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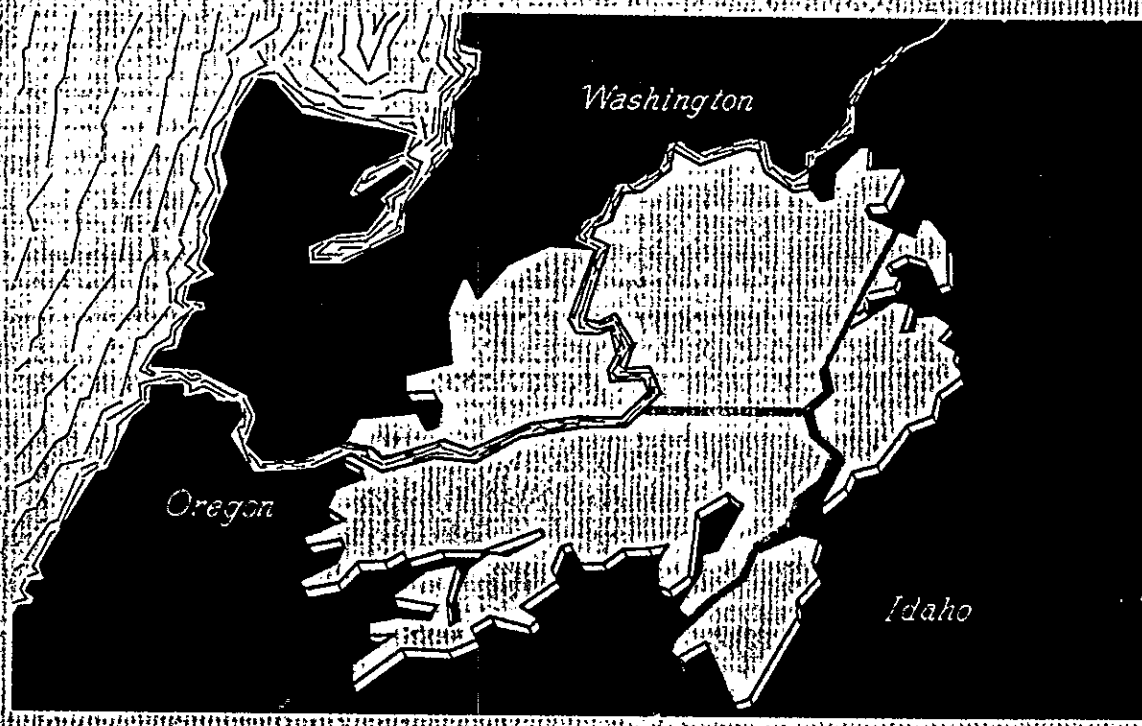
Geologic Studies of the COLUMBIA PLATEAU

A Status Report
October 1979



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A STATUS REPORT

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October 1979

GEOLOGIC STUDIES OF THE COLUMBIA PLATEAU: A STATUS REPORT

This document represents a compilation of data and interpretive studies conducted as part of the geologic program of the Basalt Waste Isolation Project. The overall objective of these studies is to provide geologic information necessary to identify areas beneath the Hanford Site within the State of Washington that have a high probability of containing basaltic rock suitable for a nuclear waste repository.

This report is being given a broad distribution extending throughout the scientific community to ensure that input and comments are received regarding the information contained herein. If you have any comments or suggestions regarding the information contained in this report or suggestions regarding additional areas of study, please contact Dr. Raul A. Deju, Director of the Basalt Waste Isolation Project, Rockwell Hanford Operations, Post Office Box 800, Richland, Washington 99352.

Sincerely,

R. A. Deju, Director
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SUMMARY

INTRODUCTION (CHAPTER I)

The overall objective of the geologic studies has been to provide geologic information necessary to identify areas beneath the Hanford Site that have a high probability of containing basaltic rock suitable for a nuclear waste repository. Geologic investigations have included reconnaissance studies, studies within a large region representing much of the outcrop extent of the Columbia River basalt, and detailed studies within the Pasco Basin where the Hanford Site is located. Both regional and Pasco Basin studies have emphasized those aspects of the lithology, stratigraphy, structure, and tectonic stability of the Columbia River Basalt Group that relate to geologic considerations for repository site selection and evaluation within the Hanford Site.

Some specific accomplishments of the regional and Pasco Basin studies are as follows:

(a) Surface geologic mapping has been completed within the Pasco Basin and within the Washington State portion of the Columbia Plateau;

(b) Aeromagnetic, magnetotelluric, and other geophysical surveys have been completed within the Pasco Basin;

(c) Preliminary basin-wide subsurface maps and cross sections have been prepared across the Pasco Basin using results from the surface mapping and geophysical surveys and the results from deep boreholes; and,

(d) Results of earthquake monitoring within the region have been summarized and an assessment of the tectonic stability of the Pasco Basin has begun.

REGIONAL STUDIES (CHAPTER II)

Regional studies included a literature search, surface geologic mapping, and a photolineament analysis. Regional studies have been primarily of a reconnaissance nature and were designed to augment detailed studies conducted concurrently within the Pasco Basin.

The literature search served as a basis for evaluating the magnitude of additional stratigraphic, structural, and tectonic studies required to formulate a regional geologic understanding of the Columbia Plateau. The survey involved a review of published and unpublished documents available from governmental agencies, universities, and private industry. The review resulted in the compilation of bibliographies containing over 3,000 Columbia Plateau references.

The stratigraphy and structure of the Columbia River Basalt Group within Washington State have been defined through the compilation of a regional geologic map at a scale of 1:250,000. The map was produced through a synthesis of previously existing data and new field studies. The map compilation shows that a plateau-wide basalt stratigraphy is present, and that basalt flows throughout the region can be correlated through a combination of chemical, paleomagnetic, and field techniques.

In the map area, the Columbia River Basalt Group within Washington State has been divided into 4 formations, 14 members, and 4 informal paleomagnetic subdivisions. The oldest formation, the Imnaha Basalt, crops out only within the extreme southeastern portion of the plateau where it is conformably overlain by flows of the Grande Ronde Basalt. The Grande Ronde Basalt is the most areally extensive unit of the Columbia River Basalt Group and it underlies most of the map area, including the Pasco Basin. The basalt comprising this formation was extruded between 14 and 16 million years before present from vents, now exposed as dikes, in the southeastern portion of the plateau. The known thickness of the Grande Ronde Basalt ranges from tens of feet (meters) along the margins of the Columbia Plateau to more than 3,000 feet (1,000 meters) within the Pasco Basin.

Grande Ronde Basalt flows within the mapped area have a continuous range in chemical composition. However, the flows can be divided into two chemical types on the basis of MgO content (termed low-MgO and high-MgO). Within localized areas of the plateau, chemical "breaks" between sequences of flows having low-MgO and high-MgO chemical compositions have been used for correlation and mapping purposes. However, the only known, consistently mappable, regional subdivisions of the Grande Ronde Basalt are four magnetostratigraphic units defined on the basis of dominant magnetic polarity: reversed-one (R_1); normal-one (N_1); reversed-two (R_2); and, normal-two (N_2) (listed in order of decreasing age).

Further subdivision of Grande Ronde Basalt, beyond the regional magnetic units, has not been recorded on the reconnaissance geologic map. However, previous work and work for the regional mapping effort have revealed distinctive Grande Ronde Basalt flows, herein termed "through-running" flows. They are identifiable through a combination of chemical, paleomagnetic, and field techniques, and generally have a known areal extent of over 100 square miles (250 square kilometers) and a thickness of over 100 feet (30 meters). They are particularly evident in the deep canyon exposures of Grande Ronde Basalt in the southeastern portion of the plateau. Such flows have also been recognized in the Pasco Basin.

The Grande Ronde Basalt sequence is overlain by the Wanapum Basalt sequence, the second-most voluminous of the four formations. Wanapum Basalt flows define the plateau surface throughout much of the mapped area. These flows can be subdivided into four recognized members, which generally have a relatively "high" FeO and TiO_2 content in comparison to flows of the underlying Grande Ronde Basalt. Source dikes for three of the four members have been identified.

Saddle Mountains Basalt is the youngest formation of the Columbia River Basalt Group and is divisible into 10 members. Members of the Saddle Mountains Basalt display the greatest petrographic, chemical, and paleomagnetic variability of any formation of the Columbia River Basalt Group. Because of their distinctive character, these members form distinctive, mappable horizons throughout the region.

The Saddle Mountains Basalt was extruded between 6 and 13.5 million years before present. The extrusion period was marked by waning volcanism, by the development of thick, sedimentary units between flows, and by accelerated folding and canyon cutting. Most of the flows were erupted from fissures located in the southeastern and south-central portions of the plateau. The distribution of several of the Saddle Mountains Basalt members in relation to their source vents indicates they advanced down ancestral drainages (primarily the Snake River) to reach the central and western portions of the Columbia Plateau. The distribution

of Saddle Mountains Basalt flows, and intercalated sedimentary units, can be used to indicate the locations and timing of the development of structures within the plateau.

The stratigraphy and structure of late Cenozoic sediments within Washington State have also been defined through the compilation of a regional geologic map at a scale of 1:250,000. In the map area, late Cenozoic sediments were divided into 18 map units. Of these units, the most widespread includes the Pliocene suprabasalt Ellensburg and Ringold Formations, the Pleistocene catastrophic flood deposits, and Pleistocene to Recent eolian loess deposits.

The Ellensburg Formation includes weakly lithified clastic and volcaniclastic sediments which occur within the western and central portions of the Columbia Plateau. Units of the formation underlie, interfinger, and overlie flows of the Columbia River Basalt Group. Because of this stratigraphic relationship, Ellensburg deposits are recorded on both the Columbia River basalt and the late Cenozoic map sets. The Ellensburg deposits are thicker and coarser grained in the far western portion of the Columbia Plateau and reflect a nearby Cascade Range source area.

The Ringold Formation overlies the Columbia River Basalt Group in the central plateau. Sediments of this formation may be, in part, time correlative with the uppermost Ellensburg Formation.

The central and eastern portions of the map area are dominated by erosional features and sedimentary deposits of the Channeled Scablands. During Pleistocene glaciation, the present scabland area was subjected to a number of catastrophic floods which resulted from the break-up of ice dams impounding glacial lakes in Idaho, Montana, and northeastern Washington. The number and sequence of floods are not known, but most surficial flood deposits are thought to be associated with the last major flood dated at approximately 13,000 years before present.

The eastern portion of the plateau is covered by eolian loess which includes four distinct units; three Pleistocene units and a younger late Wisconsinan to Recent loess have been correlated with glacial events in the region.

The stratigraphic framework established by the geologic mapping was used to interpret the structural character of the Washington State portion of the Columbia Plateau. In general, the plateau can be divided into three areas of different structural character, informally termed the Yakima Fold Belt subprovince, the Palouse subprovince, and the Blue Mountains subprovince.

