled or are planned at borehole sites DC-19 (DC-19A, DC-19B, and DC-19C), DC-20 (DC-20A, DC-20B, DC-20C, and DC-20D), DC-22 (DC-22A, DC-22B, DC-22C, and DC-22D), DC-23 (DC-23W and DC-23GR), DC-24 (DC-24CX), and DC-25 (DC-25CX). Boreholes DC-19C, DC-20C, DC-22C, and DC-23GR penetrate into or through the Umtanum flow. Borehole DC-23W ends in the first Grande Ronde Basalt flow; boreholes DC-24CX and DC-25CX are planned but not yet drilled.

1.6.2 MINING

The only subsurface excavations within the vicinity of the reference repository location are the Near-Surface Test Facility and the 213 Storage Tunnel both located on Gable Mountain. A discussion of the Near-Surface Test Facility is contained in Chapter 2 (see Section 2.0.2 and Fig. 2.0-1). The 213 Storage Tunnel was a storage facility excavated in sediments on the south side of Gable Mountain. The facility has been decontaminated and decommissioned (ERDA, 1975, p. II.1-26). Several quarries exist in surface exposures of basalt and gravel; some are still actively used (Section 1.7.1).

1.6.3 CURRENT STATUS OF DRILLING AND MINING

No subsurface penetrations, other than boreholes, the Near-Surface Test Facility, and the 213 Storage Tunnel exist within 10 km (6 mi) of the reference repository location or within the controlled area study zone. The locations and status of boreholes within the Hanford Site reference repository location are well documented. Locations and status of water-supply wells outside the Hanford Site and within the Pasco Basin are generally known or traceable through drilling records, although not all such wells may have available records. None of the known offsite water-supply wells within the Pasco Basin penetrate to depths of the Cohassett flow.

Certain records used as references, such as drillers' logs from as long as 60 yr ago, are of indeterminate quality but are used as they are the only records available. No attempt has been made to establish or evaluate the validity of those records beyond that contained in individual cited references.

All boreholes within the reference repository location and the controlled area study zone that penetrate the Grande Ronde Basalt and the Cohassett flow contain grouted-in piezometers or removable bridge plugs to prevent aquifer interconnection or crossflow (Swanson and Leventhal, 1984; Jackson et al., 1984). No boreholes within the reference repository location or the controlled area study zone that penetrate the basalts were abandoned or plugged back to the surface. Outside the reference repository location, aquifer interconnection and potential crossflow may be possible in two deep boreholes (RSH-1 and WW-6) in the Grande Ronde Basalt and is discussed in Chapter 3.

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1.7 MINERAL AND HYDROCARBON RESOURCES

This section describes the known and potential mineral, hydrocarbon, and geothermal resources of the site and region. Information on these natural resources will be used to determine the potential for future exploration and development activities that could affect waste containment and isolation at the reference repository site. A description of the possibility for future development of resources is part of the site-selection process required by 10 CFR 960.4-2-8 (DOE, 1987b). Predicting future development will be done during site characterization (Section 8.3.1.6). For the following discussion, resources are defined as naturally occurring materials (1) for which economic extraction is potentially feasible during the foreseeable future or (2) that have greater than average value for other analog areas of similar size that are representative of the same geologic setting.

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Background information

Resource exploration and evaluation has not occurred on the Hanford Site since the early 1940's, when the site was closed to all resource exploration. During the 1930's, a small gas field was developed on the north flank of Rattlesnake Mountain (southwest boundary area of the Hanford Site). The field was abandoned during the early 1940's. Otherwise, the only mineral production on the Hanford Site consisted of crushed rock products from basalt quarries and products from sand and gravel deposits.

Mineral deposits known to occur within the Columbia Plateau consist of low-unit-value minerals and rock products (e.g., diatomite, pumice sand and gravel, and quarry stone). Low-grade placer deposits of gold (Blalock Island on the Columbia River) are the only known mineral deposits that have potential for high unit value. The discovery of high-grade gold deposits near Wenatchee (approximately 81 km (50 mi) northwest of the Hanford Site) in 1984 by Asmera Inc., and Breakwater Resources Ltd., will not impact Columbia Plateau mineral resources because the deposits are localized in prebasalt siliceous intrusives. Subbituminous coal deposits were mined in the Roslyn Formation near Cle Elum and Rosyln (approximately 97 km (60 mi) northeast of the Hanford Site) during the 1930's and 1940's and were abandoned by the late 1940's. The presence of potential commercial grade coal in prebasalt beds of the Roslyn Formation, thin coal beds in the Swauk Formation, and low-grade coal in the Chumstick Formation will not impact the repository as a potential resource because, if present, they would underlie the Columbia River Basalt Group at great depth. No commercial coal production has been reported in the Columbia Basin. Present information from wells and borings that have penetrated the Ellensburg suprabasalt section and basalt interbeds indicates that (1) the beds are too thin or impure or the (2) coal rank is too low to be considered for potential development. However, the presence of coal beds and organic matter in the sub-basalt sediments indicates a potential for generation of hydrocarbons deep in the Columbia Basin.

During the late 1920's and 1930's exploration for oil and gas occurred throughout the Columbia Basin. The Rattlesnake Gas Field on the southwest border of the Hanford Site, now abandoned, was discovered during this period

(Section 1.7.1.2). Renewed interest in exploration for oil and gas in the Columbia Plateau began in the 1950's when several major oil companies conducted geologic and geophysical surveys. These activities resulted in the leasing of several hundred thousand acres of Federal land and the drilling of two deep exploratory wells:

1. The Standard Oil Company Rattlesnake Hills No. 1 in Benton County, Washington--total depth of 3,247 m (10,655 ft).

2. The Kirkpatrick No. 1 in Morrow County, Oregon--total depth of 2,660 m (8,726 ft).

The cost of drilling deep exploration wells in the Columbia Basin for sub-basalt objectives made exploration uneconomical at the late 1950's prices of $2.00/barrel for crude oil and $0.10/28.3 m^3 (1,000 ft^3) for natural gas. From 1980 to the present, Shell Oil Company has drilled four deep exploration wells in the Yakima Fold Belt. These wells have logged significant, but noncommercial, gas shows. The activity set off a major leasing program for major oil companies and independents. More than 4,047,000 ha (10 million acres) of lands in the Columbia Basin were leased during this period. Results of the Shell Oil Company exploration wells are discussed in Section 1.7.2.2.

An evaluation was made by Geosciences Group and George Leaming Associates (GG/GLA, 1981) on the occurrence and production value of known mineral resources for the region within a 100 km (62 mi) radius of the Hanford Site for data available prior to 1981. Information on mineral resources is presented in Section 1.7.1.

The geothermal resource potential of the Columbia Basin is described by Bloomquist (1985). The potential of the Pasco Basin is described by Murphy and Johnpeer (1981; Section 1.3.2.6.2.4). Information on geothermal resources of the Pasco Basin is summarized in Section 1.7.3.

Surface water and groundwater resources of the Pasco Basin and vicinity are discussed in Chapter 3, Sections 3.3, 3.8, and 3.9.7. Water is used primarily for irrigation and industry, with a small percentage devoted to municipal and domestic purposes. Surface water currently supplies over 90% of the total water demand in the Pasco Basin. Groundwater withdrawals are significant in some areas (e.g., upper Cold Creek Valley). Demand for both surface water and groundwater is likely to increase in the future, and the projected magnitude of this increase must be evaluated as part of the site characterization. Plans to evaluate the water resource studies are described in Section 8.3.1.6.

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1.7.1 MINERAL RESOURCES

1.7.1.1 Existing resource evaluation

The resource evaluation of known mineral occurrences conducted by GG/GLA (1981) for the Hanford Site contained a compilation of current and past resource production data and a projection of these data to the year 2009. The area within 100 km (62 mi) of the repository site was chosen to provide a more representative basis for evaluation than could be provided by considering only the Hanford Site. These data are shown in Figure 1.7-1. The remainder of the Columbia Basin was studied more generally. For the economic evaluation, a 25-yr projection was considered to be the maximum foreseeable forecast period.

The GG/GLA (1981) used data from other areas in the Columbia Basin for production estimates that could be reasonably expected from potential but as yet undiscovered resources in the immediate vicinity of the repository site. Economic evaluation was confined to resources known to exist, or whose occurrence is geologically feasible, in potentially commercial quantities. These commodities are clay, diatomaceous earth, gold, peat, perlite, pumice, saline compounds, and sand and gravel.

No attempt was made to compare the mineral resources of the repository site with other areas of similar size and geology within the Columbia Plateau. Plans to address these analog comparisons will be presented in Section 8.3.1.6.

Assessment of occurrence and development potential of uranium mineralization within the Pasco Basin and vicinity by GG/GLA (1981) focused on the interbeds of the Ellensburg Formation and the sedimentary sequence beneath the basalts. The report indicates that by analogy, the potential for sub-basalt uranium mineralization is probably not substantial. In addition, development potential to depths of greater than 3,000 m (9,800 ft) for potential occurrences beneath the basalts would not be considered. The basalt interbeds of the Ellensburg Formation may have a small potential for uranium mineralization within the Pasco Basin and vicinity (Milne, 1979; GG/GLA, 1981).

Results of the National Uranium Resource Evaluation Program for the Ritzville Quadrangle of Washington (Fleshman and Dodd, 1982, pp. 51-58) indicate that the suprabasalt Ringold Formation is considered unfavorable as a uranium resource. The Columbia River Basalts are considered deficient in uranium and are a poor source, as well as a poor host, for uranium deposits. Additional information about the basalt interbeds is required before an area can be designated favorable or the environment dismissed as being unfavorable.

The GG/GLA (1981) report, based on the absence of significant known occurrences of base and precious metals from Columbia River basalts and interbeds, indicates mineralization occurrence and development potential within a 100-km (62 mi) radius of the Hanford Site is negligible. Although

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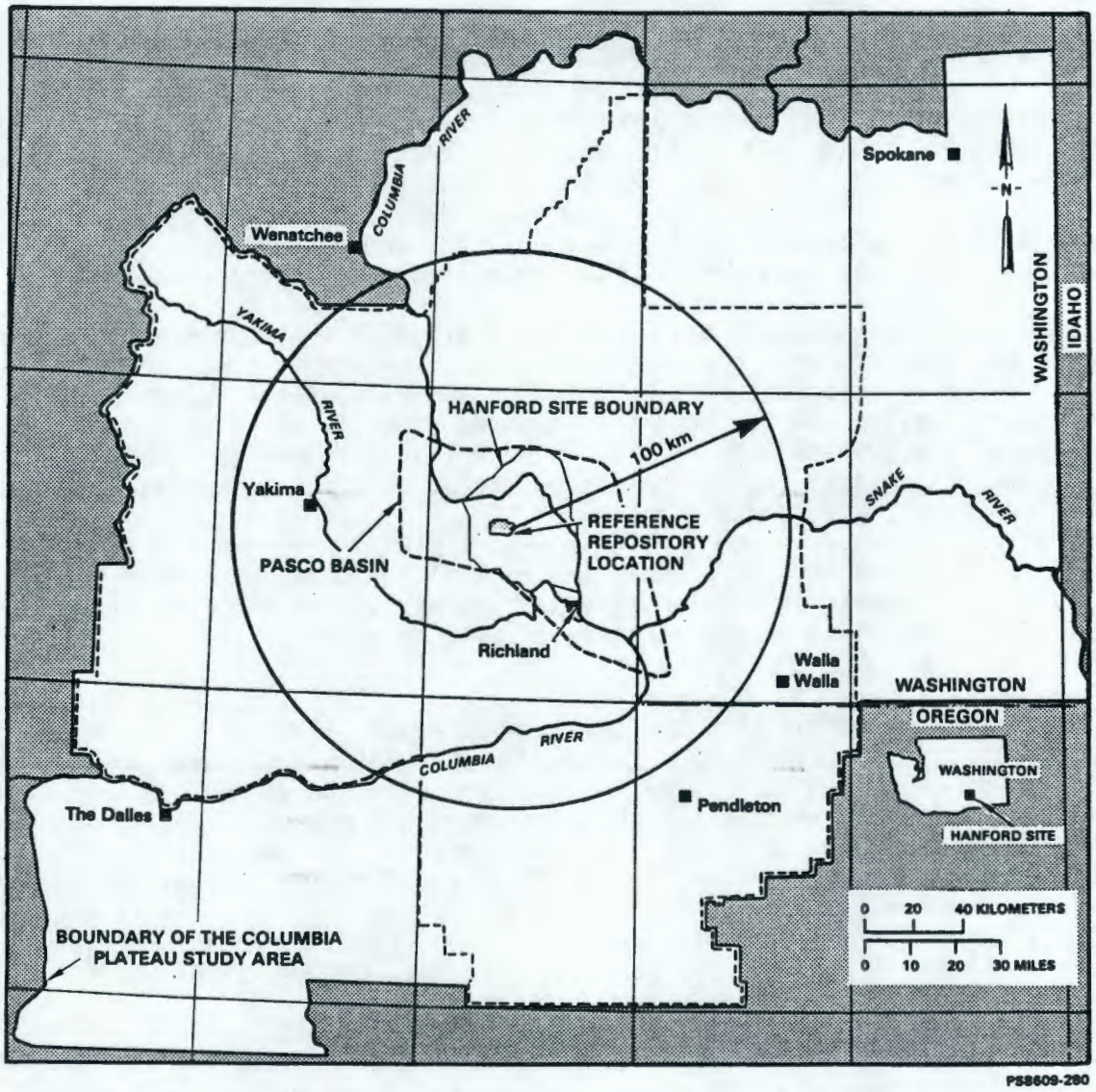

Figure 1.7-1. Location map for resource analysis conducted by the Basalt Waste Isolation Project and George Leaming Associates (from GG/GLA, 1981).

mineralization occurrence potential in lithologies beneath the basalt is not known, the potential for development of possible mineralization in the sub-basalt section is judged to be negligible because of the considerable depth of the basalt.