The Yakima Fold Belt subprovince covers the central and western parts of the Columbia Plateau. This subprovince is characterized by linear anticlines and broad synclines. These structures extend eastward from the western margin to the approximate center of the plateau, where they generally die out. Most known faults are associated with the anticlinal fold axes and probably developed at the same time as the folding. It is interpreted on the basis of flow and interbed distribution that, although the formation of these folds began as early as late Grande Ronde time (late N_2 time), deformation was most rapid during late Saddle Mountains time. Sediments of the Ellensburg Formation and Ringold Formation were involved in the folding process, but younger sediments are generally undeformed. However, an area of possible Holocene faulting was observed along Toppenish Ridge, located about 50 miles (80 kilometers) to the southwest of the Pasco Basin.

The Palouse subprovince is located in the northeastern portion of the Columbia Plateau. This subprovince is underlain by basalt flows with a regional dip of less than 5 degrees to the southwest. The distribution of basalt flows indicates that this dip is a reflection of regional subsidence that began in early Grande Ronde time. In general, the Palouse subprovince is structurally simple, with the most prominent structures consisting of broad folds with tens of feet (meters) of amplitude.

Only the extreme northeastern section of the Blue Mountains subprovince is located within Washington State. This subprovince is essentially a broad, northeast-trending anticlinal arch that was uplifted during Miocene-Pliocene time. With the exception of the Walla Walla, Washington area, deformation involving late Cenozoic sediments was not observed within the subprovince.

Regional geologic mapping studies were supported by an analysis of Landsat satellite imagery and U-2 aerial photography. The purpose of this analysis was to identify regional and localized surface features of potential significance to the structural geology of the Columbia Plateau. The analysis of U-2 imagery significantly enhanced the geologic interpretation of photolineaments. A comparison of field and remote sensing results indicated that structures with distinct topographic expressions are best identified using satellite and aerial imagery.

PASCO BASIN STUDIES (CHAPTER III)

Pasco Basin studies included surface geologic mapping, borehole studies, and geophysical surveys to determine the stratigraphy, structure, and tectonic stability of the Pasco Basin. The Pasco Basin includes the Hanford Site of the U.S. Department of Energy.

The thickness, sequence, and lateral extent of Grande Ronde Basalt flows in the Pasco Basin subsurface have been determined through the use of basin-wide correlations combined with surface mapping and deep core drilling. Basalt unit identifications were made using chemical composition, paleomagnetism, and borehole geophysical logs. Grande Ronde Basalt flows in the Pasco Basin are subdivided into two distinct sequences of flows; a lower sequence, informally named the Schwana sequence, and an upper sequence, informally named the Sentinel Bluffs sequence. The Schwana sequence is at least 2,500 feet (750 meters) thick and consists of at least 15 to 25 separate flows. Overall, the Schwana sequence flows average about 3.5 percent MgO (low-MgO chemical type) except for a thin sequence of low K_2O flows which average 5.5-6.0 percent MgO (very high MgO chemical type). The N_2/R_2 and possibly R_2/N_1 regional magnetostratigraphic horizons and 5 chemical-stratigraphic units have been identified and correlated within the Schwana sequence. The Sentinel Bluffs sequence averages about 895 feet (272 meters) thick in the central Pasco Basin and consists of 5 to 12 flows. The Sentinel Bluffs sequence flows average about 5 percent MgO (high-MgO chemical type) and contain two correlative magneto-stratigraphic horizons.

The upper Grande Ronde Basalt in the Pasco Basin contains at least two units currently interpreted as individual flows that are laterally continuous throughout the central Pasco Basin and are relatively thick compared to other flows in the upper Grande Ronde Basalt. One of the thick "through-running" flows, the Umtanum flow, has an anomalously low paleomagnetic inclination and is effectively a marker horizon throughout the Pasco Basin subsurface. Because

of their thickness and lateral extent, the flows should be considered as candidate host rock. The two flows are separated one from another and from overlying and underlying basalt flows by sequences consisting of thinner flows, some of which appear to pinch out within the central Pasco Basin, but are probably laterally extensive across the basin. This report contains a stratigraphic section and a discussion of the above relationships.

The major geologic structures that have deformed the upper Grande Ronde Basalt flows in the Pasco Basin since their emplacement and cooling have been identified. Foremost among these are the Yakima Folds. Individual folds trend east in the northwestern part of the basin and southeast in the southeastern part of the basin. Structural relief decreases to the east, but varies locally because of culminations and depressions along the hinge zone of individual folds. Folds are locally faulted along their steep limbs and contain subsidiary folds and faults on their gently dipping limbs. Generally, anticlinal hinge zones are more deformed than synclinal hinge zones. Most subsidiary, second-order structures are parallel to the trend of the first-order structures, but some structures have been identified which cross-cut the structural hinge zones at an oblique angle and might extend down the limbs across synclines. Aeromagnetic surveys have been used to locate and trace buried first-order folds and second-order structures on the flanks of first-order folds. Reflection seismic survey results have also revealed buried second-order structures. Preliminary structure contour maps, structure cross sections, and isopach maps have been prepared. These maps indicate that potential host rock units are at depths of approximately 2,500 to 4,500 feet (762 to 1,372 meters) in the central Pasco Basin, and dips average less than 3 degrees across areas in excess of tens of square miles (kilometers) in the central Pasco Basin subsurface.

Structural analysis of the axial zone of eastern Umtanum Ridge indicates that the structure is an asymmetrical, non-cylindrical, overturned, plunging anticline. The axial zone is interpreted to be characterized by four longitudinal blocks separated by thrust faults and large shear zones. These blocks maintain their same relative position along strike, but differ from one another in their degree and type of internal deformation. The gently dipping, southern limb of the fold is characterized by little deformation other than tectonic master jointing. The hinge area is extensively "shatter brecciated" and the vertical to overturned northern limb is extensively sheared parallel to the layering.

Internal variation in cooling fracture pattern and lithologic properties has been examined in Grande Ronde Basalt flows in the Pasco Basin subsurface through a combination of surface outcrop studies and core studies. These studies, in essence, examined internal homogeneity and uniformity of the candidate basalt host rocks. Extensive surface exposures of Grande Ronde Basalt were studied to characterize the spectrum of intraflow structural types--mainly geometry of fracture patterns that developed during flow cooling.

Three types of intraflow structural types (with gradations) were recognized: (a) Type 1 flows have irregular columns, no entablature, are thin, and have a diktytaxitic texture; (b) Type 2 flows are thick, have a tiered structure consisting of alternating layers of different column sizes; and, (c) Type 3 flows are thick and generally lack flow top, but have well-developed colonnade and entablature separated by a sharp contact. Lateral variations were observed in thickness and fracture pattern within intraflow structural units. Gradual variations in fracture geometry were observed across distances of about 10 miles

(16 kilometers) in most flows, but in a few flows the variations were observed to occur abruptly across distances of several hundred feet (meters).

Two intraflow structures have been recognized that are of particular importance; flow-top breccia and pillow breccia. Flow-top breccia has been observed in several upper Grande Ronde Basalt flows in the Pasco Basin, including the Umtanum flow in places. Origin of the flow-top breccia is uncertain, but, where developed, it appears to partially replace what would otherwise be the entablature portion of the flow, thereby reducing the thickness of the flow interior. Pillow breccia has been observed in upper Grande Ronde Basalt flows, but not in the central Pasco Basin. Pillow breccia forms when lava enters water and, where developed, appears to partially replace what would otherwise be the colonnade or entablature portions of a flow.

Lithologic logs, geophysical logs, and petrographic data have been used to make preliminary interpretations of intraflow structures in the Umtanum flow, a potential repository host rock, across the Pasco Basin subsurface. The Umtanum flow averages about 200 feet (61 meters) total thickness across the central Pasco Basin. The flow top is typically a 25- to 50-foot (8- to 15-meter) thick rubble, but locally a flow-top breccia is developed and has a much greater thickness. The flow interior of the Umtanum flow is typically 150 to 175 feet (46 to 57 meters) thick, with the lower 10 to 60 feet (3 to 18 meters) consisting of the colonnade and the central 100 to 150 feet (30 to 46 meters) consisting of entablature. Tiered colonnade and entablature have been observed.

Results of stratigraphic analysis across a brecciated, slickensided gouge zone in core hole DB-10, located in the central Hanford Site near the Gable Mountain structure, revealed a zone containing 2 reverse faults with about 160 feet (55 meters) combined throw. This is the first unequivocal tectonic fault recognized as having been penetrated by drilling on the Hanford Site. Identification of the fault was confirmed by identifying repeated sections in the Saddle Mountains Basalt. The fault is tentatively interpreted as being the subsurface extension of a nearby structure(s) exposed in basalt bedrock on Gable Mountain.

SEISMICITY AND TECTONICS SUMMARY (CHAPTER IV)

The occurrence of earthquakes in the Columbia Plateau indicates that the area is experiencing stress, presumably tectonic, but details of the magnitude and orientation of that stress and possible variations thereof in lateral and vertical dimensions, or with geologic structure, remain to be determined. Focal mechanism solutions of a few events and composite mechanism solutions for earthquake events suggest that the principal compressive stress is nearly horizontal and oriented approximately north-south. Earthquake activity in the plateau appears to be from two different source depths: (a) shallow, low-magnitude events in small volumes of basalt; and, (b) deeper events below basalt that are of low magnitude and generally diffuse. This pattern was determined after a detailed, 10-year earthquake monitoring period. While there is no reason to suspect that the pattern will change after collecting more data, there is, similarly, no reason to assume that the pattern ascertained during the decade (1969 to 1979) will remain as it is. Cycles of activity are known in regions where a much longer historic record of earthquakes exist (for example, China and Japan). Should Columbia Plateau seismicity be cyclic, the length of the cycle, the present position within the cycle, and the nature of stress release throughout the entire cycle remain to be determined.

Most activity occurring in basalt appears to be in the form of swarms of low-magnitude, very shallow, temporally, and spatially restricted earthquake events. A typical swarm may contain events ranging in size from magnitude 0 to magnitude 3.5 to 4.0. Most swarms are characterized by several weeks to several months of activity, during which there may be a hundred to a thousand events less than magnitude 2.0. Within the 10-year period of monitoring, several areas have experienced swarms more than once.

Much geologic evidence from the regional and Pasco Basin studies suggests some tectonic deformation began as early as late Grande Ronde time (approximately 14 to 15 million years before present). This deformation was localized along present Yakima Fold trends and northwest-trending structures. The rate of tectonic deformation (i.e., an increase in structural relief) increased locally along these same trends, but was generally subdued through Wanapum time (approximately 13.6 to 14.5 million years before present). The rate of deformation was greatest in the Pasco Basin after late Saddle Mountains time (approximately 8.5 to 10.5 million years to approximately 5 million years before present). The extent of involvement of Ringold sediments in deformation appears to decrease from lower to upper Ringold units, suggesting that deformation continued into Ringold time possibly at a reduced rate. Upper Ringold sediments (less than 3.5 million years old) along the White Bluffs appear to be only slightly tilted, but here they overlie relatively gently dipping basalt.

The Miocene to Pliocene development of the Yakima Fold Belt subprovince generally has been attributed to north-south compression. Fault plane solutions (mostly composited from low-magnitude events in shallow swarms) indicate that the central Columbia Plateau is under a general north-south compression today. The main question to be tested regarding the tectonic stability of the Pasco Basin is the rate and recurrence interval of deformation along existing structures within the Yakima Basalt.

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CHAPTER I

INTRODUCTION

SCOPE

The results of recent geologic studies of the Columbia Plateau, with emphasis on work completed under the Basalt Waste Isolation Project, Rockwell Hanford Operations, are summarized in this report. Geologic studies were performed mostly during the period from 1977 to 1979. The major objective of these studies was to examine the feasibility of using deep underground tunnels mined into Columbia River basalt beneath the Hanford Site (Figure I-1) for final storage of nuclear waste.

The results are presented in four chapters: Introduction; Regional Geology; Pasco Basin Geology; and, Seismicity and Tectonics. Results from surface mapping and remote sensing studies in the Washington State portion of the Columbia Plateau are presented in the Regional Geology chapter. Results from surface mapping, borehole studies, and geophysical surveys in the Pasco Basin are presented in the Pasco Basin Geology chapter. Results that relate to the tectonic stability of the Pasco Basin and Columbia Plateau and discussion of findings from earthquake monitoring in the region for the past ten years are summarized in the Seismicity and Tectonics chapter.

A volume of Appendices is included. This volume contains a description of study tasks, a description of the methodology used in geophysical surveys, the geophysical survey results, a summary of earthquake records in eastern Washington, a description of tectonic provinces, and a preliminary description of the regional tectonic setting of the Columbia Plateau.

BACKGROUND

In February 1976, the U.S. Energy Research and Development Administration (currently the U.S. Department of Energy) expanded the commercial radioactive waste management programs and established the National Waste Terminal Storage Program. Its mission was to provide multiple facilities in various deep geologic formations within the United States. The Office of Waste Isolation was established within the Union Carbide Corporation-Nuclear Division to provide program management of the National Waste Terminal Storage Program. The overall program consisted of investigating a number of geologic rock types to determine their suitability for terminal storage of radioactive waste. Basalt, such as the Columbia River basalt which underlies a large portion of the Pacific Northwest and the Hanford Site, was selected for initial geologic reconnaissance. Atlantic Richfield Hanford Company was asked in May 1976 by the Office of Waste Isolation to plan and execute a basalt feasibility study. Geologic exploration of Columbia River basalt was needed to determine the feasibility of utilizing those formations as a site for terminal storage of commercial nuclear waste.

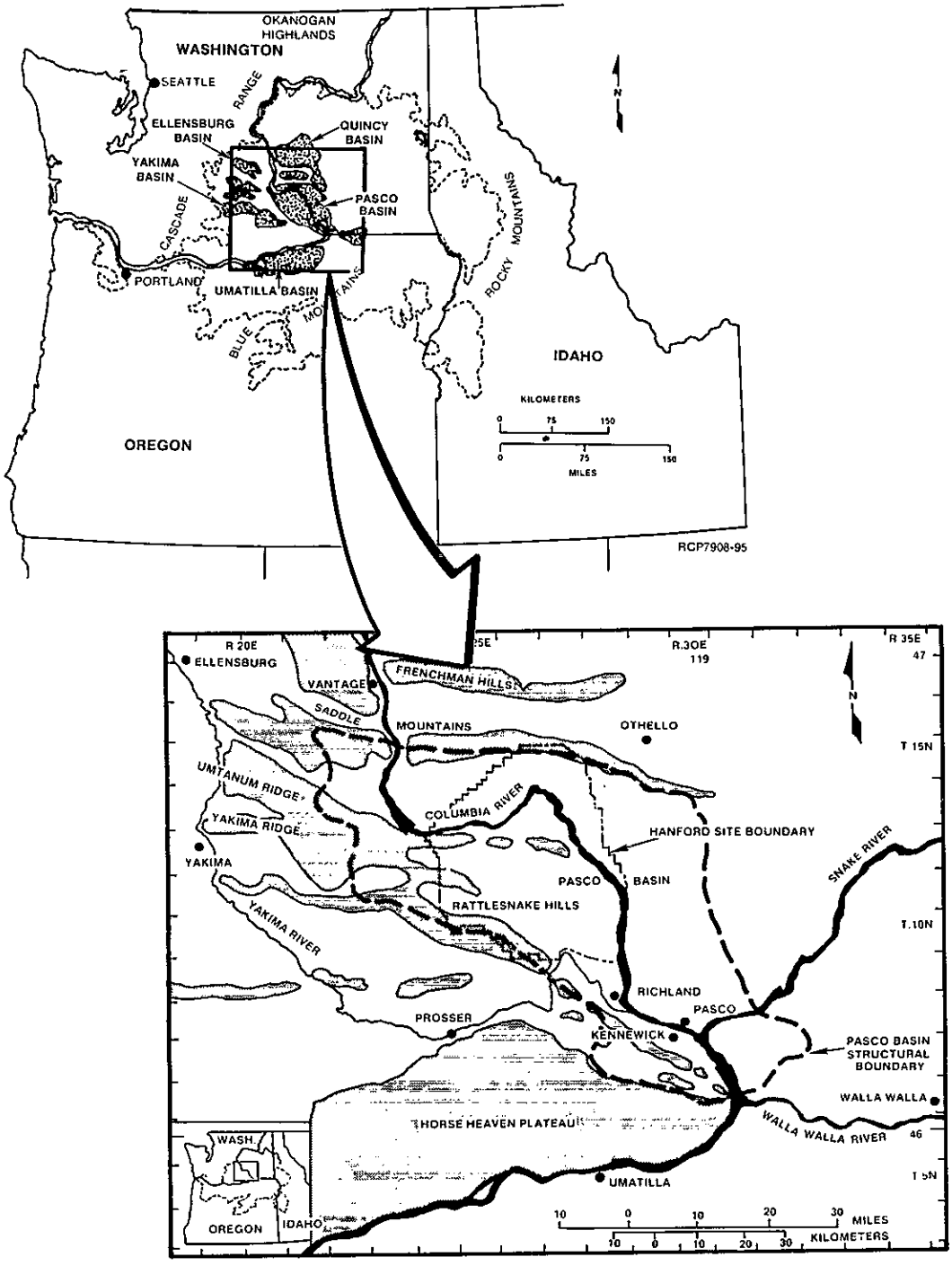

FIGURE I-1. Location Map, Columbia River Basalt, Pasco Basin, Hanford Site.

In September 1977, the National Waste Terminal Storage Program was restructured. While emphasis was still on a salt repository, additional funds were given to support investigations of two U.S. Department of Energy sites--Hanford and Nevada. The Hanford program is presently the responsibility of the U.S. Department of Energy-Richland Operations Office. Rockwell Hanford Operations (successor to Atlantic Richfield Hanford Company) is the prime contractor responsible for this work. The Basalt Waste Isolation Project within Rockwell Hanford Operations has been chartered with the responsibility of conducting these investigations. This report presents the results of geological work completed to date under this project.

Objective

The overall objective of the geologic studies has been to provide geologic information necessary to help identify and evaluate volumes of rock beneath the Hanford Site (Figure I-1) that have a high probability of containing basaltic rock suitable for a nuclear waste repository. The geologic investigations have included reconnaissance studies within a large region representing much of the outcrop extent of the Columbia River basalt and detailed studies within the Pasco Basin where the Hanford Site is located. Both regional and Pasco Basin studies, however, have emphasized those aspects of the lithology, stratigraphy, structure, and tectonic stability of the Columbia River basalt that relate to geologic considerations for repository siting and evaluation at the Hanford Site.

To achieve the overall objective noted in the preceding paragraph, several specific objectives were formulated (Table I-1) and work tasks were planned to meet these objectives.

Considerations

To assure isolation of hazardous radionuclides from the biosphere, any potential repository host rock must satisfy the following requirements:

(a) Be at sufficient depth;

(b) Have suitable dimensions;

(c) Be in a sufficiently stable tectonic environment;

(d) Be in an acceptable structural configuration; and,

(e) Have suitable lithologic properties.

Depth, rock mass dimensions, tectonics, structure, and lithology thus constitute five major geologic considerations for repository site selection and qualification. Knowledge of these major considerations requires, in turn, a detailed knowledge of geologic factors that are site specific. The objectives of the Rockwell Hanford Operations' geologic studies were formulated, therefore, to concentrate on those geologic factors judged most important to determine depth, dimensions, tectonics, structure, and lithology of selected units of the Columbia River basalt in the Pasco Basin.

TABLE I-1. Specific Geologic Objectives

REGIONAL GEOLOGY OBJECTIVES

- Collect, centralize, and evaluate currently available geologic data for those portions of Washington, Idaho, and Oregon contiguous to and covered by the Columbia River basalt.
- Prepare a reconnaissance geologic map of the Columbia Plateau including Columbia River basalt and late Cenozoic sediments.
- Analyze available remote sensing imagery to identify structural and tectonic features of potential significance.

PASCO BASIN GEOLOGY OBJECTIVES

- Prepare a detailed geologic map of the surface exposures of Columbia River basalt in the Pasco Basin study area.
- Utilizing surface geologic mapping, borehole data, and geophysical surveys, develop stratigraphic and structural interpretations of the Columbia River basalt and the overlying late Cenozoic sediments in the Pasco Basin with emphasis on the detailed stratigraphy of the Grande Ronde Basalt.
- Examine the lithologic properties of the Columbia River basalt in the Pasco Basin.
- Examine key results from previous and current work relating to the tectonic stability of the Pasco Basin and surrounding region.

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Previous work (ARHCO, 1976) indicated that geologic efforts for site selection should concentrate on the Grande Ronde Basalt, a formation within the Columbia River Basalt Group known to contain thick, internally dense flows.

Table I-2 shows that the major considerations that relate to the depth, dimensions, structure, tectonics, and lithology of the Grande Ronde Basalt in the Pasco Basin can be evaluated through knowledge of the factors of stratigraphy, structure, lithologic properties, intraflow structures, tectonic stability, and geomorphology. Furthermore, the data needed to evaluate subsurface basalt stratigraphy and lithology factors have been obtained mostly through surface mapping and drilling. Data needed to evaluate subsurface structure factors have been obtained largely through a combination of surface mapping, drilling, and geophysical surveys. Data needed to evaluate tectonic stability factors, however, require the integration of results from surface mapping, drilling, geophysical surveys (and other work not shown on Table I-2 such as seismic monitoring, geodetic surveys, crustal modeling studies, and in situ stress determinations).

Approach

Two key elements were used in setting priorities for this study. These were: (a) the determination of geologic conditions favorable to ground-water transport; and, (b) the determination of subsurface fracturing potential. Both of these elements are important inasmuch as they lead to adverse conditions that would preclude the siting of a repository within the Hanford Site.