1.7.1.2 Resources in the vicinity of the site

Mineral resources known to exist within 100 km (62 mi) of the repository site are summarized in Table 1.7-1. Current mining activity within this area is limited to surface extraction of diatomaceous earth, sand and gravel, and stone. Other relatively low unit value minerals, including peat, pumicite, and quarry rock, also occur within 100 km (62 mi) of the repository site. These are surficial deposits and are not concentrated within the Pasco Basin relative to the remainder of the Columbia Basin. With the exception of small, low-grade, gold placers along the Columbia River (at Blalock Island, located 68 km (42 mi) south of the candidate site), no high unit value mineral resources are known to occur within 100 km (62 mi) of the repository site.

1.7.1.3 Impact of a waste repository on potential resource production

The GG/GLA (1981) report determined that current mining activity, or activity that can be reasonably expected during the next 25 yr, within 100 km (62 mi) of the repository site location would not be affected by a nuclear waste repository located at the proposed depth of approximately 1,000 m (3,000 ft). To date, the geologic setting of the repository site has not been attractive for subsurface mineral exploration and development. However, because the value of a resource can fluctuate, a reevaluation of these potential mineral resources is planned (Section 8.3.1.6.3.3.1).

1.7.2 HYDROCARBON RESOURCES

This section summarizes the results of hydrocarbon exploration within the Columbia Basin. Columbia Basin, as used here, refers to the thick sequence of Miocene basalt flows and interbeds whose center is near the community of Prosser, Washington. Geophysical data indicate a basalt section of over 5 km (3 mi) in thickness and a possible 7 km (4 mi) sediment section beneath the basalt near Yakima, Washington (Section 1.3, Fig. 1.3-41 and 1.3-42). Although commercial production has not been established, the results of recent deep exploration wells drilled by the Shell Oil Company indicate possible commercial hydrocarbon potential within and beneath the Columbia River Basalt Group. Exploratory interest is currently focused on the large basalt anticlinal ridges with the sub-basalt sedimentary section as the primary reservoir objective. Basalt structures in areas of more subdued topography to the east of the Hanford Site are also being explored.

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Table 1.7-1. Mineral resources within 100 km (62 mi) of the reference repository location (sheet 1 of 2)

Commodity	Location(s)	Description
	Energy	
Lignite	Interbeds in borehole RSH-1	Ellensburg Formation interbeds. Maximum rank-lignite. Beds less than 0.7 m (2.3 ft) thick at depths in excess of 1,000 m (3,281 ft) and therefore not exploitable with current or foreseeable technology. No past exploitation.
Peat	Crab Lake, near Ephrata, Washington	As much as 21 x 10^6 m^3 (7.4 x 10^8 ft^3) of relatively poor quality. No past exploitation.
Natural gas	Rattlesnake Hills gas field, central Benton County. Numerous shows of gas in water wells and oil and gas exploration wells in basalt. Shows of gas with distillate in deep sub-basalt exploration wells.	Rattlesnake Hills field discovered in 1913; in commercial production from 1929-1941. The field yielded 37 x 10^6 m^3 (1.3 x 10^9 ft^3) of low-pressure, high-methane gas. Isotopic analyses of methane from nearby water wells suggest that the gas originated from organic matter trapped in volcaniclastic sediments interbedded with Columbia River Basalt Group flows. No associated oil reported. Assessment of oil and gas potential of sediments postulated to underlie the Columbia Plateau flood basalts requires their penetration by drilling. No current commercial production from Columbia Plateau. Potential undiscovered resources in immediate vicinity study area estimated at three times that produced in the past from within the Columbia River Basalt Group.
Geothermal	City of Yakima	One low-temperature (35 °C) artesian well used for recreational purposes. No production for purposes of energy use.
	City of Ephrata	Low-temperature resources being explored for space heating.
	Metallic minerals	
Gold	Placer deposits along the Columbia River. Mouth of Artesian Coulee, Berrian Island, and Blalock Island, Benton County; north of Vantage and east of Priest Rapids, Grant County.	Only place of potential commercial interest is Blalock Island. Estimated as 10.2 x 10^6 m^3 (13.3 x 10^6 yd^3) of sand and gravel containing 0.00127 oz. gold/m^3 (0.00167 oz. gold/yd^3).

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Table 1.7-1. Mineral resources within 100 km (62 mi) of the reference repository location (sheet 2 of 2)

Commodity	Location(s)	Description
Industrial rocks and minerals		
Clays		Small, scattered occurrences sporadically worked in the past. No current production.
Diatomaceous earth	Mostly in Grant County. Scattered occurrences in Yakima, Kittitas, Klickitat, Adams, and Benton Counties.	Currently mined in Grant County by Witco Chemical Company, at a rate of approximately 60,000 short tons/yr from shallow surface pits. Small, scattered occurrences elsewhere not currently being worked.
Mineral waters	Moses Lake and Soap Lake, Grant County.	Lakes containing dilute sodium sulfate, sodium chloride, and carbonates of sodium, magnesium, and calcium. No past production. Recreational use only.
Perlite, pumice, pumicite	Near Beverly, Grant County. Near Roza, southeast Kittitas County, and Hanford Site, Benton County.	Scattered, sporadic past production. No current use.
Sand, gravel, and stone	Near urbanized areas adjacent to river beds.	From 1977 through 1979, production has averaged 3.2 x 10^6 short tons/yr.

Source: Modified from Leaming and Davis (1983, p. 7).

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Currently, there is no production of natural gas in Washington State. The nearest gas production is from Eocene marine sediments at the Mist Gas Field, located in northwest Oregon, 325 km (200 mi) southwest of the repository site.

Subcommercial oil production was established on the Washington State coast at Ocean City Field, Grays Harbor County, from marine Oligocene and Miocene rocks in 1954. From 1954 to 1964 one well produced 12,000 barrels of high-gravity oil. The Ocean City area is 515 km (230 mi) northwest of the Hanford Site.

1.7.2.1 Hydrocarbon exploration within the Columbia River Basalt Group

The search for hydrocarbons in the Columbia River basalts during the past 70 yr has involved a number of companies and has included exploration over a wide area of the Columbia Basin. Table 1.7-2 describes the exploration wells drilled to date in the Columbia Basin.

Reports on hydrocarbon resources and the potential for hydrocarbon production in the Columbia Basin have been published by Felts (1954), Deacon and Benson (1971), McFarland (1983), Campbell (1985), Petroleum Information Corporation (1985), Fritts and Fisk (1985a, 1985b), and Lingley and Walsh (1986). The Rattlesnake Gas Field is discussed in publications by Shedd (1925), Hammer (1934), Glover (1936), and McFarland (1983). None of these reports, however, provides an economic assessment of the hydrocarbon resources of the Columbia Basin.

In 1913, natural gas was discovered in basalts on the northern flank of Rattlesnake Mountain 19 km (12 mi) south of the repository site. The Rattlesnake Hills Gas Field (Fig. 1.7-2) covers an area of about 30 km^2 (12 mi^2). The field had a 12-yr cumulative production of 39 x 10^6 m^3 (1.4 x 10^9 ft^3) from 16 wells of methane gas with varying amounts of nitrogen. The Btu values were generally 1,000 Btu or greater. Analyses of the gas composition and Btu content from 20 wells in the field are presented in Table 1.7-3.

Discussions of the Rattlesnake Gas Field and the 26 wells associated with it are presented in Hammer (1934, pp. 846-859), Glover (1936, pp. 10-14), Shedd (1925, pp. 110-125), and McFarland (1983, pp. 3-4). Gas production from the field began in 1929 and ceased in 1941. The production zone, which ranged in depth (below ground surface) from 215 m (705 ft) to 370 m (1,213 ft), was a vesicular flow top, most likely the Priest Rapids Member of the Wanapum Basalt. The overlying Mabton interbed provided the seal. Hammer (1934) presented subsurface information that indicates that the gas field trap is a closure on the down thrown side of a fault. The source of the gas is unknown; it may have migrated laterally along interbeds in the basalt or upward from sub-basalt sedimentary rocks beneath the basalt. Studies designed to identify the source are presented in Section 8.3.1.6. Present geologic information is

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Table 1.7-2. Columbia Basin exploratory wells

Well no.[a]	Well name	Geologic structure	Total depth		Year drilled	Comments: reported oil/gas shows
			Meters	Feet		
	Shell Oil Company					
1[b]	Yakima Minerals Well No. 1-33	Selah Butte anticline	4,939	16,199	1980	Gas
1[b]	Yakima Minerals Well No. 2-33	Selah Butte anticline	1,007	6,600	1981	Gas
2[b,d]	Bissa No. 1-29	Whiskey Dick anticline	4,562	14,965	1982	Gas
3[b]	BN No. 1-9	Saddle Mountains anticline	5,341	17,518	1983	Gas (3.5 mcf/d)[c]
	Standard Oil Company					
4	Rattlesnake Unit No. 1	Rattlesnake Hills anticline	3,248	10,655	1958	Gas
5[b]	Kirkpatrick No. 1	Condon anticline	2,660	8,726	1956	No shows
	Snowbird Resources					
6	Moses Lake No. 1a	Unknown	2,128	6,979	1981	No shows
	Peoples Gas and Oil Development Co					
7	Donney Boy No. 1	Frenchman Hills anticline	1,394	4,575	1934	Gas
	Development Associates Inc.					
8[b,e]	Basalt Explorer No. 1	Unknown	1,427	4,682	1965	No shows
	Delta Gas and Oil Company Inc.					
9	Alt No. 1	Unknown	402	1,320	1960	No shows
	Norco First Drilling Company					
10[b]	Norco No. 1	Unknown	1,494	4,903	1933	Gas, oil
	Miocene Petroleum Company					
11	Union Gap	Ahtanum anticline	1,161	3,810	1929	Gas, oil
	Simco Oil Company					
12	Simco No. 1	Ahtanum anticline	841	2,760	1924	No shows
	Paul John Hunt					
13	Snipes No. 1	Snipes Ridge anticline	429	1,408	1944	Gas
	City of Mabton					
14	No. 1	Unknown	347	1,140	1922	Gas
	Columbia Hydrocarbon					
15	Moon No. 1	Unknown	501	1,645	1982	Gas
	Blue Light Gas and Oil Company					
16	Alder Creek No. 1	Unknown	471	1,545	?	Gas
	Scott Drilling Company					
17	Benson Ranch	Benson Ranch syncline	610	2,000	1929	Oil
18	Rattlesnake Hills gas field - discovery well Conservative Land and Development Co. Walla Walla No. 1	Rattlesnake Hills anticline	376	1,234	1913	Gas (500 mcf/d)[c]

[a]See Figure 1.7-2 for well location maps.
[b]Well penetrated sub-basalt sediments.
[c]mcf/d (thousand cubic feet/day) = 28.32 m^3/d.
[d]Bottomed in probable basement.
[e]Bottomed in granite basement