Geochemical leaching followed by ground-water transport is generally acknowledged as the most probable mechanism by which radioactive wastes might migrate from a geologic repository (Bredehoeft and Others, 1978; National Academy of Sciences, 1978). Geologic studies for site selection and qualification have, therefore, concentrated on those aspects of the geologic environment that influence ground-water transport. This concentration has been reflected by the priorities given various types of geologic work on the Pasco Basin. Emphasis has been on the identification of potential flow paths along structures (faults, fracture zones, joints, dikes, or folds), potential flow paths along stratigraphic units (interbeds, interflow zones, pillow breccia zones, flow-top breccia, unconformities, or certain types of intraflow zones), and additional factors that might alter existing flow paths or generate new ones (primarily tectonic stability factors).

For preliminary site selection, priority was given to answering questions related to the structure and stratigraphy of basalt and secondarily to lithology and tectonics during site selection. During the site qualification phase, priority will be given to answering questions relating to lithology and tectonics.

TABLE I-2. Geological Considerations, Factors, and Data-Gathering Tasks in the Pasco Basin.

Major Geologic Considerations for Potential Host Rock					Specific Geologic Factors Relating to Potential Grande Ronde Basalt Host Rock in the Pasco Basin	Data Gathering Tasks: SURFACE GEOLOGIC MAPPING AND RELATED STUDIES					BOREHOLE STUDIES			GEOPHYSICAL SURVEYS: HIGH RESOLUTION SURVEYS					STANDARD SURVEYS				ANALYTICAL SUPPORT STUDIES					
Sufficient Depth	Suitable Dimensions	Acceptable Structural Configuration	Sufficiently Stable Tectonic Environment	Suitable Lithology		Geologic Mapping - Basalt	Geologic Mapping-Late Cenozoic Sediments	Yakima Fold Structural Analysis	Basalt Intrusion Structures Study	Remote Sensing	Drilling Logs - Core Logging	Borehole Geophysical Logging	Fracture Logging	Ground Magnetic	Turam	D.C. Resistivity	Gravity	Refraction Seismic	Aeromagnetic	Reflection Seismic	Magnetotelluric	Gravity	X-ray Fluorescence	Neutron Activation	Paleomagnetic Analysis	Caliche Dating	^{14}C	Petrographic
					STRATIGRAPHY																							
–	●	○	–	○	Thickness	●	–	–	○	–	●	●	–	–	–	–	–	–	–	–	–	–	○	○	○	–	–	○
●	○	○	–	○	Sequence	●	–	–	–	–	●	●	–	–	–	–	–	–	–	–	–	–	●	○	●	–	–	○
●	●	○	–	○	Lateral Extent	●	–	–	–	–	○	●	–	–	–	–	–	–	–	–	–	–	○	○	○	–	–	○
–	●	○	–	○	Volume	●	–	–	○	–	○	●	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	○
					STRUCTURE																							
●	○	○	○	○	Depth	○	–	○	–	–	●	●	–	○	○	○	○	○	○	●	○	○	–	–	–	–	–	–
○	●	●	○	–	Attitude	○	–	○	–	–	○	○	–	●	●	○	●	●	●	●	○	●	–	–	○	–	–	–
–	–	●	●	–	Regional folds, faults, and fracture zones	●	○	●	–	●	○	○	○	○	○	○	●	○	●	●	●	●	–	–	–	–	–	–
–	○	●	●	–	Pasco Basin folds, faults, and fracture zones	●	○	●	–	●	○	○	○	●	●	●	●	●	●	●	○	●	–	–	–	–	–	–
–	○	●	○	–	Buried Dikes	●	–	○	○	○	○	○	–	○	○	○	○	○	○	○	○	○	–	–	○	–	–	–
					LITHOLOGIC PROPERTIES AND INTRAFLOW STRUCTURES																							
–	●	●	–	○	Intraflow Structures	○	–	○	●	–	○	●	○	–	–	–	–	–	–	–	–	–	–	○	○	–	–	●
–	○	○	–	●	Mineralogy and Petrology	●	–	–	●	–	○	○	○	–	–	–	–	–	–	–	–	–	●	●	–	–	–	●
–	○	○	–	●	Chemical Composition	●	–	–	○	–	○	○	–	–	–	–	–	–	–	–	–	–	●	●	–	–	–	–
					TECTONIC STABILITY																							
●	–	○	●	–	Orogenesis } active faulting, folding, fracturing rates	●	●	●	–	●	○	○	–	○	○	○	○	○	○	○	○	○	–	–	○	○	○	–
–	–	○	●	–	Seismicity	–	○	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	○	○	○	–
●	–	○	●	–	Epeirogenesis } broad uplifting and downwarping rates	○	○	○	–	○	○	○	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
○	–	○	●	–	Volcanism and Plutonism	○	○	–	–	–	○	○	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
					GEOMORPHOLOGY																							
●	–	–	○	–	Surficial Processes	●	●	○	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	○	○	–
●	–	–	○	–	Denudation Rates	○	○	○	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–

● Gives information directly related to the indicated factor or consideration

○ Gives information indirectly related to the factor or consideration

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There are several reasons for this order of priority. Although ground motion and surface displacement generated by movement along faults are usually the prime tectonic concerns for the siting and design of nuclear power plants, the siting and design of underground nuclear waste repositories is concerned mostly with subsurface fracturing, and only secondarily with ground vibration. As underground operations have shown, these vibrations should cause little or no damage (National Academy of Sciences, 1978). Subsurface fracturing can be caused by slow or abrupt movement along a fault or fold. Such fracturing, however, is a concern for underground nuclear waste repositories because of its potential to change ground-water flow paths or rates along the breakages.

In areas where nuclear power plants are under construction and underground nuclear waste repositories are being considered, such as the Hanford Site, the preliminary safety analysis report for the nuclear power plants can be used advantageously, particularly for seismic risk analysis associated with the repository surface facilities. But, because these preliminary safety analysis reports usually concentrate on the causes for ground motion and surface rupture effects on a surface facility which is designed for only a 25- to 50-year lifetime, they will, in most cases, be inadequate for determining the effects of future tectonism upon a permanent subsurface waste isolation facility. Consequently, tectonic stability studies for underground nuclear waste repositories must have a broader scope than those used in the preliminary safety analysis reports for nuclear power plants.

Much of the preliminary safety analysis report work by the Washington Public Power Supply System, Inc. for siting its Hanford power reactors was concerned with tectonic stability as related to capable faults (U.S. Nuclear Regulatory Commission, 1975). The scope of the Washington Public Power Supply System, Inc. work was judged sufficient by Rockwell Hanford Operations' geologists to constitute an early assessment of fault capability appropriate for the needs of the Basalt Waste Isolation Project during the site selection phase. Beginning with preliminary site qualification in 1980, however, new geologic mapping and new geophysical surveys will be needed so that specific locations on specific structures can be scrutinized for a more detailed assessment of capability. Moreover, a detailed understanding of the Plio-Pleistocene sedimentary stratigraphy will be developed to help in this assessment. Thus, the major tectonic stability studies by the Basalt Waste Isolation Project are planned for fiscal year 1980. Similarly, much of the early work on the basalts preceding this report (ARHCO, 1976) provided sufficient information on the lithology of the basalts to justify postponing extensive additional lithologic studies until future stratigraphic and structural work is completed.

Need

The Need for Surface Geologic Maps of the Pasco Basin. Although drilling and geophysical surveys can provide both direct and indirect information on the subsurface geology of an area, much additional information can be obtained through the interpretation of detailed

surface geologic maps of the same area. This is particularly true for the Pasco Basin where subsurface geologic relationships can be inferred by projecting structural and stratigraphic features mapped in the bedrock exposures of the anticlinal ridges around the basin margin into the sediment-filled synclinal portions of the basin interior. Thus, the primary need for a detailed surface geologic map of the Pasco Basin is directly related to the need for detailed information of the basin subsurface. The first step in obtaining a surface geologic map covering the Pasco Basin was to determine the adequacy of existing geologic maps of the basin. By mid-1977, the existing geologic maps covering parts of the Pasco Basin had been reviewed, and information had been obtained regarding ongoing and mapping projects that were planned by other organizations. The findings of this review were that the existing and planned geologic maps provided useful information, but were inadequate for the needs of the Basalt Waste Isolation Project. The main findings were as follows:

(a) The maps did not sufficiently cover the Pasco Basin, even if combined;

(b) Some maps were prepared over a short period of time, and many structures and other geologic features could have been overlooked or insufficiently examined;

(c) Insufficient attention was given to details of basalt flow stratigraphy--details that are needed for structural and tectonic interpretations;

(d) The purpose for which many maps were prepared did not place enough emphasis on the study of surface geologic features that are related to geologic conditions in the deep Pasco Basin subsurface.

During the summer of 1977, it was, therefore, decided to complete a geologic map of the Pasco Basin. It was also decided that the mapping should produce basalt outcrop maps at a scale of 1:24,000. The sediment outcrops were also to be mapped, but in less detail at a scale of 1:62,500. The mapping was planned as a 2-year effort concentrating in the western Pasco Basin during fiscal year 1978 and in the eastern Pasco Basin during fiscal year 1979. The methodology used for surface geologic mapping in the Pasco Basin is described in Appendix A.

The Need for Geophysical Surveys. The decisions on the location and kinds of geophysical surveys required in the Pasco Basin were determined largely by three factors: (a) the geologic environment of the Pasco Basin; (b) the type of geophysical information needed; and, (c) the coverage of previous geophysical surveys.

The sedimentary fill that overlies the basalt bedrock in the Pasco Basin varies from 0 to 700+ feet (213+ meters) in thickness and the total section of the basalt bedrock plus other volcanics is at least 10,666 feet (3,251 meters) (Raymond and Tillson, 1968). Within the upper approximately 4,000 feet (1,219 meters) of the bedrock section is

Columbia River basalt that is interpreted to overlie a sequence of older volcanic rocks. Several boreholes in the Pasco Basin have penetrated to depths of about 4,000 feet (1,219 meters) and have bottomed within the Columbia River basalt. Thus, the Pasco Basin subsurface can be considered as including two regions: (a) one from 0 to 4,000 feet (1,219 meters) within which the geology is reasonably well known from drilling; and, (b) the other deeper than 4,000 feet (1,219 meters) within which the geology must be inferred from geophysical evidence.

Detailed information was needed on the geologic conditions in the Pasco Basin to depths of about 5,000 feet (1,524 meters) because the rock units currently being considered for repository hosts occur to this depth. The type of information needed included basalt stratigraphy and structure (particularly for the Grande Ronde Basalt), and the location, character, and stability of any tectonic structures. Conditions below 5,000 feet (1,524 meters) must also be investigated, even though rocks at these depths are not currently being considered as repository hosts. Geologic knowledge of rocks at these depths is needed to help develop a crustal model of deep rock units and structures within the Pasco Basin and to help assess tectonic interrelationships that exist between the central Columbia Plateau and the surrounding areas.

The overall approach was to use standard geophysical surveys to identify deep structures and high-resolution surveys to give details on the shallow structures. Many of these structures were already identified by surface mapping, drilling, and by previous geophysical surveys. Four types of standard geophysical surveys were used: (a) gravity; (b) aeromagnetics; (c) reflection seismic; and, (d) magnetotellurics. Two of these techniques, reflection seismic and aeromagnetics, are responsive to structures in the shallow region of the basalt section and to certain horizons within the first few thousand feet (meters). Gravity and magnetotelluric surveying are responsive to both the shallow and the deep regions.