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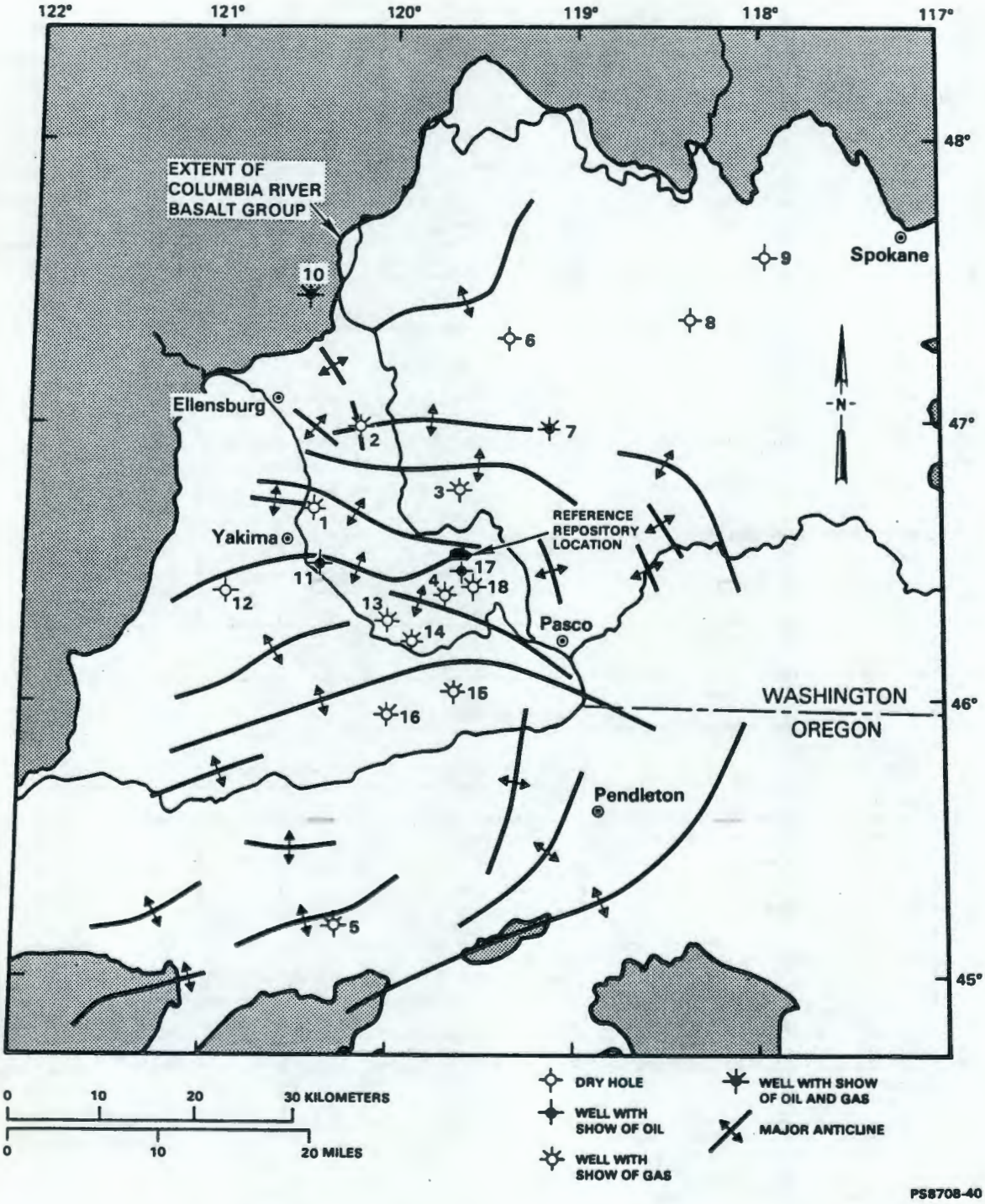

Figure 1.7-2. Location map for Columbia Basin wells. Structures modified from Tolan (1986). (See Table 1.7-2 for further descriptions of numbered wells.)

Table 1.7-3. Analyses of gas from the Rattlesnake Hills gas field (GG/GLA, 1981)

Well number	Analyzed or reported by	Methane	Ethane	Oxygen	Nitrogen	Carbon dioxide	Specific gravity	Btu
Walla Walla 2	U.S. Bureau of Mines[a]	71.12	0.00	5.35	23.05	0.48	--	--
Walla Walla 2	U.S. Bureau of Mines[a]	87.9	0.00	2.40	9.40	0.30	--	--
Yellowhawk 1	U.S. Bureau of Mines[a]	44.7	0.00	11.2	44.1	0.00	--	--
Well No. 2	U.S. Bureau of Mines[a]	93.0	0 00	0 70	6.00	0.30	--	--
Well No. 5	U.S. Bureau of Mines[a]	70.9	0.00	4.30	24.60	0.20	--	--
Well No. 6	U.S. Bureau of Mines[a]	94.9	0 0	0.30	4.80	0.00	--	--
Well No. 8	U.S. Bureau of Mines[a]	87.7	0.00	4.60	7.60	0.10	--	--
Walla Walla 7	U.S. Bureau of Mines[a]	44 1	0.00	11.90	43.90	0.10	--	--
Walla Walla 8	U.S. Bureau of Mines[a]	30.8	0.00	14.7	54.4	0.10	--	--
No name	Bessemer Gas Engine Co[b]	76.70	12.00	0.40	--	0.00	0.560	--
No name	University of Oregon[c]	--	--	--	68.5	--	--	--
Well No. 1	Pacific Power and Light	98.75	--	--	1.25	--	0.560	996
Big Bend 2	Pacific Power and Light	99.34	--	--	0.66	--	0.558	1,002
Big Bend 1	Pacific Power and Light	99.35	--	--	0.65	--	0.558	1,002
Well No. 2	Pacific Power and Light	99.35	--	--	0.65	--	0.558	1,002
Well No. 5	Pacific Power and Light	99.36	--	--	0.64	--	0.558	1,002
Well No. 6	Pacific Power and Light	99.35	--	--	0.65	--	0.558	1,002
Well No. 7	Pacific Power and Light	99.34	--	--	0.66	--	0.558	1,002
Well No. 8	Pacific Power and Light	95.57	--	--	4.63	--	0.573	914
Composite sample from Grandview pipeline	Pacific Power and Light	99.35	--	--	0.65	--	0.550	1,002
No name	Hammer (1934)	97.25	0.00	0.15	2.45	0.15	--	--

[a]Cryogenic laboratory, Amarillo, Texas.
[b]This analysis gave also: propane 7.20% and butane 3.80%.
[c]This analysis gave also: saturated hydrocarbons 17.50% and hydrogen 14%.

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not sufficient to determine whether the gas field was developed to its maximum potential. Proposed geologic studies to evaluate the Rattlesnake Gas Field are described in Section 8.3.1.6.

A number of shallow to moderate depth hydrocarbon exploration wells have been drilled in the Columbia Basin (see Fig. 1.7-2 and Table 1.7-2). In 1929, Miocene Petroleum Company's Union Gap well was drilled to a depth of 1,192 m (3,910 ft) and bottomed in basalt. The well encountered gas and tarry oil shows in the basalt section (McFarland, 1983). In 1934, Donny Boy No. 1, located near the east end of Frenchman Hills, had small shows of oil and gas (McFarland, 1983).

In 1957, Standard Oil Company of California drilled the Rattlesnake Hills Well No. 1 to a total depth of 3,247 m (10,655 ft) with no shows reported (McFarland, 1983). The well bottomed in lower Grande Ronde Basalt (Reidel et al., 1981, p. 1). Battelle (Raymond and Tillson, 1968) reopened the well in 1968 to conduct detailed logging, testing, and sampling of the basalt section for evaluation of radioactive waste storage.

Wireline logs run in Rattlesnake Hills Well No. 1 (RSH-1) included the dual induction laterolog, self potential, caliper, temperature, borehole compensated sonic, compensated formation density, sidewall neutron porosity, and variable density sonic waveform. Crossplot analysis of borehole compensated sonic, compensated formation density, and sidewall neutron porosity log data indicated a scattered relationship, not entirely related to borehole conditions, between porosities derived from these logging measurements. Offsets in the sidewall neutron porosity derived porosities observed in the borehole compensated sonic/sidewall neutron porosity and compensated formation density/sidewall neutron porosity crossplots indicate an incorrect matrix selection (limestone) used in calculating the sidewall neutron porosity. Raymond and Tillson (1968) concluded that porosity values from at least two logs should be in good agreement for quantitative analysis. It should be noted that these porosity analyses were not tied to porosity measurements on core obtained in RSH-1. In 1957, 1.7 m (5.5 ft) of core was recovered from the depth interval 2,464 to 2,469 m (8,084 to 8,100 ft). Descriptions of thin sections taken from this core are presented in Raymond and Tillson (1968).

Seven drill stem tests were run in separate zones between 580 and 2,560 m (1,900 and 8,400 ft) to determine the formation fluid hydrostatic pressures, measure formation permeability, and sample formation fluid. Permeabilities determined from drill stem test data ranged from 0.03 to 19.5 millidarcies, with only three zones exhibiting permeabilities greater than 1.0 millidarcies. Drill stem tests run in the intervals 979 to 1,002 m (3,213 to 3,289 ft) and 1,473 to 1,496 m (4,832 to 4,908 ft) flowed gas while the drill stem test tool was open, but no low rates or pressures were measured. Formation fluid obtained from the interval 1,804 to 1,828 m (5,921 to 5,997 ft) was analyzed and contained methane, but test data were not included in this report.

Porosity and permeability estimates may be made for the two intervals that showed gas using wireline log and drill stem test data. However, it is

not possible to estimate the volume of recoverable gas from these zones as the drill stem tests in these intervals did not measure flow rate or pressure of the gas produced during the test. Thus, data obtained in RSH-1 to date is not adequate to provide estimates of the volume of gas resources within this well. Further studies of the hydrocarbon potential of the basalt section will be conducted in site characterization plan investigations as described in Chapter 8.3.1.6 and the mineral, hydrocarbon, and geothermal resource study plan.

The Basalt Explorer No. 1, located north of the Hanford Site near Odessa, Washington, was drilled in 1960 to a total depth of approximately 1,425 m (4,680 ft). The well was a dry hole and reportedly (McFarland, 1983) penetrated approximately 61 m (200 ft) of continental sediments beneath the basalt and bottomed in granite.

A number of other hydrocarbon wells were drilled to depths ranging from 305 m (1,000 ft) to 915 m (3,000 ft). Several of the reported boreholes encountered shows of gas (McFarland, 1983; Fig. 1.7-2 and Table 1.7-2).

In the Oregon part of the Columbia Basin, the deepest well drilled was the Standard Oil Company of California Kirkpatrick No. 1 with a total depth of 2,660 m (8,726 ft). The borehole penetrated the Grande Ronde Basalt early Tertiary volcaniclastic sediments and bottomed in Cretaceous marine strata (Fox and Reidel, 1987). No significant gas or oil shows were reported. Other hydrocarbon wells have been drilled to depths of less than 305 m (1,000 ft), and no significant gas or oil shows were reported (see Fig. 1.7-2 and Table 1.7-2).

Based on the stratigraphic and structural occurrence of the gas produced from the Rattlesnake Gas Field, it is probable that other similar geologic conditions are present in the Columbia Plateau. Natural gas and possibly oil could be present in Columbia Plateau basalt flows in anticlinal and other structural traps containing permeable basalt reservoirs, sealing conditions, and migration paths for hydrocarbons sources from the sub-basalt sediments. Fold axes in the Pasco Basin are shown in Figure 1.7-3. The plans for assessing the hydrocarbon resource potential of the Columbia River Basalt Group and sub-basalt section are discussed in Section 8.3.1.6.3.3.1.2.

1.7.2.2 Hydrocarbon exploration in sub-basalt rocks

Since 1980, Shell Oil Company has drilled four deep exploration wells to the north and northwest of the Hanford Site. The wells penetrated the entire basalt section and partial sections of sub-basalt sediments and recovered natural gas in noncommercial quantities. Exploration is currently being conducted by five major oil companies in the Columbia Basin. Stratigraphic units penetrated by the Shell wells, according to Campbell (1987), can be correlated with sub-basalt sediments along the basalt margin to the northwest of the wells. Stratigraphic units exposed along the basalt margin are summarized by Campbell (1986; Fig. 1.7-4) and Gresens and Stewart (1981,

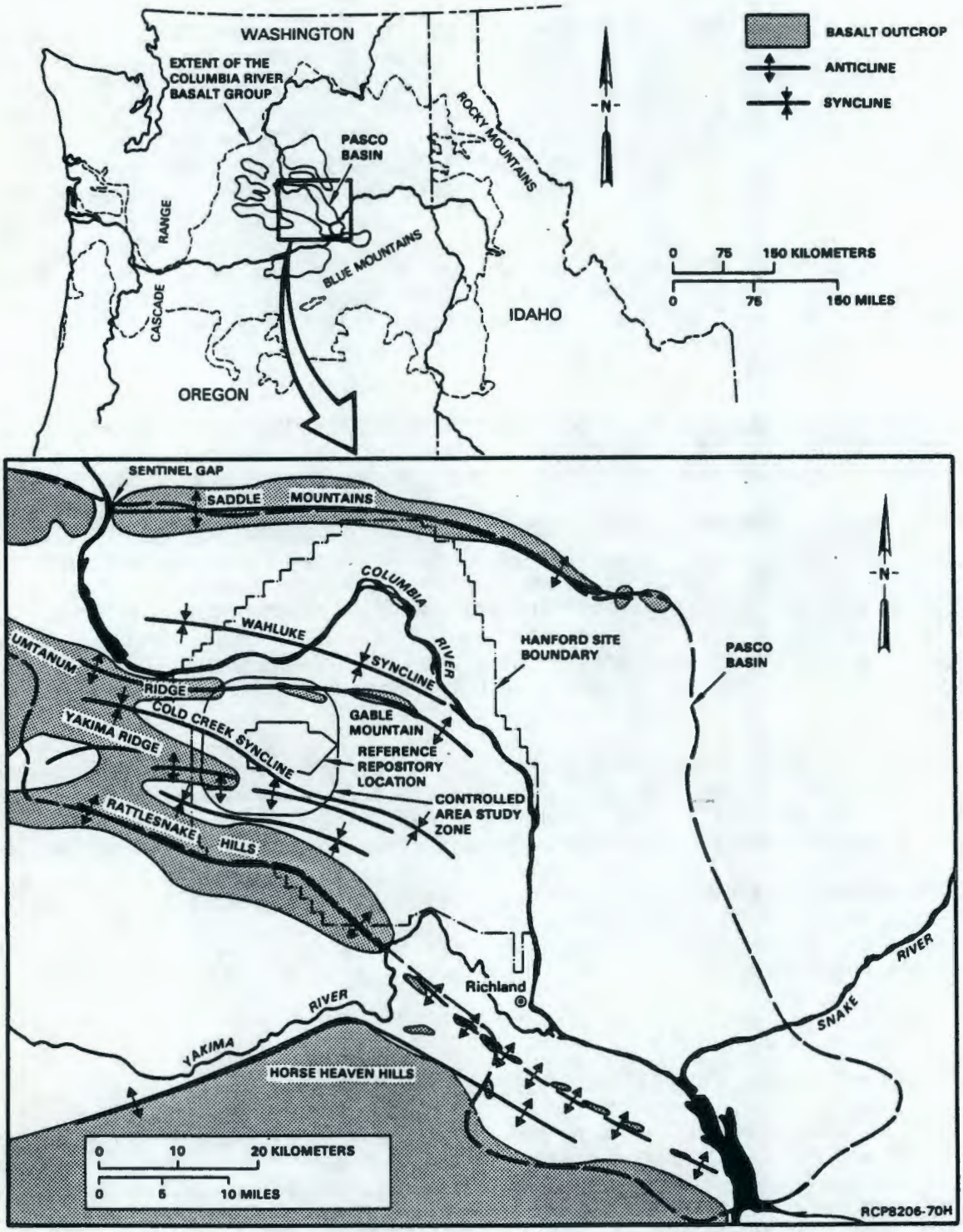

Figure 1.7-3. Location map of structural axes in the Pasco Basin.

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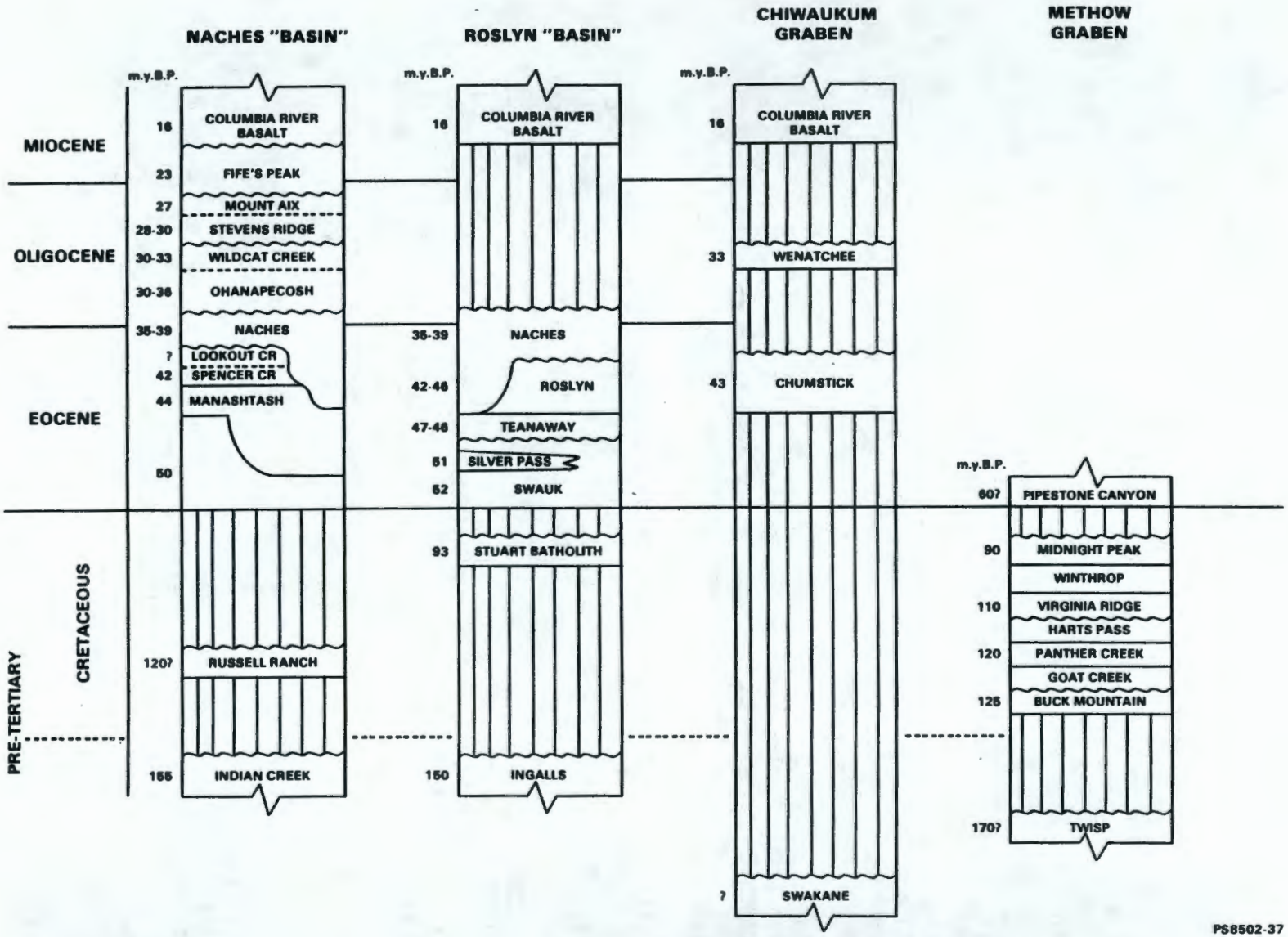

Figure 1.7-4. Stratigraphic correlation of major rock units found along the northwest Columbia Basin basalt margin and in the Methow graben (modified from Campbell, 1985, Fig. 3 and p. 19). The four groups of formations follow the informal terminology of Campbell and represent distinctive tectonic and depositional depressions.

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p. 157). These units include, from youngest to oldest, the Oligocene fluvial Wenatchee Formation and the Eocene fluvial, deltaic, and lacustrine sequences of the Roslyn, Chumstick, Naches, Manastash, and Swauk Formations.

The first two wells drilled by Shell Oil Company in 1980 and 1981 are located at the same site on the Selah Butte anticline between Yakima and Ellensburg, Washington. The two wells are Yakima Mineral Company (YM) No. 1-33, with a total depth of 4,937 m (16,197 ft) and YM No. 2-33, with a total depth of 1,708 m (5,604 ft) (see Fig. 1.7-2). The YM No. 2-33 was drilled to test zones in the YM No. 1-33 that could not be tested because of hole conditions. Formation tests run on perforated casing on two zones, one 3,955 to 4,135 m (12,976 to 13,568 ft) and one at 3,773 to 3,788 m (12,380 to 12,430 ft), in YM No. 1-33 tested gas at noncommercial rates of about 14,160 m^3/d (0.5 mmcf/d). This well created widespread interest in the oil industry because it penetrated the basalt section at a depth of 1,524 m (5,000 ft) and logged gas shows in sub-basalt sediments (Gresens and Stewart, 1981). Testing of zones at about 1,524 m (5,000 ft) in the YM No. 2-33 also indicated noncommercial rates.

In 1980, Bissa No. 1-29 well, with a total depth of 4,561 m (14,964 ft), was drilled at the intersection of the Whiskey Dick Ridge (westerly extension of the Frenchman Hills anticline) and the north-south-trending Hog Ranch-Naneum Ridge anticline. Gas shows were reported, but no tests were run (Bowen, 1986).

The last well drilled, Shell/ARCO BN No. 1-9 with a total depth of 5,339 m (17,516 ft), is located on the Saddle Mountains anticline about 19 km (12 mi) east of Sentinel Gap and about 16 km (10 mi) north of the Hanford Site; it is the deepest well in Washington State. The BN No. 1-9 penetrated the basalt section at a depth of 3,490 m (11,450 ft) and encountered gas shows in several zones below 3,658 m (12,000 ft). Extensive tests run through perforated casing in the zone at 4,076 to 4,081 m (13,372 to 13,388 ft) recovered 87,792 m^3/d (3.1 mmcf/d) gas with two barrels of 32 API gravity distillate, and tests on the zone at 3,870 to 3,871 m (12,697 to 12,699 ft), recovered gas at 67,968 m^3/d (2.4 mmcf/d) for a combined total in both zones to 155,760 m^3/d (5.5 mmcf/d) (Bowen, 1986; Lingley and Walsh, 1986). The operators considered the production rate as noncommercial and the well was abandoned.

On the basis of information developed in the four deep wells drilled by Shell Oil Company, commercial deposits of natural gas could be present in subbasalt sediments under favorable reservoir and entrapping conditions (Deacon, 1987; Lingley and Walsh, 1987). Sub-basalt anticlines are considered the primary exploration trap, but present data are insufficient to determine the relationship with sub-basalt sediment structure and the basalt anticlines. If sub-basalt sediments are conformable to the large basalt anticlines, major reservoirs could be present (Deacon, 1987; Lingley and Walsh, 1987).

Lingley and Walsh (1986) compiled vitrinite reflectance data from four deep boreholes (three deep boreholes from Shell Oil Company and the Norco No. 1) that indicate the sub-basalt sediments have been heated to the

maturation levels necessary for oil gas generation. Total organic carbon content, which is a measure of the amount of material available for hydrocarbon generation, is not presented in the report. Plans to obtain these data and other source rock information are presented in Section 8.3.1.6.3.3.2.

A reservoir with high permeability and porosity is necessary to hold major hydrocarbon reserves. Permeable sandstone facies are present in the Eocene Swauk, Manastash, Naches, Chumstick, and Roslyn Formations and in the Oligocene Wenatchee Formation in outcrop sections along the basalt margin. Possible correlative sandstone facies were penetrated in the four deep Shell Oil Company wells but were reportedly of low porosity and permeability (Lingley and Walsh, 1986). Studies to determine sandstone porosity and permeability are described in Section 8.3.1.6.3.3.2, which includes an analysis of wireline logs from the deep Shell Oil Company wells.

The thick basalt section creates a severe problem in seismic imaging of structural closures in the sub-basalt rocks. Gravity methods may be useful in identifying major structural hydrocarbon traps when used in conjunction with other geophysical and borehole data. Oil companies have been conducting extensive seismic reflection surveys in the Columbia Basin for the past 5 yr and are reportedly obtaining adequate processed sections from within and below the basalt to map structural conditions. As a part of the studies of structural geology (Section 8.3.1.2.3.3.4), deep seismic reflection surveys are planned to assist the hydrocarbon evaluation.

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1.7.2.3 Impact of a nuclear waste repository on future production of hydrocarbons

Present information is insufficient for a definitive evaluation of the hydrocarbon potential of the reference repository location and controlled area study zone. However, the data that are available on the geologic setting of the Cold Creek syncline, which is the dominant structure of the repository site and the controlled area study zone suggest that structural conditions are not favorable for entrapment of hydrocarbons.

Structural and stratigraphic conditions of the sub-basalt sediment section are unknown. Studies to determine the structural condition of the deep basalt flow and sub-basalt sediments are described in Section 8.3.1.2.3. Additional studies to assess the hydrocarbon potential of the site are presented in Section 8.3.1.6. A position paper evaluating the need to drill a multipurpose deep borehole near the controlled area study zone is being prepared. Such a borehole could provide more direct information on the hydrocarbon potential of the repository site.

1.7.3 GEOTHERMAL RESOURCES

1.7.3.1 Available data and analysis of known occurrences

Geothermal resources have not been utilized to any significant extent within 100 km (62 mi) of the Hanford Site, except for one artesian well (33 °C) near Yakima, Washington (see Table 1.7-1). Geothermal resource potential assessments have been made by Blackwell (1974), Washington State; Murphy and Johnpeer (1981), Pasco Basin and vicinity; GG/GLA (1981), Pasco Basin and vicinity; Widness (1983), Moses Lake-Ritzville-Connell area, Washington; BLM (1985), Columbia Basin Province; Bloomquist (1985), Washington, Oregon, Idaho, and Montana; and McEuen (1975), Washington Cascade Mountains (see also Section 1.3.2.5.2.4).

An assessment of geothermal resource potential for the Pasco Basin and vicinity was prepared by Murphy and Johnpeer (1981). These authors selected data from Korosec and Schuster (1980) and from the BWIP, using only what they considered to be the most reliable data. The thermal gradients that they determined were within the range of 35 to 45 °C/km and are considered a normal gradient. However, within the Hanford Site several exceptions were listed, with three boreholes having slightly elevated geothermal gradients of 45 to 50 °C/km (0.62 mi). In addition, a group of five wells located approximately 64 km (40 mi) northeast of the site and outside of the Pasco Basin had measured and calculated gradients above normal (40 to 90 °C/km).

Although the authors indicated that further investigation of the causes for these elevated gradients is warranted, "The potential for high-and intermediate-temperature geothermal systems in the Pasco Basin is judged to be insignificant because neither localized heat sources nor high heat flow from the mantle are available as potential heat sources." (Murphy and Johnpeer, 1981). From their studies, Murphy and Johnpeer (1981) concluded that there is no indication that a localized heat source is present within the Pasco Basin or that the region is characterized by anomalously high heat flow. For comparison, regional heat flow temperatures in areas of Idaho, the Imperial Valley, and the Rio Grande Rift average over 100 mW/m^2 and much of the western United States ranges from 60 to 90 mW/m^2 (Blackwell, 1978; Sass et al., 1971). This compares to 45 to 64 mW/m^2 in the Pasco Basin (Murphy and Johnpeer, 1981).