Prior to 1978, the configuration of the basalt bedrock surface beneath the surficial sediment was known mainly from boreholes and gravity surveys (Richard and Deju, 1977). Elevations of deeper basalt units were known only from deep and intermediate-depth boreholes. The decision was made to test reflection seismic surveying as a means for mapping continuously the buried bedrock surface and to determine if reflecting horizons within the basalt sequence could also be traced. In fiscal year 1978, a test of various reflection seismic survey techniques was reported by Edwards in BWIP (1978). Based on the results of this test, a reflection seismic survey was made in fiscal year 1979.

By proper integration of the reflection seismic, magnetotelluric, gravity, and aeromagnetic results, complementary structural interpretations can be made. By comparison and evaluation of these four techniques in conjunction with geologic considerations, an interpretation of the structural features within a given area can be obtained.

The Need for Regional Geologic Studies. The integrity of a repository will be greatly influenced by the stratigraphic, structural, and tectonic setting of the repository site within the region. Thus, through the study of the Columbia River basalt and younger late Cenozoic sediments within the Columbia Plateau, the location, geometry, and age of regional structures which trend into the Pasco Basin can be determined, and the long-term stability of the Pasco Basin can be assessed. In addition, flows of the Grande Ronde Basalt are present virtually throughout the Columbia Plateau subsurface and crop out extensively in many areas. But because the Grande Ronde Basalt flows beneath the Pasco Basin cannot be directly observed, a study of regional exposures of this unit is necessary to develop a broader understanding of its stratigraphic and lithologic characteristics. Also, interpretations of the ground-water flow paths within the Grande Ronde Basalt beneath the Pasco Basin require a knowledge of how these flow paths relate to the regional stratigraphy and structure.

The regional geology effort was formally initiated in fiscal year 1978 (October 1977). The first half of fiscal year 1978 (October 1977 to March 1978) was primarily concerned with the collection, centralization, and evaluation of currently available geologic data. The primary purpose was to identify existing data sources and to formulate the magnitude and direction of additional studies necessary to provide an adequate geologic picture of the Columbia Plateau. The results of this literature analysis were used to identify and prioritize areas requiring additional geologic data within the Columbia Plateau. The second phase of the regional effort, initiated in March 1978, primarily involved reconnaissance geologic mapping and remote sensing work necessary to begin the acquisition of these additional data. At the time of preparation of this report, such reconnaissance work had only been completed within Washington State. Consequently, the contents of the Regional Geology chapter of this report are restricted, for the most part, to a discussion of the surficial geology of the Washington State portion of the plateau.

Work Breakdown

The geological and geophysical studies reported herein were subdivided for study purposes into the following categories:

(a) Regional Studies;

(b) Pasco Basin Studies; and,

(c) Analytical Support Studies.

The work breakdown structure used to guide this study is shown as Table I-3, along with the scope, location, and some comments on the individual tasks and subtasks. A description of the study tasks on the work breakdown structure is in Appendix A.

TABLE I-3. Work Breakdown Structure.

TASK		SUBTASK	SCOPE	LOCATION	COMMENT
REGIONAL STUDIES		• Literature Search and Index Map Compilation	Compilation of bibliographies containing over 3,000 published and unpublished documents from local, state and federal agencies, public utilities, universities and private industry. Compilation of index maps showing areas and scales of available geologic mapping and geophysical surveys and locations of boreholes, basalt excavations, mineral occurrences, and other specific types of geologic information	Washington State Oregon State Idaho State	Bibliography compilation and index map compilation were performed by the following state agencies • Washington Department of Natural Resources, Division of Geology and Earth Resources • Idaho Bureau of Mines and Geology; • Oregon Department of Geology and Mineral Industries
		• Surface Geologic Mapping-Columbia River Basalt	Mapping of the eastern Washington State portion of the Columbia Plateau at a scale of 1:250,000	Washington State	Plates II-1 through II-10 of this report are the result. Mapping was performed by the U.S. Geological Survey
		• Surface Geologic Mapping-Late Cenozoic Sediments	Mapping of the eastern Washington portion of the Columbia Plateau at a scale of 1:250,000	Washington State	Plates II-10 through II-19 of this report are the result. Mapping was performed by the Washington Department of Natural Resources Division of Geology and Earth Resources
		• Analysis of Satellite and Aerial Imagery	Photo lineament analysis of Landsat and U-2 imagery covering the eastern Washington State portion of the Columbia Plateau	Washington State	Plates II-20 through II-26 of this report are the result. Photolineament analysis was performed by Pacific Northwest Laboratory
PASCO BASIN STUDIES	SURFACE GEOLOGIC MAPPING AND RELATED STUDIES	• Literature Search	Mainly a review of reports published by Rockwell Hanford Operations and its predecessors		Bibliographies produced by the regional literature search were used
		• Surface Geologic Mapping		Pasco Basin Study Area	Plate III-1 of this report is the result. Geologic mapping of the basalt outcrop areas and the late Cenozoic sediment outcrop areas were both compiled at a scale of 1:62,500. The mapping was completed over a 2-year period from 1977 to 1979
		- Columbia River Basalt	Mapping of approximately 3100 square miles (~8,000 square kilometers) at a scale of 1:24,000	Pasco Basin Study Area	
		- Late Cenozoic Sediments	Mapping of approximately 2500 square miles (~6,500 square kilometers) at a scale of 1:62,500		
		• Structural Analysis of Umtanum Ridge	Surface measurements of strain features in basalt bedrock, and mapping at a scale of 1:6,000 or larger	Eastern Umtanum Ridge	Erosion along the north flank of Umtanum Ridge has provided exposure of the internal structure of a Yakima fold in the Pasco Basin
		• Study of Basalt Intraflow Structures at Sentinel Gap, Emerson Nipple, and Crescent Bar	Fracture characterization and mapping of basalt intraflow structures at a scale of 1:400 along cliff exposures	Near Emerson Nipple on Umtanum Ridge, at Sentinel Gap, and outside the Pasco Basin at Crescent Bar located about 16 miles (25.7 kilometers) north of Sentinel Gap	Measured stratigraphic sections made at Sentinel Gap and Emerson Nipple are shown on Plate III-3
		• Analysis of Satellite and Aerial Imagery		Pasco Basin Study Area	Pasco Basin remote sensing work was a part of the regional studies
	BOREHOLE STUDIES	• Drillers Logs, Cable Tool Samples, Drilling Rate Logs, and Chip Samples	Preparation and analysis of borehole records, samples and logs	Pasco Basin Study Area	A listing of borehole information is in Appendix A of this report
		• Borehole Geophysical Logging	Natural gamma, sonic, density, porosity and other logs	DDH-3, DH-4, DH-5, DC-2, DC-3, DC-4, DC-5, DC-6, DC-7, and DC-8	A listing of borehole geophysical log coverage is on file in the Basalt Waste Isolation Project Library
		• Core Logging and Sampling	36,000 linear feet (~11,000 meters) of core have been logged about 700 samples were collected for x-ray fluorescence analysis	DDH-3, DH-4, DH-5, DC-2, DC-4, DC-6, DC-8, DC-10, DC-11, and all DB core holes	Lithologic logs of some pre-1977 boreholes are given in ARHCO (1978). Other logs are on file with the Basalt Waste Isolation Project Library. Some samples were collected for rock mechanics testing
		• Fracture Logging	Fractures were logged and analyzed in 3 flows at Sentinel Gap and in 3 flows in DH-5. Core holes DC-4, DC-6, and DC-8 were logged but data have not been analyzed	DH-5, DC-4, DC-6 and DC-8 and the surface sections at Sentinel Gap	This work represented an attempt to identify intraflow structural types using fracture characteristics
	GEOPHYSICAL SURVEYS	• Ground Magnetic (High-Resolution Surveys)	Approximately 30 line-miles (~50 kilometers) of data were collected at station intervals of 50 feet (15.3 meters)	Saddle Mountains, Wahluke Slope, Cold Creek Valley, Gable Mountain, Gable Butte	Used to locate shallow structures in the basalt, locate buried channels eroded into the top of the basalt, and measure the attitude of the buried basalt surface
		• Turam (High-Resolution Surveys)	Approximately 2.8 square miles (~7.3 square kilometers) were surveyed	Saddle Mountains and the Gable Mountain-Gable Butte Area	
		• Direct Current Resistivity (High-Resolution Surveys)	Made 14 vertical, electrical soundings using Wenner spread with maximum spacing of 900 feet (275 meters)	Saddle Mountains	
		• Gravity (High-Resolution Surveys)	Approximately 7 line-miles (~11.3 kilometers) of data were collected at 100 (30.5), 200 (60) and 500-foot (150-meter) intervals	Saddle Mountains, Wahluke Slope and northeast flank of Rattlesnake Mountain	
		• Refraction Seismic (High-Resolution Surveys)	3,000 linear feet (~900 meters) were surveyed	Saddle Mountains and northeast flank of Rattlesnake Mountain	
		• Aeromagnetic (Standard Surveys)	600 square miles (1,550 square kilometers) of constant elevation data were collected on a 0.5 mile by 0.5-mile (0.8-kilometer by 0.8-kilometer) grid	Central Pasco Basin Study Area	Preliminary interpretation has shown subsurface continuations of known surface structures
		• Reflection Seismic (Standard Surveys)	87 line-miles (140 kilometers) of data	Pasco Basin Study Area	Seismic reflection data have been used to refine subsurface geologic maps
		• Magnetotelluric (Standard Surveys)	29 tensor stations and 18 scalar stations surveyed on a grid pattern	Pasco Basin Study Area	Survey has shown 5 geoelectric layers beneath the Pasco Basin
		• Gravity (Standard Surveys)	Approximately 65 line-miles (105 kilometers)	Pasco Basin Study Area	
ANALYTICAL SUPPORT STUDIES		• X-Ray Fluorescence	1,000 samples from outcrops in the Columbia Plateau, 1,800 samples from outcrops and core holes in the Pasco Basin	Columbia Plateau and Pasco Basin Study Area	Major element analyses were used for basalt unit identification
		• Neutron Activation	200 samples from surface outcrops and boreholes	Pasco Basin Study Area	Minor and trace element analyses were used for refinement of basalt unit identifications
		• Paleomagnetic Analyses	1,200 samples from core holes and surface outcrops	Pasco Basin Study Area	Paleomagnetic measurements of basalt and Ringold samples. Basalt analyses were used for unit identification. Ringold samples were used for age dating
		• Caliche	3 samples from outcrop	Badger Coulee, Pasco Basin	Caliche coating on cobbles
		• Carbon-14	1 sample from outcrop	Gable Mountain Bar, Pasco Basin	Wood samples

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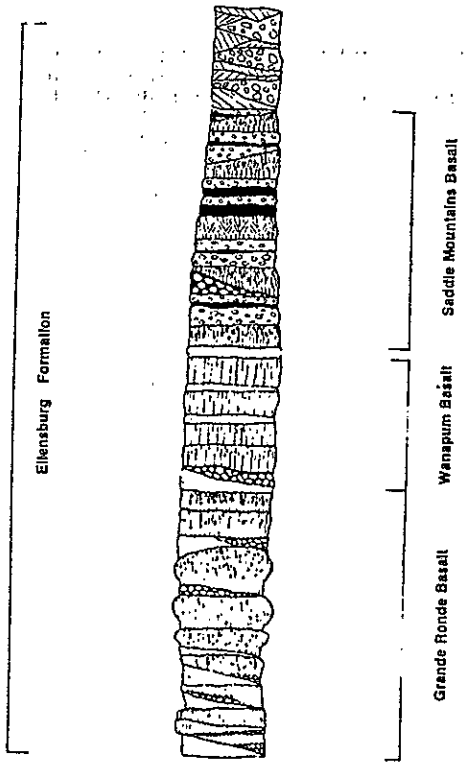
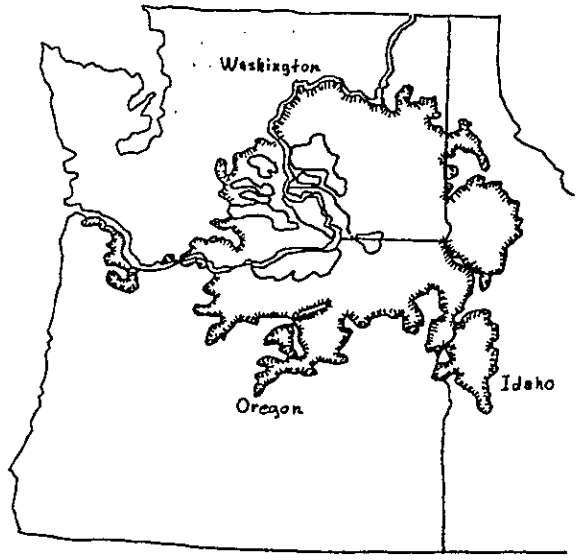
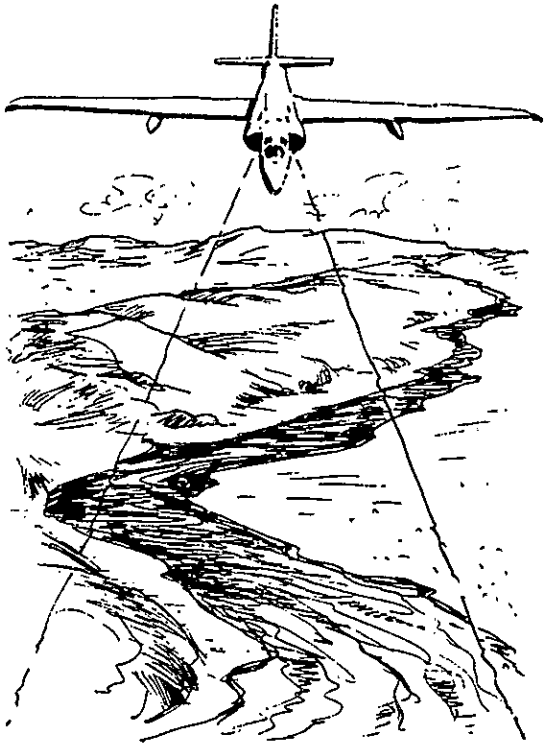
REGIONAL GEOLOGY







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CHAPTER II-REGIONAL GEOLOGY

INTRODUCTION

CHAPTER ORGANIZATION

Chapter II includes a broad discussion of the area covered by the Columbia River Basalt Group in Washington State (east of the Cascade Range) (Figure II-1). This discussion synthesizes available data pertaining to the stratigraphy, structure, geologic history, and geomorphology of this area. Such information provides a framework required to assess the regional geologic factors pertinent to siting a nuclear waste repository within flows of the Columbia River Basalt Group.

The contents of Chapter II are organized into four main sections. The first section, Introduction, contains a discussion of the general geologic setting of the area covered by, and contiguous to, the Columbia River Basalt Group. In addition, this section includes a general summary of previous work which served as a basis for further regional geologic studies conducted under Rockwell Hanford Operations' Basalt Waste Isolation Project.

The second section, Regional Stratigraphy, is a summary of stratigraphic nomenclature and major properties of the Columbia River Basalt Group and older, contemporaneous, and younger stratigraphic units within the study area (Figure II-1). This section is supplemented by descriptive tables and figures and geologic maps which accompany the report.

The third section, Regional Structure, includes a description of the major deformational features of the Washington State portion of the Columbia Plateau and a general discussion of the timing of their development. This section is also supplemented by descriptive tables and figures, geologic maps, and photolineament maps which accompany the report. The Regional Structure section provides information which serves as a basis for discussions in Chapter IV, Seismicity and Tectonics.

The fourth section, Regional Geomorphology, is a description of general physiographic divisions of the Columbia Plateau (Figure II-1) within Washington State. This section emphasizes the origin and development of major landforms within each division and briefly considers modern geomorphic processes.

GENERAL SETTING

The Columbia River Basalt Group covers southeastern Washington and adjoining portions of northern Oregon and western Idaho (Figure II-1). The area underlain by basalts of this group is commonly referred to as the Columbia Plateau province, and this informal usage will be adhered to throughout this report. Geologic provinces contiguous to the plateau

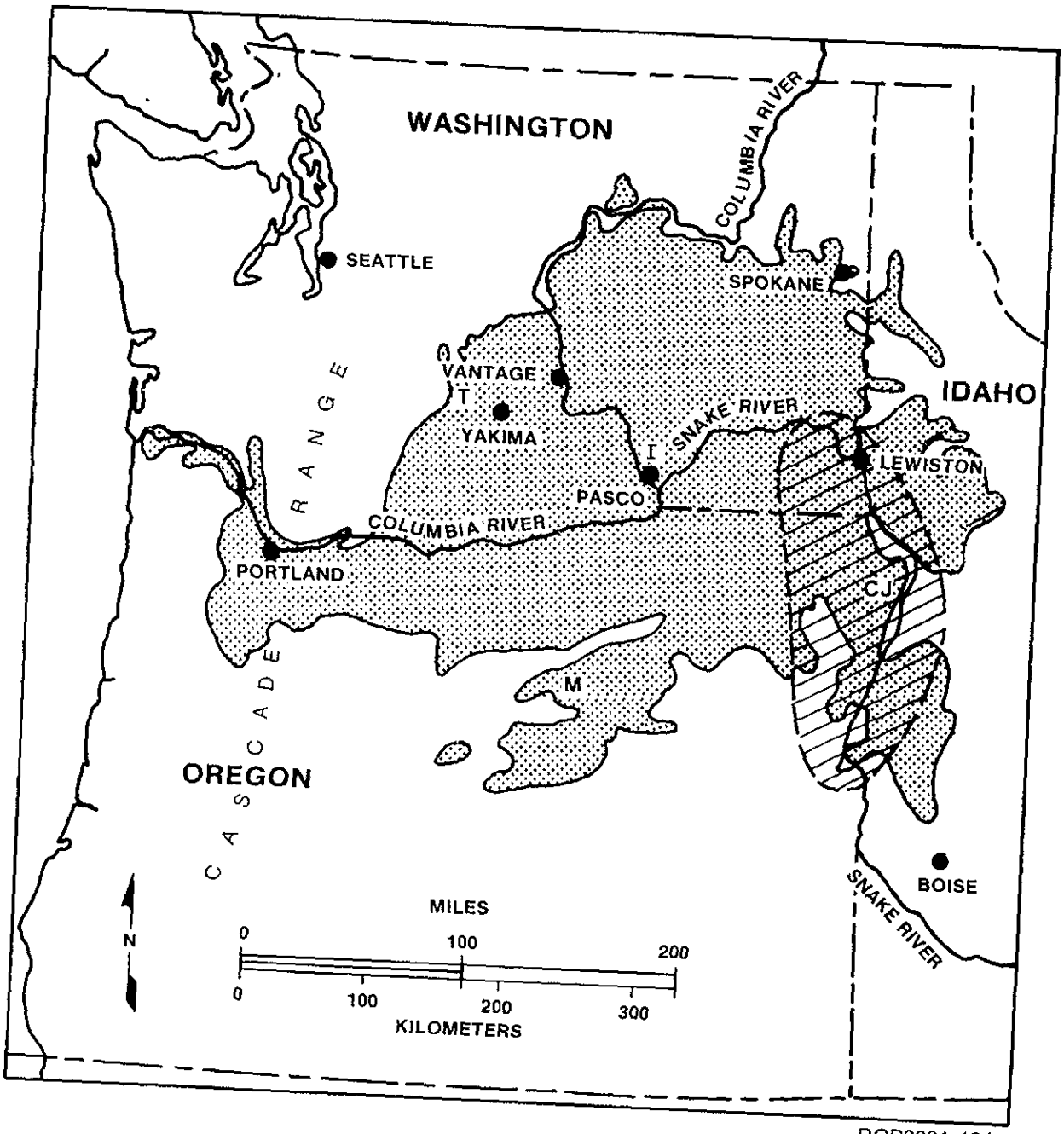

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FIGURE II-1. Generalized Map (after Waters, 1961) of Northwestern United States Showing Distribution of the Columbia River Basalt Group (Stippled). Locations of Monument (M) and Tieton (T) dike swarms as defined by Waters (1961), Chief Joseph dike swarm (CJ, lined area) as defined by Taubeneck (1970), and Ice Harbor vent system (I) as defined by Swanson and Others (1975) are also shown.

include the Cascade Range province to the west, the Okanogan Highlands province to the north, the Northern Rocky Mountains and Idaho Batholith provinces to the east, and the High Lava Plains province to the south (Figure II-2). The character of the Columbia Plateau and its surrounding geologic provinces is described briefly below.

Columbia Plateau Province

The lavas of the Columbia Plateau comprise a tholeiitic flood-basalt province of moderate size covering an area of approximately 78,000 square miles (200,000 square kilometers) and having an estimated volume of 41,000 cubic miles (200,000 cubic kilometers). The plateau is both a structural and topographic depression with its low point near the center of the province, the approximate location of the Pasco Basin. Here, the accumulation of flows of the Columbia River Basalt Group and interbedded sediments attain their maximum known thickness, over 4,500 feet (1,500 meters) (ARHCO, 1976). The character of the older Precambrian to early Tertiary rocks covered by Columbia River basalt is visible now only within highlands surrounding the plateau. Within the interior of the province, the lithology, structure, and topography of the pre-basalt surface is hidden beneath the thick accumulation of lava.