Bloomquist (1985) evaluated and ranked geothermal resources in the states of Idaho, Montana, Oregon, and Washington (including the Pasco Basin). This study provides data for sites in the Pasco Basin that have the potential for low temperature geothermal resource for direct use (e.g., agriculture, space heating). The BLM (1985) evaluation also indicates there may be moderate to low temperature geothermal resources in the Columbia Basin.

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Low temperature geothermal waters (25 to 55 °C) are present at depths ranging from 915 m (3,000 ft) to 1,524 m (5,000 ft) in boreholes drilled at the controlled area study zone. With present technology, these waters could be developed for direct use. However, such waters are present in areas adjacent to the Hanford Site; it is unlikely that there would be a need to develop this in the Hanford Site. Studies to evaluate the geothermal resource potential for the Hanford Site are described in Section 8.3.1.6.3.3.3.

1.7.3.2 Impact of a waste repository on potential future production of geothermal resources

Present information indicates that there is no potential for high-temperature geothermal resources that could be developed for the generation of electrical power in the Hanford Site, Pasco Basin, or Columbia Basin; therefore, it is unlikely that exploration of geothermal resources, including low-temperature geothermal waters, would impact the repository site.

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1.8 SUMMARY

This section provides a link between the description of the geologic characteristics of the candidate site presented in Chapter 1, and the description of issues to be resolved and the planned activities to resolve them presented in Chapter 8. The summary highlights the main geologic characteristics of the candidate site, discusses the relationship of these characteristics to design, summarizes the information needs that have been identified in Chapter 8, and describes the relationship of material presented in Chapter 1 to the information required by NRC Regulatory Guide 4.17 (NRC, 1985).

1.8.1 SUMMARY OF SIGNIFICANT RESULTS

The following summaries by geology subdiscipline highlight the main features about the candidate site that have been established from exploration activities conducted to date. The emphasis in conducting the studies that have resulted in this information has been site selection according to the guidelines established in 10 CFR 960 (DOE, 1987b), although information from other programs of basic and applied research on the Hanford Site has been used as well for this description. The purpose in presenting these highlights is to provide a brief review of the geology of the candidate site that will aid the reader in understanding the discussion of issues presented in Section 8.2 and the description of site characterization activities presented in Section 8.3.

1.8.1.1 Geomorphology

The reference repository location is located within the Columbia Basin subprovince of the Columbia Intermontane physiographic province. The area is characterized by relatively low-relief topography and a dry climate. The Yakima folds and the Central Plains are the geomorphic units containing or bordering the reference repository location. The Yakima folds consist of east-west-trending, asymmetric anticlinal bedrock ridges. Erosion by fluvial incision and mass wasting has continued on these ridges concurrent with their tectonic development. The Central Plains include the sediment-filled, low-relief synclinal areas adjacent to the Yakima folds, such as the Pasco Basin with its Cold Creek Valley, which contains the reference repository location. Except for minor fluvial and eolian activity, the Central Plains have remained essentially unchanged geomorphically since the end of the Pleistocene, approximately 13,000 yr ago.

Geomorphic processes are considered during the siting investigations because of the possibility for (1) exhumation of the repository and (2) their influence on the hydrologic regime. Geologic processes that are likely to be

active during the next 100,000 yr and that could conceivably affect the waste isolation capability of the repository by influencing geomorphic processes, are given below.

Geologic process	Influence on geomorphology of region
Tectonism	Changes in drainage patterns, erosion, deposition, and flooding characteristics; altered base level; changes in topography resulting in mass wasting.
Volcanism	Lava and debris flows altering drainage characteristics; airfall tephra deposition.
Glacial-proglacial activity	Glacial scour; altered drainage characteristics, flooding; altered base level; isostatic effects of ice.
Fluvial-lacustrine activity	Erosion, deposition of sediment; modification of land surface by channel migration; flooding; incision at site.
Eolian activity	Erosion, deposition of sediment; redistribution of minor landforms.
Mass wasting	Slope failure such as landsliding, slumping, soil creep, and rockfall; altered drainage characteristics.
Weathering	Rates of erosion; sediment characteristics.

Of the processes likely to act on the candidate site, those related to renewed glacial or proglacial activity are most likely to have an impact. Based on preliminary modeling, the probability of renewed glaciation is very high over the next 100,000 yr but very low for the next 10,000 yr. The effects of climatic change or glaciation near the candidate site are not completely understood; likely effects include increases in groundwater recharge and changes in volume and location of surface runoff. This could lead to changes in the deep groundwater flow system. Loading and unloading of an ice sheet, either directly over or near the candidate site, could induce fracturing or tectonic movements within the crust.

The potential for breaching of a repository is highly unlikely through any combination of geomorphic processes over the next 100,000 yr, based on present and projected tectonic and climatic settings and the proposed depth of a repository. The effects of normal denudation processes (e.g., weathering, erosion, and transportation), however, could expose new areas to groundwater recharge. The impact of this on deep aquifers within the Pasco Basin are uncertain. Studies to further characterize geomorphic processes and their impact on waste isolation are described in Section 8.3.1.2.4.3.1.

1.8.1.2 Stratigraphy and lithology

The stratigraphic and lithologic characteristics of the candidate area and site provide important information to (1) develop a framework for other geologic and hydrologic systems; (2) identify a host rock that meets the requirements for thickness and lateral continuity; (3) identify host rock properties that could influence repository design; (4) identify isolation capabilities of the rock; (5) provide input to the assessment of the resource potential of the site; and (6) provide data for repository design and performance assessment.

The controlled area study zone is located within the Pasco Basin, which is a topographic and structural depression within the Columbia Plateau. The Columbia Plateau is underlain primarily by volcanic rocks of the Columbia River Basalt Group, which is more than 3 km (1.8 mi) thick in the Pasco Basin. Subbasalt rocks have been interpreted to include Cretaceous to Eocene sedimentary units, that are 6.1 km (4 mi) thick, directly below the basalt and crystalline basement rock, 10 km (6 mi) thick. Details of the structure, stratigraphy, and hydrocarbon resource potential of the sub-basalt rocks are poorly understood.

The Columbia River Basalt Group, a thick sequence of Miocene tholeiitic lava flows, is the youngest known assemblage of continental flood basalts in the world. These flows cover an area of more than 163,000 km^2 (63,000 mi^2) in Washington, Oregon, and Idaho with a total volume of about 170,000 km^3 (40,800 mi^3). Individual flows are generally 20 to 30 m (65 to 100 ft) thick with volumes of approximately 10 to 30 km^3 (2 to 7 mi^3); however, these values are variable. The basalt flows of the Columbia River Basalt Group were erupted from about 17 to 6 m.y.B.P., although more than 98% of the basalt, by volume was erupted between 17 and 14.5 m.y.B.P. (see Section 1.2.1.2).

The Columbia River Basalt Group is divided into five formations, listed from oldest to youngest: Imnaha, Picture Gorge, Grande Ronde, Wanapum, and Saddle Mountains Basalts. The Imnaha and Picture Gorge Basalts are not known to occur in the Pasco Basin. The Grande Ronde Basalt, which contains the repository horizon (the Cohassett flow), is the most extensive and voluminous formation. It contains more than 149,000 km^3 (35,700 mi^3) of basalt. This formation erupted from 16.9 to 15.6 m.y.B.P. This represents about 87.5 vol% of the total Columbia River Basalt Group. The thickest known section of Grande Ronde Basalt (more than 2,700 m (8,850 ft) thick) occurs along the western edge of the Pasco Basin. Flows of the Grande Ronde Basalt are typically aphyric, although a few flows contain sparse to abundant plagioclase phenocrysts.

Within the Pasco Basin, the Grande Ronde Basalt is divided into two informal sequences, the Schwana and the Sentinel Bluffs sequences. The Umtanum flow is the second uppermost flow of the Schwana sequence. The Sentinel Bluffs sequence includes 13 individual flows. The Cohassett flow is within the middle portion of the Sentinel Bluffs sequence. Within the controlled area study zone, the Sentinel Bluffs sequence contains eight to nine flows. The Cohassett flow is the thickest within the controlled area

study zone and varies from about 66 to 81 m (218 to 268 ft) thick; the top of the flow varies from 671 to 943 m (2,220 to 3,093 ft) below the ground surface.

The Wanapum Basalt regionally is comprised of up to 26 flows that were erupted from about 15.6 to 14.5 m.y.B.P. The formation contains 10,600 km^3 (2,550 mi^3) of basalt that constitute 7.5 vol% of the entire Columbia River Basalt Group. Within the controlled area study zone, the Wanapum Basalt is approximately 357 m (1,170 ft) thick and consists of up to 12 individual flows.

The Saddle Mountains Basalt is comprised of 14 chemically diverse members (only four occur in the controlled area study zone) that were erupted intermittently from 14.5 to 6 m.y.B.P. and represents the final phase of the Columbia River basalt volcanism. The Saddle Mountains Basalt is estimated to have a volume of 2,390 km^3 (574 mi^3) and represents only 1.4 vol% of the entire Columbia River Basalt Group. Lateral distribution of the formation members is limited. The thickness of the Saddle Mountains Basalt varies significantly across the controlled area study zone (see Section 1.2.2.1.3 for a discussion of this thinning).

Interbedded sediments of the Ellensburg Formation occur between flows of the Columbia River Basalt Group, and suprabasalt sediments of late Miiocene to Holocene age lie on top of the Columbia River Basalt Group. In the controlled area study zone, the Ellensburg Formation consists of five continuous and several discontinuous interbeds. Three of the continuous interbeds are within the Saddle Mountains Basalt. They are, from oldest to youngest, the Cold Creek, Selah, and Rattlesnake Ridge interbeds. One interbed, the Mabton, separates the Saddle Mountains and Wanapum Basalts; and the fifth and lowest continuous interbed, the Vantage, separates the Wanapum and Grande Ronde Basalts. The Vantage interbed is the closest interbed to the Cohassett flow. It averages about 2.7 m (9 ft) thick across the controlled area study zone. The interbeds of the Ellensburg Formation are typically quartzitic to arkosic sandstone and mudstone with minor conglomerate. The characterization of the interbeds within the controlled area study zone is incomplete, and their lithologic and hydrologic properties are currently uncertain. A variety of stratigraphic studies is planned to further characterize the Ellensburg Formation (see Section 8.3.1.2.3.3.1.1).

Suprabasalt sediments within the controlled area study zone include the fluvial-lacustrine Ringold Formation and the glaciofluvial Hanford Formation. The Ringold Formation consists of four subunits and is about 110 to 215 m (350 to 700 ft) thick in the central Cold Creek syncline. A plio-pleistocene unit lies between the Ringold and Hanford Formations. The sediments of the Hanford Formation vary from 5 to 65 m (15 to 210 ft) thick and record late Pleistocene cataclysmic floods with coarse gravel (Pasco Gravels) and fine-grained slackwater (Touchet Beds) deposits. Other Quaternary suprabasalt sediments that occur in the Pasco Basin and the controlled area study zone include alluvium, colluvium, dune sand, loess, and landslide deposits.

The flows of the Columbia River Basalt Group contain internal features that result from the cooling of the lava. These intraflow structures include the flow top, flow bottom, and flow interior. The flow top is the chilled, glassy upper crust that is often vesicular to scoriaceous, or rubbly to brecciated. The flow top typically represents about 10% of the total flow thickness. The flow bottom is typically only a few centimeters thick and consists of a glassy, vesicular chilled zone. Flow bottoms can, however, be much thicker (e.g., greater than 25 m (75 ft)) and occupy up to 30% of the flow at locations where the molten lava encountered standing water. Cooling joints and fractures predominate within the flow interiors and form colonnade and entablature structures. The colonnade usually occurs at the base of the flow interior and consists of relatively well-formed, vertically oriented, polygonal columns of basalt. The entablature is composed of irregularly to regularly jointed small columns, which are commonly fractured into hackly fist-size fragments. Entablature columns can be oriented vertically, exhibit regular patterns (e.g., rosettes or fans), or be disordered. Contacts between colonnade and entablature may be distinct or gradational. Other intraflow structures include vesicle pipes, cylinders, sheets, and zones; laminae or dispersed diktytaxitic vesiculation; and platy fracturing.

The internal characteristics of the Cohassett flow within the controlled area study zone are similar to other Columbia River Basalt flows in that there is a flow top, flow interior, and a discontinuous flow bottom. The Cohassett flow-top thickness ranges from 4.0 to 23.2 m (13 to 76 ft) across the controlled area study zone and consists of flow-top breccia and rubble overlying vesicular and vuggy basalt. Field studies north of the controlled area study zone suggest that flow-top thickness variations of 10 m (33 ft) may occur over lateral distances of about 100 m (330 ft). The interior of the Cohassett flow ranges from 42.7 to 75.6 m (140 to 248 ft) within the controlled area study zone. A laterally extensive vesicular zone occurs within the Cohassett flow interior. The flow interior, above the vesicular zone and below the flow top, ranges from 16 to 22.3 m (53 to 73 ft) thick; whereas the flow interior below the vesicular zone and above the flow bottom is from 29 to 45.4 m (95 to 149 ft) thick. Virtually all (99.4%) of the cooling joints in the flow interior are filled with clay, silica, or zeolite. The flow bottom of the Cohassett flow in the controlled area study zone is typically a thin zone of vesicular basalt. The flow bottom ranges from 0 to 6 m (0 to 20 ft) in thickness across the controlled area study zone.