The Columbia Plateau, the earth's youngest recognized flood-basalt province, formed between 6 and 16.5 million years before present (Watkins and Baksi, 1974; McKee and Others, 1977) when large volumes of lava were erupted from north-northwest-trending linear vent systems now preserved as dikes (Waters, 1961; Taubeneck, 1970; Swanson and Others, 1975; Fruchter and Baldwin, 1975; Price, 1977; Swanson and Others, 1977). Individual Columbia River basalt flows are voluminous, generally 2 to 6 cubic miles (10 to 29 cubic kilometers), with a maximum known volume of 145 cubic miles (696 cubic kilometers). Flows range in thickness from a few inches (centimeters) to more than 300 feet (91 meters), with an average thickness of 90 to 120 feet (22 to 36 meters). The thickest flows generally record ponding in pre-basalt valleys, in structurally controlled basins that developed during volcanism, or in narrow canyons previously eroded into older flows (termed intracanyon flows) (Swanson and Wright, 1978).

Flows of the Columbia River Basalt Group are interbedded with and overlapped by Miocene-Pliocene epiclastic and volcaniclastic sediments, especially along the margin of the province. Invasive flows, formed when lava "burrowed" into surficial deposits of unconsolidated sediments, are also common (Byerly and Swanson, 1978). The youngest suprabasalt sedimentary units on the plateau are fluvial, lacustrine, glaciofluvial, and eolian deposits of Pliocene to Holocene age. However, localized accumulations of Pliocene to Pleistocene lavas are also present within the western and southern portions of the province.

The topography of the Columbia Plateau generally reflects structural deformation. As such, the contrasting structural fabric of the province provides a basis for defining three informal geologic subprovinces: the Yakima Fold Belt subprovince; the Blue Mountains subprovince; and the Palouse subprovince (Figure II-2).

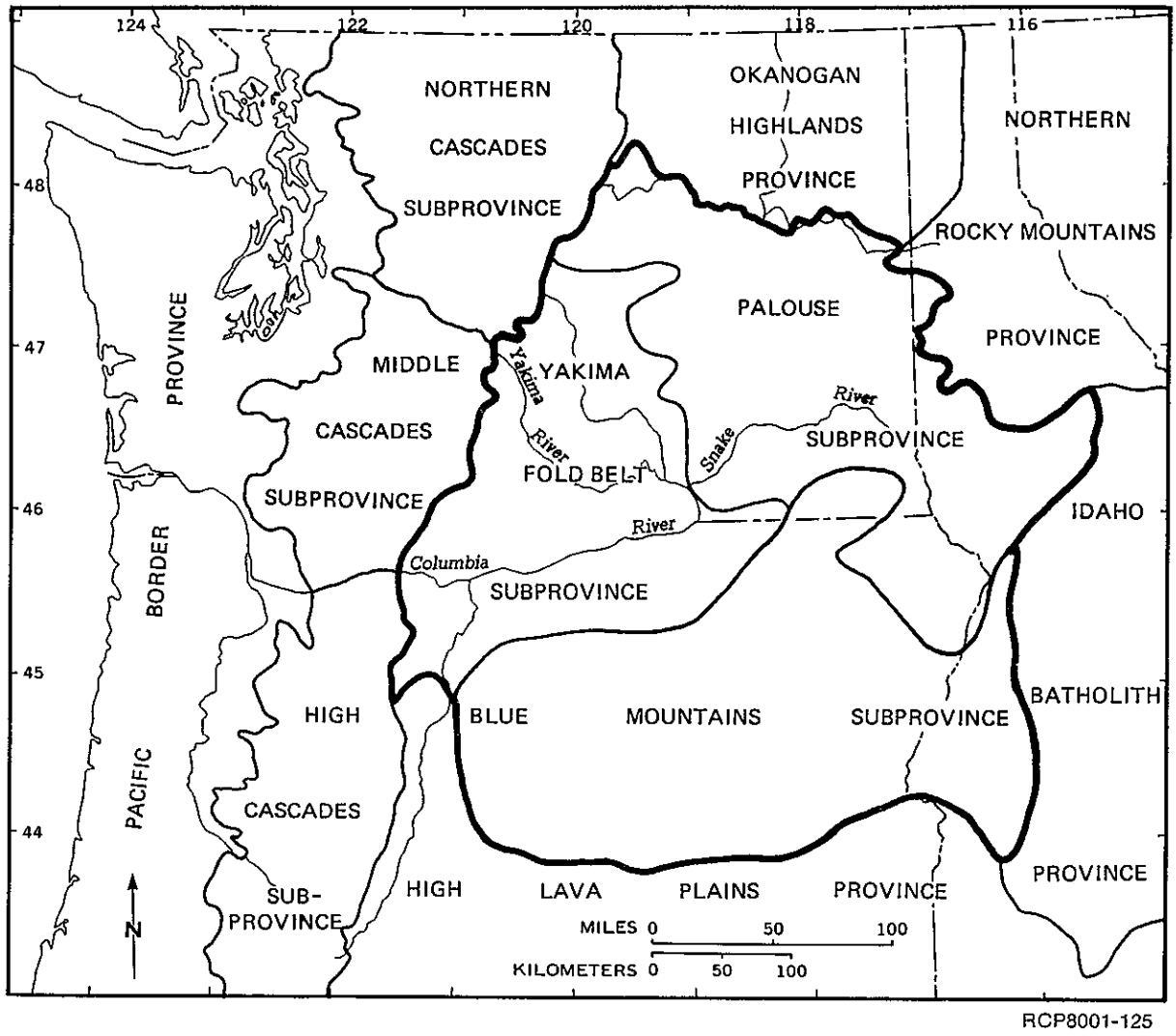

FIGURE II-2. Informal Geologic Subdivisions of the Columbia Plateau Province (Bold Outline) and Contiguous Areas.

The Yakima Fold Belt subprovince covers the central and western parts of the Columbia Plateau and is characterized by linear anticlines and broad synclines extending generally eastward from the Cascade Range province (Figure II-2). Formation of these folds and associated faults, was initiated primarily during the later stages of basalt extrusion and was most intense during Pliocene time (WPPSS, 1977).

The Blue Mountains subprovince is located in the southern portion of the plateau (Figure II-2) and represents a broad anticlinal arch which was uplifted predominantly in Mio-Pliocene time (McKee, 1972). This broad arch extends eastward from the Cascade Range province in central Oregon and continues east and northeast to the Snake River Canyon. The general trend of the Blue Mountains province is cut by north-to-northwest-oriented folds and near-vertical faults along its southern margin. This northerly trend of structures is similar to the deformational pattern developed in the High Lava Plains province located to the south (Figure II-2).

The Palouse subprovince is situated in the northeastern portion of the plateau, and is distinguished from the Yakima Fold Belt and Blue Mountains subprovinces by its relative lack of deformation. In this subprovince, the plateau surface has been shaped predominantly by geomorphic rather than by structural processes. The eastern portion of the subprovince is mantled by Pliocene-Pleistocene loess deposits comprising the rolling Palouse Hills. The remainder of the subprovince has been dramatically modified by late Pleistocene catastrophic floods. These floods stemmed from the breakup of glacial ice dams impounding huge glacial lakes in the Northern Rocky Mountains province (Figure II-2). The release of colossal volumes of water produced a system of anastomosing drainages, or coulees, generally referred to as the Channeled Scablands (Bretz, 1929). Most of the coulees are now dry, and the Columbia, Snake, Yakima, Spokane, and Palouse Rivers comprise the major active drainage system within the modern plateau (Figure II-2). The development of the present drainage system was well initiated by at least late Miocene time (Swanson and Wright, 1978; Swanson and Others, 1979a).

Cascade Range Province

The western margin of the Columbia Plateau is bordered by the Cascade Range province, a relatively narrow, north-south-trending, geologic province less than 100 miles (160 kilometers) in width (Figure II-2). The Cascade Range has an average elevation of 5,000 feet (1,515 meters) with elevations generally increasing progressively northward. The most prominent features within the province are the young stratovolcanoes which reach elevations of more than 10,000 feet (3,030 meters). The topography of the range has been largely molded by continental and alpine glaciation.

On the basis of petrology, structure, and topography, the Cascade Range province has been divided into three geologic subprovinces. Two of these subprovinces, the Middle Cascades subprovince and the Northern Cascades subprovince, are located within Washington (Figure II-2). The

core of the Middle Cascades subprovince consists almost entirely of moderately deformed, non-marine, sedimentary, and volcanic rocks of early Tertiary age intruded by small plutons of Miocene-Pliocene age. In contrast, the core of the more rugged Northern Cascades subprovince consists of Paleozoic and Mesozoic marine strata and Mesozoic and early Tertiary continental arkosic and volcaniclastic deposits. These rocks have been severely deformed, regionally metamorphosed, and invaded by numerous igneous intrusions of Cretaceous and Tertiary age. Most late Cenozoic rocks within both subprovinces consist of Pliocene and Pleistocene andesitic and basaltic lavas associated with Cascade volcanism (McKee, 1972; WPPSS, 1977).

Folds and faults within the Cascade Range province trend predominantly north and northwest and are developed primarily in rocks of pre-middle Miocene age. In general, late Cenozoic volcanoes within the province are aligned along this north-south structural trend. The modern Cascade Range stemmed from broad uplift along a north-south axis which began in late Cenozoic time, essentially concurrent with the initiation of andesitic volcanism. Such uplift is reflected by upward tilting of originally horizontal Columbia River basalt layers along the east flank of the Cascade Range.

Okanogan Highlands Province

The Okanogan Highlands province is located east of the Cascade Range province and north of the Columbia Plateau (Figure II-2). The province consists of broad, rounded hills, mostly less than 5,000 feet (1,515 meters) in elevation. Major drainage in the Okanogan Highlands province is by the Columbia River, which flows north-south through the province and east-west along its southern boundary. The north-south course of this river divides the "highlands" into two geologic subprovinces termed the Eastern subprovince and the Western subprovince (Yates and Others, 1966). The Eastern subprovince is underlain by Precambrian metasedimentary and lower Paleozoic miogeosynclinal rocks. Folds in this subprovince generally trend northerly and are cut by pre-Tertiary faults. The Western subprovince is composed of an upper Paleozoic and Mesozoic eugeosynclinal, lithologic sequence which was folded and faulted commonly along north to northwest trends during late Jurassic or early Cretaceous time. In late Triassic to Eocene time, both the Eastern and Western subprovinces were intruded by widespread batholiths (Miller, 1975). Latitic volcanic rocks were extruded in both subprovinces during early and middle Eocene time. Present-day topography of the Okanogan Highlands province has been largely molded by glacial and glaciofluvial processes which were active during late Pleistocene time.

Northern Rocky Mountains and Idaho Batholith Provinces

The Northern Rocky Mountains province is located to the east of the Okanogan Highlands province and to the northeast of the Columbia Plateau province (Figure II-2). Mountains of this province which border the plateau belong to the Coeur d'Alene and Clearwater ranges. Major

drainages which flow toward the plateau from these ranges include the Spokane, Clearwater, and Salmon Rivers. Near the plateau margin, rocks of the Northern Rocky Mountains province are predominantly slates, argillites, and quartzites of the Precambrian Belt Supergroup. These rocks are cut by a series of pre-Tertiary and Tertiary, predominantly north-northwest-trending faults.