An understanding of the characteristics of intraflow structures and their vertical and lateral variability across the controlled area study zone is necessary for repository design and performance assessment. The present geologic data base is incomplete and results in uncertainty in predictions of the variability of intraflow structures and lateral thickness variations of these features. Therefore, further studies are planned to provide a more complete and detailed data base that will be used to reduce the uncertainties in understanding the stratigraphic, lithologic, and structural characteristics of the basalt layers in the controlled area study zone (Section 8.3.1.2.3.3.2).

Analyses of cooling joint data from core within the controlled area study zone have provided information on seven cooling joint parameters: frequency, width, orientation, percent infilling by secondary minerals, infilling type, core-break frequency, and wall-rock alteration. Data on persistence and roughness from boreholes within the controlled area study zone have not yet been analyzed. Plans for the analysis of these parameters is discussed in Chapter 8 (Section 8.3.1.2.3.3.3). An understanding of the characteristics of cooling joints is necessary for radionuclide transport models in assessing the performance of the site and for design activities. Further studies are planned in determining the characteristics of cooling joints and are discussed in Section 8.3.1.2.3.3.3.

1.8.1.3 Structural geology and tectonics of the candidate area and site

The study and characterization of the structural geology and tectonics of the candidate area and site are necessary to understand the geometry of the bedrock and tectonic structures and of tectonic processes and evolution in the Columbia Plateau. This information is important for repository design and for performance analysis of the repository.

The Columbia Plateau is part of the North American continental plate that is separated from the oceanic Juan de Fuca plate to the west, and by the Cascadia subduction zone. The Columbia Plateau lies in a back arc environment in the context of plate tectonics. While this Cenozoic plate-tectonic framework is reasonably well understood, the details of the characteristics of plate geometry and the nature of plate interactions are not clear, particularly the impacts of plate motion on the candidate area and site. Therefore, studies are planned to address these uncertainties (Section 8.3.1.2.4).

Igneous activity during the Cenozoic in the region of the candidate site has been both intrusive and extrusive. The eruption of the voluminous Columbia River flood basalts, from 17 to 6 m.y.B.P., has been the most prominent form of this igneous activity. Extrusive and intrusive igneous activity in the Cascade Range began about 38 m.y.B.P. The rocks representing the youngest and present period of Cascade Range volcanism are less than 5 m.y. old. The only deposits present in the Pasco Basin derived from Cascade Range volcanism are airfall tephra (volcanic ash) and reworked tuffaceous sediments.

The Pasco Basin and the controlled area study zone are located within the Yakima Fold Belt tectonic subprovince of the Columbia Plateau. The Yakima Fold Belt is bounded on the east by the Palouse subprovince and on the south by the Blue Mountains subprovince. The Palouse subprovince contains two subunits: northern Palouse Slope and southern Clearwater Embayment. The Palouse Slope is a regional structural slope that dips gently westward and exhibits only minor tectonic deformation compared to other subprovinces. The Clearwater Embayment consists of structural basins and uplifted blocks that

are tilted, gently folded, and broken by numerous faults having a variety of trends. The Blue Mountains subprovince is structurally diverse, dominated by the complexly faulted Blue Mountains anticlinorium in its northern portion and a series of structural basins in its central and southern portions. The structural basins are either fault-bounded or fold-bounded. The major structural elements of the Blue Mountains subprovince are the Blue Mountains anticlinorium, Hite Fault System, La Grande Fault System, Service anticline, Wallula Fault zone, and southern Olympic-Wallowa lineament. At present, there is uncertainty regarding the nature and characteristics of these major structural elements, their structural and tectonic relationships to each other, age and rates of tectonic deformation associated with each structure, and implications and impacts that each may have on the repository site. Studies are planned to address these uncertainties (Sections 8.3.1.2.3 and 8.3.1.2.4).

The Yakima Fold Belt subprovince contains four structural elements: Yakima folds, Cle Elum-Wallula disturbed zone, Hog Ranch-Naneum Ridge anticline, and northwest-trending wrench faults. The Yakima folds are a series of east-west-trending, narrow, asymmetric anticlines that have wavelengths of about 5 to 30 km (3 to 19 mi) and amplitudes generally less than 1 km (0.6 mi). The anticlines are separated by broad synclines or basins (e.g., the Cold Creek syncline where the reference repository is located) that, in many cases, contain thick sequences of post-basalt Neogene- to Quaternary-age sediments. The Yakima folds appear to have formed as the result of regional, north-south compression. The cross-sectional geometry of the anticlines varies from symmetrical, open folds to asymmetric folds with one steep or overturned limb. The anticlines are often segmented by cross-trending folds or faults. The cross-sectional geometry of the synclines between the anticlines is also variable and dependent on the wavelength of the folds; the broader the wavelength the more poorly defined the syncline.

Thrust or high-angle reverse faults that strike roughly parallel to the anticlines are often found along both limbs of the folds. The amount of vertical offset across these faults is commonly greater than hundreds of meters.

The total amount of shortening across the Yakima Fold Belt is not known, but may be on the order of 25% to 35% due to both folding and faulting. Individual anticlines have approximately 1 to 3 km (0.6 to 2 mi) of shortening.

Deformation initiating the folding in the Yakima Fold Belt appears to have begun at least by Grande Ronde Basalt time. Deformation continued at least into the late Miocene or Pliocene in the Pasco Basin, as indicated by the thinning across the folds by sediments of that age. There is little direct field evidence for Quaternary deformation along the Yakima folds (e.g., faulting or folding). Only three cases of suspected Quaternary faulting associated with Yakima fold anticlines have been documented: (1) small displacement of the Central Gable Mountain fault (on the Umtanum Ridge-Gable Mountain structure), located 8 km (5 mi) north of the reference repository location; (2) apparent surface rupture along the Toppenish Ridge anticline,

located 75 km (45 mi) west of the reference repository location; and (3) displacement of Pleistocene-age gravel by the Union Gap fault along Ahtanum Ridge, about 60 km (38 mi) west of the reference repository location. Despite the paucity of evidence for Quaternary deformation, limited geologic evidence, geodetic evidence, and seismologic data suggest that the Yakima folds have continued to develop in post-basalt (past 6 m.y.) time, but at low-average rates. The rate of uplift of the folds at the close of Columbia River basalt volcanism was about 40 m/m.y. (130 ft/m.y.), and this rate appears to have continued through the Pliocene and into the early Quaternary. The low observed rates of geodetic strain plus the low seismicity of the Columbia Plateau tend to suggest that current deformation is continuing at low-average rates. However, the current data are incomplete in terms of characterizing the tectonic evolution of individual Yakima folds. Studies are planned to characterize the major structures of the Yakima folds (Sections 8.3.1.2.3 and 8.3.1.2.4).

The Cle Elum-Wallula disturbed zone is a narrow zone (10 km (6 mi) wide) that transects the Yakima Fold Belt in a northwest trend. The Cle Elum-Wallula disturbed zone is defined and characterized by an abrupt change in trend of Yakima folds, an aligned belt of doubly plunging anticlines, and the Wallula fault zone. The age and timing of deformation along the Cle Elum-Wallula disturbed zone are not well constrained. Available data indicate that deformation began by at least late Grande Ronde time and continued through the Miocene. Evidence for Quaternary deformation has been reported at six localities either within or directly associated with the Cle Elum-Wallula disturbed zone. However, there is no evidence for Quaternary deformation northwest of Finley Quarry, which is located 65 km (40 mi) south of the reference repository location. This may be due to a lack of the appropriate age stratigrapic record rather than to a lack of deformation along the Cle Elum-Wallula disturbed zone. Additional studies are planned to reduce the uncertainties in interpreting tectonic evolution of the Cle Elum-Wallula disturbed zone (Sections 8.3.1.2.3 and 8.3.1.2.4).

The Hog Ranch-Naneum Ridge anticline is a broad, structural arch that trends north-northwest and forms a portion of the western boundary of the Pasco Basin. It extends from near Wenatchee, Washington, south to at least Yakima Ridge and possibly as far south as Horse Heaven Hills. Little is known about the structural geology of this feature, and studies are planned to further characterize its structural nature and tectonic relationship to the folds of the Yakima Fold Belt (Section 8.3.1.2.3).

Numerous northwest-trending, dextral strike-slip (wrench) faults occur in the western Columbia Plateau west of longitude 120°. At least four of these faults are greater than 100 km (60 mi) long, and they cross the trends of several Yakima folds. Less numerous sinistral strike-slip wrench are also present. The wrench faults of regional extent appear to have developed contemporaneously with the Yakima folds and deformation along at least some of these features has continued into the Holocene. The reason for the apparent absence of these structures in the central portion of the Columbia Plateau (i.e., the Pasco Basin) is not known, nor is their role in the tectonic development of the Columbia Plateau. Studies are planned to address these uncertainties (Sections 8.3.1.2.3 and 8.3.1.2.4).

The reference repository location lies within the Cold Creek syncline, located within the Yakima Fold Belt. It is bounded on the north by the Umtanum Ridge-Gable Mountain structure and on the south by Yakima Ridge. The Cold Creek syncline is asymmetric; basalt beds beneath the reference repository location dip gently to the southwest.

Deformation in the Columbia Plateau appears to be the result of north-south directed compression. This compression formed the Yakima folds and their associated faults and tectonic joints. Faulting, folding, and jointing were concentrated along the anticlinal crests during regional compression, with substantially less deformation occurring in the synclines. The gently dipping limbs of the anticlines contain widely spaced, discrete shear zones and faults that range from a few centimeters to 1 m (3.3 ft) wide. Zones of concentrated deformation tend to occur along the steeply dipping limbs of the anticlines. Paleomagnetic evidence for rotation within the basalts indicates that it is concentrated along the anticlinal axes, further suggesting that deformation is concentrated along anticlines. Seismologic evidence, geodetic data, and in situ stress measurements all indicate that the Columbia Plateau is currently within a predominantly north-south compressive stress regime. The implications of such a compressive stress regime, with respect to further deformation of the folds and faults, are not clearly understood. Studies are planned to address further these uncertainties (Sections 8.3.1.2.3 and 8.3.1.2.4).

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1.8.1.4 Seismology of candidate area and site

The historical record of seismicity for the Pacific Northwest dates from about 1840 and suggests that moderately strong earthquakes (i.e., modified Mercalli intensity of VII or greater) are infrequent in the Columbia Plateau. The region is best characterized as having relatively continuous, low-level strain release, with small, shallow earthquakes. In contrast, the Puget Sound area to the west of the Cascade Range is characterized by moderate- to large-magnitude and intensity events that have relatively deep foci of greater than 10 km (6 mi).

The majority of the historic earthquakes that have occurred in the candidate area prior to 1969, which are located primarily from "felt" reports, have had modified Mercalli intensities of less than V and magnitudes less than 4.5. This seismicity has been concentrated around the northern, southern, and western parts of the Columbia Plateau. The largest earthquake recorded within the Columbia Plateau occurred on July 16, 1936, near Milton-Freewater, Oregon. It had an estimated surface-wave magnitude of 5.7 to 5.8 and was located near Waitsburg, Washington, about 130 km (81 mi) east of the controlled area study zone. Fault plane solutions from aftershocks suggest that fault slip was consistent with the north-northeast-trending Hite Fault; however, the trend of aftershocks lies to the west of the Hite Fault. Because there is no clear association of the earthquake to the Hite Fault, it may be associated with Rattlesnake-Wallula Alignment or some as-yet unmapped fault.

Most of the seismicity that is presently occurring in the central Columbia Plateau is concentrated between the Saddle Mountains and the Frenchman Hills, and between the Saddle Mountains and Gable Mountain. The most frequent activity typically occurs at focal depths of 4 km (2.5 mi) or less, and consists of swarms of microearthquakes (i.e., magnitudes of less than 3.0). By depth, Columbia Plateau seismicity separates into three zones; 0 to 4 km (0 to 2.5 mi), 4 to 8 km (2.5 to 5 mi), and deeper than 8 km (5 mi). No seismicity has been observed at depths greater than 30 km (19 mi), which is the depth of the Moho in the region.

Microearthquake swarms are the predominant type of seismic activity recorded in the Columbia Plateau. The microearthquake swarms contain from several to as many as 100 events, and typically last a few days to several months. They appear to occur mostly within the Columbia River basalt, and are confined to an area of typically 100 km^2 (39 mi^2) with a depth of 3 to 5 km (1.0 to 3.1 mi). Individual events generally range in magnitude from 1.0 to 3.5, but most events are less than 2.0. Linear east-west trends of epicenters may be apparent within individual microearthquake swarms, while the entire swarm body is roughly oriented northwest-southeast. Although the microearthquake swarm bodies are roughly parallel to the structural trends within the Yakima Fold Belt, they cannot be related to individual mapped faults, and they are not concentrated on single planes but are rather diffuse in pattern. Microearthquake swarms often occur more than once in the same general area. The largest swarm-related earthquake had a magnitude of 4.4 and occurred on December 20, 1973 on the Royal Slope, about 40 km (25 mi) north of the controlled area study zone.

The closest swarms to the controlled area study zone are at Wooded Island, 26 km (16 mi) east-southeast; Coyote Rapids, 8 km (5 mi) north; and Cold Creek, 5 to 8 km (3 to 5 mi) south. Microearthquake swarm activity appears to be generally confined to the Columbia River basalts although infrequent swarm events may occur below the base of the basalts. Activity also appears to be spatially correlated to bedrock folds although a causal relationship has not yet been determined.

Deep, individual earthquakes occur generally below the base of the basalts to depths of about 30 km (19 mi). These deep events occur in a diffuse pattern and have not been directly related to mapped surface structures. However, some clustering of deep earthquakes occurs below the Horse Heaven Hills near Prosser, located 50 km (31 mi) to the south of the controlled area study zone, and also near the eastern end of the Saddle Mountains. Uncertainty in the velocity model currently used to locate these earthquakes results in their vertical distribution being imprecisely known. Relocation of these events using an improved velocity model is discussed in Section 8.3.1.2.4.3.2; this will hopefully help to better distinguish possible depth grouping of events.

Focal mechanism solutions for earthquakes are widely variable across the Columbia Plateau, although the principal compression axes are frequently horizontal and are oriented with a range of west-northwest to north-northeast. focal mechanism solutions for swarm areas suggest that rupture occurs on several planes.

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The current tectonic stress regime in the central Columbia Plateau, as derived from earthquake focal mechanism solutions and hydrofracturing measurements, indicates a predominance of north-south compression and vertical tension. This suggests that the majority of the current swarm-type tectonic deformation may be occurring on numerous high-angle reverse faults oriented roughly east-west rather than on single planes.

Seismicity within about 10 km (6 mi) of the reference repository location since 1969 is characterized primarily by shallow microearthquake swarms and infrequent deep earthquakes, the latter having occurred during two distinct time periods. The shallow microearthquake swarms include the Coyote Rapids swarm, located 8 km (5 mi) north of the controlled area study zone, and the Cold Creek swarm, located 5 to 8 km (3 to 5 mi) south of the controlled area study zone. The Coyote Rapids swarm includes 91 earthquakes, with 70% occurring at depths generally less than 4 km (2.5 mi) and 98% at depths less than 8 km (5 mi). The two largest events were magnitudes 3.4 and 3.8; most are magnitude 1.5 or less. The Cold Creek swarm includes 15 events from two periods of activity since 1979. They have occurred at depths less than 5 km (3 mi) and the largest event was magnitude 2.4.

Deep earthquake activity at the reference repository location has been limited to two time periods containing a few small-magnitude events each. The first was in November, 1969 and included four microearthquakes aligned on an apparent north-south trend through the reference repository location that occurred at depths of 3 to 10.3 km (1.6 to 6.4 mi) with magnitudes from 1.3 to 2.2. The second period occurred between March and September, 1971 and included six events below the central northern border of the reference repository location. These occurred at depths of 6.5 to 8.0 km (4 to 5 mi) with magnitudes from 0.4 to 1.1.

The characteristics and generating mechanisms of the shallow microearthquake swarm events and the deep seismicity are not well understood. Thus, the significance to the repository of particular events or series of swarms is uncertain. Studies are planned to investigate the nature and mechanism of shallow and deep seismicity in the area of the repository (Section 8.3.1.2.4.3.3.5).

Previous work on the Hanford Site for the siting and licensing of commercial nuclear powerplants has identified several potential Pasco Basin earthquake sources and their characteristics for use in seismic design. These studies provide a preliminary basis for the identification of earthquake sources, the estimation of source characteristics, the estimation of seismic hazard, and the development of estimates of ground motions for the repository. However, because of the different nature of surface powerplants and a subsurface repository, and their differing time frames of 100 yr versus 10,000 yr, the direct applicability to repository siting of the previous seismic hazard and design efforts for commercial reactors at the Hanford Site is uncertain. Therefore, further studies are planned in seismology, as well as structural geology and tectonics, to characterize potential earthquake sources; study the differences of seismic wave transmission between the surface and subsurface; estimate vibratory ground motion; estimate the seismic

hazard; and estimate the potential for induced seismicity affecting the candidate site (see Sections 8.3.1.2.3.3.4, 8.3.1.2.4.3.2, and 8.3.1.2.4.3.3).

1.8.1.5 Long-term regional stability with respect to tectonic and geologic processes

Geologic processes that are part of the assessment of geologic stability include tectonic, volcanic, and geomorphic processes. The assessment of their stability emphasizes the postclosure, long-term isolation period, considered to be the next 10,000 yr. The approach to such assessments is based on the investigation, analysis, and interpretation of past and present geologic processes so that mechanisms and rates may be projected to the future. Models that describe the processes are developed to provide qualitative and (or) quantitative characteristics of the nature, mechanism, and rates of each process. The assessment of geologic and tectonic stability is important in characterizing the repository environment, assessing repository performance, and providing information used in repository design.

The assessment of tectonic stability is based on the development of one or more tectonic models. The tectonic model is a nonnumerical descriptive theory or concept that incorporates geological, geophysical, seismological, and geodetic data into a satisfactory explanation of the evolution of stress and strain in the Earth's crust--in this case for the candidate area and candidate site. Thus, a tectonic model can be used to predict the character of future processes, such as preclosure vibratory ground motion and displacement and postclosure displacement or strain, that could affect the groundwater flow regime and, thus, potentially impact waste isolation.

The scales at which tectonic models exist to describe the candidate area and candidate site are for the Pacific Northwest, the Columbia Plateau, and the Pasco Basin. No single model satisfactorily addresses or explains all of the data and observations. However, a unique model is not required if several preferred models predict, with reasonable assurance, that the consequences of future tectonic events and processes will permit operation and performance of the repository within regulatory requirements.

Development of preferred tectonic models for the analysis of tectonic stability is continuing. Such development must consider the origin, nature and characteristics of specific structures, and rate of tectonic development, of the Yakima folds; why the folds and faults are located where they are; and the relationship of the Pasco Basin to the more regional tectonic framework and processes. Studies to address further development of tectonic models and to reduce the uncertainties in data and intepretations that support the models are described in Sections 8.3.1.2.3 and 8.3.1.2.4.

Volcanism that has affected the candidate area and candidate site in the past has come from two sources: (1) eruption of flood basalts in the Columbia Plateau and (2) eruption of calc-alkaline and basaltic deposits from the Cascade Range, located west of the Pasco Basin. These two areas are

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considered to be the only geologically likely areas in which volcanism may recur in the next 10,000 yr and may potentially affect a repository in the Pasco Basin.

Volcanism that produced the Columbia River basalt started about 17 m.y.B.P. and occurred intermittently until about 6 m.y.B.P. There has not been any basalt volcanism in the Columbia Plateau since 6 m.y.B.P. This past 6-m.y. period of inactivity plus the relatively low-average heat flow of the Columbia Plateau strongly suggests that Columbia River basalt volcanism is unlikely during the postclosure (10,000-yr) period. However, if such volcanism were to recur, the consequences (e.g., breach of the repository by dikes, thermally induced stress, changes to the groundwater regime, and topographic changes to the surface water regime) could adversely affect the repository. Therefore, studies are planned to address the consequences and the probabilities of renewed Columbia River basalt volcanism (Section 8.3.1.2.4.3.3).

Arc-type volcanism in the Cascade Range, related to plate subduction, has been recurrent since about 38 m.y.B.P. The Quaternary manifestation of this activity has been eruption of the High Cascade Range volcanoes, such as Mount Baker, Glacier Peak, Mount Rainier, Mount Adams, Mount St. Helens, Mount Hood, Mount Mazama (Crater Lake), Mount Shasta, and Mount Lassen. The primary products of these eruptions have been air-fall tephra (volcanic ash), lava flows, and various forms of pyroclastic flows. Other effects have included volcanic mudflows and landslides. The Quaternary stratigraphic record in the Pasco Basin indicates that air-fall tephra and reworked tephra in stream sediments are the only likely products from Cascade Range volcanism that would be expected to potentially affect the repository during the preclosure and postclosure time periods.

The amount and characteristics of air-fall tephra that may reach the Pasco Basin depend on the location of the volcanic source, volume erupted, duration of eruption, height of eruption column, and characteristics of the prevailing wind. Design air-fall tephra estimates for the siting of nuclear reactors on the Hanford Site indicate that up to 10.6 cm (4.2 in.) of uncompacted tephra (7.4 cm (3 in.) compacted) could accumulate from a postulated future Cascade Range eruption at a distance of 165 km (103 mi). This is estimated to occur at a rate of up to 0.92 cm/h (0.36 in./h). Air-fall tephra could occur in the Pasco Basin over the next 10,000 yr, but it is likely to affect only facilities located on the surface. However, no detailed analysis has been made of the nature, magnitude, probability, and effects of renewed Cascade Range volcanism on the Pasco Basin and the reference repository location. Studies are planned to assess the impact of future Cascade Range volcanism on the candidate site (Section 8.3.1.2.4.3.3).

The geomorphic stability of the candidate area and the candidate site is, in general, a function of tectonic and climatic processes. Tectonic processes generally build the topography; whereas, processes related to climatic conditions (e.g., weathering, mass wasting, erosion) tend to degrade the topography. Future tectonic processes will be primarily the continued development of the Yakima folds. Erosion tends to be concentrated on the

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anticlinal ridges while deposition (i.e., burial) occurs in the synclinal basins. Because the reference repository location is situated in the Cold Creek syncline, it is likely to experience continued deposition rather than erosion during the postclosure period.

Weathering, mass wasting, and erosion are anticipated during the preclosure and postclosure periods. Because of the low relief and arid climate, these processes will likely have a minimal effect on the repository and would not be expected to change the topography of the Cold Creek valley by more than a few meters over the next 10,000 yr.

Erosion and (or) deposition resulting from glacial-induced cataclysmic flooding may occur during postclosure. However, it is most likely to occur sometime after 10,000 yr. Given the possibility of such flooding, erosion and breach of the repository is not expected because the Pasco Basin has been an environment of deposition, not erosion, during the past several events of cataclysmic flooding during the Pleistocene. Hydrostatic loading by the flood waters, however, may affect the groundwater regime in the vicinity of the repository. The potential for such loading and its effects will be studied in site characterization (Section 8.3.1.2.4.3.3).

Landslides have occurred during the Quaternary and historic time along the Columbia River. These have caused localized damming and channel adjustments. The volume of material necessary to totally dam the Columbia River, at a location where such volumes are available, and that would result in flooding of the repository is enormous and considered to be unlikely during the preclosure and postclosure periods. However, this scenario will be addressed during site characterization studies (Section 8.3.1.5).

Geomorphic processes such as tectonic uplift, subsidence, and glaciation may directly affect the groundwater regime of the repository (e.g., changes to the hydraulic gradients and (or) flow paths) or indirectly affect it through changes of the surface water regime. In addition, isostatic loading of the crust by glacier ice, even at the distances of past glaciations (130 km (80 mi)) north of the reference repository location), may result in fracturing within the basalt at the candidate site. This could lead to changes in the groundwater regime, as well as possible induced seismicity. Because of the low rates of tectonic strain and the low apparent probability for renewed glaciation during the next 10,000 yr, the potential effects of such geomorphic processes are considered to be minor. However, detailed analyses of the potential effects have not been made and such studies are planned for site characterization (Section 8.3.1.2.4.3.3).

1.8.1.6 Drilling and mining

Approximately 2,200 boreholes have been drilled on the Hanford Site and adjacent areas since about the turn of the century. These include boreholes that have been drilled for water supply, oil and gas exploration and production, surveillance and waste management, nuclear powerplant siting, and

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repository feasibility and siting. The wells drilled for water supply have all been less than 300 m (1,000 ft) deep, except for an emergency water-supply well drilled to 599 m (1,964 ft) for the Fast Flux Test Facility on the Hanford Site. Oil and gas exploration wells have penetrated to depths of 3,248 m (10,655 ft) in the Pasco Basin, but the closest one (2.5 km (1.6 mi)) to the reference repository location is only 610 m (2,000 ft) deep and penetrates only the lower Wanapum Basalt. Boreholes drilled for surveillance and waste management at the Hanford Site are generally within the suprabasalt sediments or into the top of basalt. Boreholes drilled for nuclear powerplant siting are generally shallow, with the deepest penetrating the uppermost confined aquifer, the Rattlesnake Ridge interbed. Of the boreholes drilled for repository studies, only 17 in the reference repository location extend below the top of basalt and penetrate the upper confined aquifer. Several boreholes penetrate the lower Grande Ronde Basalt.

No subsurface penetrations, other than boreholes and the Near-Surface Test Facility, exist within the reference repository location or controlled area study zone (within 10 km (6 mi) of the reference repository location). The locations and status of boreholes within the Hanford Site and the reference repository location are well documented. Locations and status of water-supply wells outside the Hanford Site and within the Pasco Basin are generally known or traceable through drilling records, although not all such wells may have available records. None of the known offsite water-supply wells penetrate to depths of the Cohassett flow.

All boreholes within the reference repository location and the controlled area study zone that penetrate the Grande Ronde Basalt and the candidate horizons contain grouted-in piezometers or removable bridge plugs to prevent aquifer interconnection or crossflow. No boreholes within the reference repository location or the controlled area study zone penetrating the basalts were abandoned or plugged back to the surface. Outside the reference repository location, aquifer interconnection and potential crossflow may be possible in two deep boreholes, Rattlesnake Hills No. 1 and Walla Walla No. 6, in the Grande Ronde Basalt.

1.8.1.7 Mineral and hydrocarbon resources

The natural resource potential of the candidate area is a consideration in evaluating the possibility for future inadvertent intrusion to the repository as a result of exploration activities. Potential mineral resources known to exist within 100 km (62 mi) of the controlled area study zone include lignite, peat, geothermal, gold, clay, diatomaceous earth, mineral water, perlite, pumice, sand, gravel, and stone. Current mining activity is limited to surface extraction of diatomaceous earth, sand and gravel, and stone. With the exception of low-grade, placer gold along the Columbia River near Blalock Island, 68 km (42 mi) south of the reference repository location, and high-grade underground gold near Wenatchee, Washington, 80 km (50 mi) northwest of the reference repository location, no high-unit-value mineral resources are known to occur within 100 km (62 mi) of the reference repository location.

Current mining activity, or activity that can be reasonably expected during the next 25 yr, within 100 km (62 mi) of the reference repository location, would not be affected by a nuclear waste repository located at the proposed depth of approximately 900 m (3,280 ft). No loss of gross or net value of mineral resources, with the possible exception of natural gas, from future mineral production is likely.

The geologic setting of the reference repository location suggests that the area is relatively unattractive for future subsurface mineral exploration and development. However, since economic conditions, especially gold prices and interest rates, have changed dramatically since 1980, studies to reevaluate these mineral resources are outlined in Section 8.3.1.6.3.3.

Exploration for hydrocarbon resources within the Columbia River basalts has occurred over the past 70 yr in the areas of Rattlesnake Mountain, Benson Ranch, and Frenchman Hills. Currently, there is no gas production from the Columbia River basalts within 100 km (62 mi) of the reference repository location. Based on the occurrence of geologic environments similar to that of the Rattlesnake Hills gas field and available drilling results, it is estimated that future shallow production of natural gas within the Columbia River Basalt Group is possible in three areas: (1) the westward or southeasterly extension of the Rattlesnake Hills gas field, Benton County, Washington; (2) the Mabton area of Yakima County, Washington; or (3) the Frenchman Hills area of Grant County, Washington. Although several deep water wells have been drilled into basalt in each of these areas, only small amounts of natural gas have been encountered in the basalt. No boreholes within the Columbia Basin, with the exception of the old Rattlesnake Hills gas field, have ever encountered commercial quantities of gas, including the numerous boreholes drilled in and around the reference repository location.

Exploration for hydrocarbon resources within the sub-basalt rocks within the candidate area has continued since 1929 and has increased since 1980. There have been at least 10 boreholes drilled that exceed 1,000 m (3,300 ft) depth. Commercial natural gas deposits could be present beneath the Columbia River basalt. Areas attracting the greatest exploration interest to date are located along anticlines. These folds are of special interest where they overlie thick sequences of potentially carbonaceous source rocks. Although noncommercial gas has been found in interbeds within the Columbia River Basalt Group, the basalt is not considered a good reservoir, although it may act as a caprock to confine upward migration of natural gas.

Currently, the thickness, distribution, and hydrocarbon potential of the sub-basalt sedimentary sequence in the Pasco Basin are unknown. However, the location of the Pasco Basin within a large regional depression suggests that the Basin is not a structurally favorable exploration target when compared with adjacent anticlinal areas of the Columbia Plateau. Additional studies to assess the hydrocarbon resource potential of the sub-basalt sequences as well as the basalt are discussed in Section 8.3.1.6.3.

1.8.2 RELATION TO DESIGN

The geologic and tectonic environment containing the candidate site has an important influence on the design of the repository and its facilities. Natural and manmade components for both surface and subsurface facilities must be able to function properly both during the preclosure and postclosure time periods to maintain waste isolation. The design of these components is based in part on information developed from the study of the geology of the candidate area and the site.

The study of stratigraphy and structure provides information to be used in the design of the repository layout; design and placement of shaft seals; and the design of roof supports and stable openings. The subsurface geometry of the Cohassett flow, which is the repository horizon, is derived from the study of stratigraphy and structure. This geometry and its lateral continuity are critical to the repository layout design as well as the placement and design of shaft seals (see Sections 6.3.2 and 6.3.5). Lateral variations in thickness of Cohassett intraflow structures versus the dense interior also affect repository layout and the design of roof support. The location, nature, frequency, and extent of rock fractures affect the design of roof support, the stability of mined openings, and shafts and provide input to the design of mine pumping capacities and construction strategies (see Sections 6.3.2, 6.3.4, 6.3.5, and 6.3.6).

The study of the seismology and tectonic evolution of the site provides input to the seismic design of surface and subsurface repository facilities (see Section 6.3.7). Important parameters provided are the location and size of the design-basis earthquake; vibratory ground motions; and the location and magnitude of potential fault displacement. The study of tectonic deformation provides information on the magnitude and direction of in situ stress, which is input to the design of stable openings and shafts (see Section 6.3.2), and used in developing estimates of rock mass strength for design of waste placement (see Section 6.3.4). The study of volcanic processes and potential volcanic hazards provides input to the analysis of the type, magnitude, and probability of volcanism in the Pasco Basin. This information may be further used in design (see Section 6.1.2.8).

The mineralogic and petrologic characteristics of the host rock and fracture infillings are used in the design of the waste package (see Section 7.2). The waste package-host rock interaction and potential changes to this interaction are affected in part by the mineralogic and petrologic conditions of the host rock and fracture-filling materials.

1.8.3 IDENTIFICATION OF INFORMATION NEEDS

Chapter 1 presents data and interpretations that have been obtained for the purpose of site selection as defined in 10 CFR 960 (DOE, 1987b). The current geologic data base contains a number of areas with incomplete data sets, inadequate detail of data, or uncertainties in data that limit analysis

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and interpretation. Additional data pertaining to the geologic characteristics of the candidate area and site must be obtained, analyzed, and interpreted for three purposes: site characterization, assessment of performance of the site as a repository, and as input to the design of a repository.

Chapter 8 presents the analysis of issues that remain to be resolved with respect to a site characterization program (Section 8.2), and also a description of the activities planned to address those issues (Section 8.3). The following is a brief summary of the geologic information that is considered necessary to complete the resolution of issues. The term "information need" is used in the context of the "Issues Hierarchy For A Mined Geologic Disposal System" as defined by DOE (1986) (see Section 8.1.1). An information need is that information required to resolve a particular issue; the information need is the level at which the issues hierarchy becomes specific for the Hanford Site.

The issues hierarchy that has been esablished for mined geologic disposal systems classifies issues into three categories: performance, design, and characterization (DOE, 1986, pp. 2-3) (see Section 8.1.1). Performance issues are questions involving performance of the disposal system with regard to regulatory requirements. Design issues are questions about the design of the repository, seals, and waste package. Characterization issues are questions about the site characteristics, processes, and events that may affect the design and performance of the disposal system. Resolution of the characterization issues provides the data that are needed to address the design and performance issues. Information needs for the resolution of all categories of issues are developed for each candidate site.

For the BWIP Site Characterization Program (Chapter 8), individual studies in geology have been designed that are parallel in organization to the information needs that have resulted from an analysis of issues (Section 8.2; see Table 8.2.2-1 for a complete list of program-wide information needs and their correlation to issues). These studies have been grouped into larger units having a common discipline; they are referred to as investigations and their titles are shown in Table 1.8-1. Note that future investigations of natural resources, while treated as part of the geologic description of the site in Chapter 1, are presented as a separate site program in Section 8.3.

The issues are listed in Table 1.8-1 are those that pertain to performance and design of a repository. Discussion of characterization issues, as defiend by DOE (1986, pp. 5-10), is incorporated into the discussion of individual studies in Section 8.3.1.2. Table 1.8-2 presents an outline of the investigations and studies for the geology and natural resources programs, along with a cross-reference to background information in Chapter 1. The studies that are listed in Table 1.8-2 can be viewed as the geologic information needs that are required to resolve characterization issues, as well as performance and design issues.

Table 1.8-1. Correlation between the geology and natural resources programs and the issues hierarchy

Specific site program (SCP Section)				Geology (8.3.1.2)										Resource Potential (8.3.1.6)	
Investigation (s = same title as study)				Stratigraphy and structure						Tectonic events and processes			S	S	S
Issue			Study/Information need	Strati-graphy	Intraflow structure	Cooling Joint Charac-teristics	Structural geology	Physical rock proper-ties	Strati-graphic and structural model	Defor-mation	Earth-quake seis-mology	Tectonic assess-ment	Mineralogy and petrology	Mineral, hydro-carbon, geo-thermal	Water resource
Key issue	Post-closure Perfor-mance	1.1	Release to accessible environment	●	●	●	●	●	●	●	●	●	●	●	●
		1.2	Individual protection	●	●	●	●		●			●	●		
		1.3	Groundwater protection	●	●	●	●	●	●			●	●		●
		1.4	Waste package containment										●		
		1.5	Radionuclide release rates										●		
		1.6	Groundwater travel time	●	●	●	●		●						
		1.7	Performance confirmation				([a])								
		1.8	NRC siting criteria* FC	5, 7	7	7	7	2, 5, 7		1		1	4, 7		
			NRC siting criteria* PAC	2, 4, 10, 17, 18, 20	20, 21	10, 20	20	20	21	11, 13, 16	4, 11, 12, 13, 14	3, 4, 13, 15	9	2, 17, 18	2
		1.9	DOE guideline findings**	A	A, C, K	A, C, K	A, C, G, K, M	C, K	A	C, E, G, K, M	G, M	E, G, J, M	A, B, F	H	H
		1.10	Waste package design												
		1.11	Repository design	●	●	●	●	●	●						
		1.12	Shaft and borehole seals	●	●	●			●		●				
	Pre-closure radio-logical safety	2.1	Public safety during normal operation												
		2.2	Radiological safety of workers												
		2.3	Public safety during accidents		●	●	●				●				
		2.4	Waste retrieval	●	●	●					●		●		
		2.5	DOE guideline findings[a]	●	●	●	●	●			●		●		
		2.6	Waste package design												
		2.7	Repository design	●	●	●	●	●			●				
	Design	4.1	DOE guideline findings[b]	●	●	●	●	●	●		●		●		
		4.2	Nonradiological worker safety	●	●	●	●	●			●		●		
		4.3	Waste package production												
		4.4	Adequacy of technology for repository												
		4.5	Costs												

[a]Uses parameters from Issues 2.1, 2.2, 2.3, 2.4, and 2.7.
[b]Uses parameters from Issues 1.10, 1.11, 1.12, 2.7, 4.2, and 4.3.

● Issue identifies site program parameter(s).
* Number refers to favorable condition (FC) and potentially adverse condition (PAC) listed in Table 8.3.1.1-1.
** Letter refers to technical guideline listed in Table 8.3.1.1-2.

DOE = U. S. Department of Energy.
NRC = U. S. Nuclear Regulatory Commission.
SCP = Site Characterization Plan.

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CONSULTATION DRAFT

Table 1.8-2. Site programs presented in Section 8.3.1.2 (geology) and Section 8.3.1.6 (natural resources) of the site characterization plan

Investigation	Information need	Chapter 8 subsection	Chapter 1 cross reference
Geology program			
Stratigraphy and structure	Stratigraphy	8.3.1.2.3.3.1	1.2
	Intraflow structure	8.3.1.2.3.3.2	1.2.1.2.2, 1.2.2.1.4
	Cooling joint	8.3.1.2.3.3.3	1.2.1.2.3, 1.2.2.1.5
	Structural geology	8.3.1.2.3.3.4	1.3
	Physical rock properties	8.3.1.2.3.3.5	1.2.1.2.4 (see Chapter 2)
	Stratigraphic/structural model	8.3.1.2.3.3.6	1.2.2, 1.3.2.2.2, 1.3.2.2.3
Tectonic events and processes	Deformation	8.3.1.2.4.3.1	1.3.2.2, 1.3.2.3, 1.3.2.4
	Earthquake seismology	8.3.1.2.4.3.2	1.4
	Tectonic assessment	8.3.1.2.4.3.3	1.5
Mineralogy and petrology	Mineralogy and petrology	8.3.1.2.5.3.1	1.2.1.2.4 (see Chapter 4)
Resource potential program			
Mineral, hydrocarbon, and geothermal resource potential	Mineral, hydrocarbon, and geothermal resource potential	8.3.1.6.3.3	1.7

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1.8.4 RELATION TO U.S. NUCLEAR REGULATORY COMMISSION REGULATORY GUIDE 4.17

The content of this chapter follows the DOE annotated outline (DOE, 1987a) that was developed directly from the NRC Regulatory Guide 4.17 (NRC, 1985). The annotated outline contains no significant changes from the regulatory guide regarding the content of this chapter, which therefore addresses the requests of the regulatory guide.

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