The Idaho Batholith province lies south of the Northern Rocky Mountains province and east of the Columbia Plateau (Figure II-2). Plateau basalts overlap the Bitteroot lobe of this 17,000-square-mile (44,200-square-kilometer) province, underlain by a plutonic sequence comprised predominantly of Mesozoic age granodiorite and quartz monzonite. A younger, less voluminous, Eocene age suite of granitic intrusions is also present. The border zone of the batholith is comprised of Precambrian age sedimentary rocks that have been locally metamorphosed to gneiss and schist and intruded by igneous rocks.

High Lava Plains Province

The High Lava Plains province is located south of the Columbia Plateau and east of the Cascade Range province (Figure II-2). This province is characterized by north-trending mountain ranges and intervening flat valleys containing alluvium or lava flows. The province has a mean elevation of about 4,000 feet (1,212 meters), with portions of the mountain ranges approaching elevations of 10,000 feet (3,030 meters). Drainage of the province is predominantly interior, although the headwaters for four rivers, the Owhyee, John Day, Deschutes, and Klamath, are located within the province (McKee, 1972).

The oldest rocks exposed within the High Lava Plains province are upper Paleozoic to upper Eocene in age and may be correlative with units within the Blue Mountains subprovince to the north (Figure II-2). Most rocks exposed within the province are high-alumina basalt flows of Miocene to Pliocene age or younger. Fissure-fed basaltic flows of at least two formations of the province, the Steens Mountains Formation and the Owyhee Formation, are coeval with Columbia River basalt (Watkins and Baksi, 1974). Younger basaltic and rhyolitic ash flows (as young as Holocene) were erupted from cinder cones and volcanic vents found within the province.

The topography of the High Lava Plains province generally reflects its underlying structure. Faults of the region trend predominantly north-south and generally define mountain fronts or coincide with alignments of volcanic vents. Faults with northwest-southeast trends are also present and are especially prominent in the McLoughlin, Eugene, Brothers, and Vale fault zones (Lawrence, 1976).

PREVIOUS WORK

Volcanic Stratigraphy

The first geologic reconnaissance studies of the Columbia Plateau were conducted near the turn of the century by members of the U.S. Geological Survey (Russell, 1893; Merriam, 1901; Smith, 1901, 1903a, 1903b, 1904; Lindgren, 1901; Calkins, 1905). The name "Columbia River basalt" originated with the earliest of these investigators, I. C. Russell (1893, 1901), who applied this nomenclature to all basaltic lavas of the Pacific Northwest (ranging in age from Eocene to Recent). However, it was not until over 50 years after the initial reconnaissance studies that the name "Columbia River basalt" was formalized and a uniform stratigraphic usage adopted. In 1961, Waters proposed that only the Miocene-Pliocene age basalts in Washington, Oregon, and Idaho (Figure II-1) be designated as flows of the Columbia River Basalt Group. On the basis of stratigraphic, petrographic, and chemical evidence, he divided this group into two formations: (a) the older Picture Gorge Basalt, initially described by Merriam (1901) as the "Columbia lava;" and, (b) the younger Yakima Basalt, as earlier defined by Smith (1901). In this same publication, Waters (1961) also addressed basaltic dikes of the plateau. He suggested that most of these dikes appear to be concentrated within the limits of definite areas, and named four dike swarms whose affinity with the Columbia River Basalt Group seemed probable: (a) the Grande Ronde; (b) the Cornucopia; (c) the Monument; and, (d) the Tieton (Figure II-1).

Efforts to differentiate individual Columbia River basalt flows began in the 1940's and 1950's in conjunction with hydrologic and hydroelectric projects. Early work by W. D. Irvin for the U.S. Bureau of Reclamation and by Waters (1955), Laval (1956), and Mackin (1961) showed that some of the plateau basalt flows do have unique features that enable them to be distinguished. By the early 1970's, studies by Bond (1962), Bingham and Grolier (1966), Schmincke (1967a, 1967b), Swanson (1967), Grolier and Bingham (1971), and Swanson and Others (1972) had revealed additional named flows which could be traced for many miles (kilometers) throughout the plateau. A key tool in much of the correlation work during this period was the application of bulk rock chemistry to enhance and support flow identifications (Myers and Brown, 1973; Brown and Ledgerwood, 1973; Ledgerwood and Others, 1973; Brock and Grolier, 1973; Wright and Others, 1973). The information provided by chemical correlation work conducted throughout the plateau enabled Wright and Others (1973) to propose an informal four-fold stratigraphic subdivision of Waters' (1961) Columbia River Basalt Group in 1973 (Figure II-3). This nomenclature (Wright and Others, 1973) was developed primarily to adequately define and emphasize the newly determined relationship between chemical composition and stratigraphic position. To elucidate this relationship between chemistry and stratigraphy, the compositional character of the basalt subdivisions was illustrated by establishing chemical types based on the averages of analyses of named flows within each formation (Wright and Others, 1973).

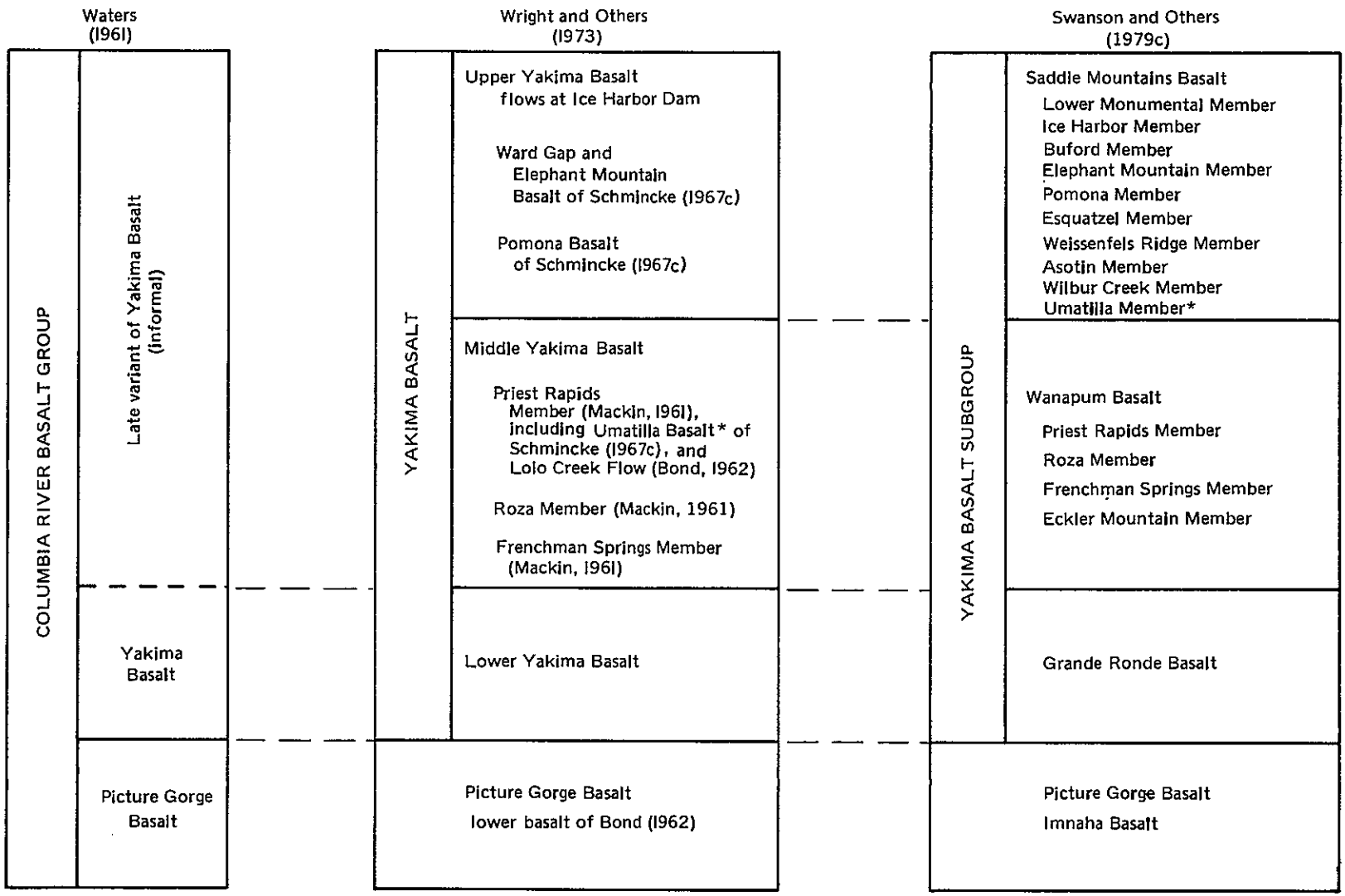

FIGURE II-3. Comparison of Applied Columbia River Basalt Group Stratigraphic Nomenclatures (after Waters, 1961; Wright and Others, 1973; Swanson and Others, 1979b).

Following its publication, the informal stratigraphic and chemical nomenclature of Wright and Others (1973) served as a basis for geologic mapping conducted throughout the plateau. For the most part, this mapping was not only supported by bulk rock chemistry, but by paleomagnetics--also shown to be an important correlation tool (Rietman, 1966; Watkins and Baksi, 1974; Lynch, 1976; Swanson and Wright, 1976). In southeastern Washington, such work culminated in the publication by Swanson and Others (1977) of a regional reconnaissance geologic map of the Columbia River Basalt Group (scale: 1:250,000). This publication has served as the "cornerstone" for further regional geologic reconnaissance mapping of Columbia River basalt conducted by Swanson and Others (1979a) for the Rockwell Hanford Operations regional program.

By 1978, sufficient field, chemical, paleomagnetic, and dating work (Watkins and Baksi, 1974; McDougall, 1976) had been carried out to allow a formalized revision of Columbia River basalt stratigraphic nomenclature. This revision, briefly outlined by Swanson and Wright (1978) and described in detail by Swanson and Others (1979b), is shown in Figure II-3. As defined by this new nomenclature, the Columbia River Basalt Group includes all extrusive volcanic rocks previously assigned to the group by Waters (1961) and excludes all formations that are largely non-basaltic (such as sedimentary interbeds discussed in the next section). The group is subdivided into 1 subgroup, 5 formations, and 14 members (Figure II-3). This stratigraphy has been used in the regional Columbia River basalt reconnaissance mapping carried out for this study.

Since Waters' 1961 publication, additional work was also conducted to refine the relationship between basalt dikes and flows. Work by Wilcox and Fisher published in 1966 further established the association between dikes of the Monument swarm (Figure II-1) and Picture Gorge Basalt. However, later work by Swanson (1967) showed that dikes comprising the Tieton swarm (Figure II-1) are older than Columbia River basalt. Additional work by Taubeneck (1970) revealed that there is no discernible break between Columbia River basalt dikes comprising Waters' (1961) Grande Ronde and Cornucopia swarms. Taubeneck suggested, therefore, that all dikes exposed within the southeastern portion of the plateau be classified as members of a single major swarm, the Chief Joseph (Figure II-1). In 1972, work by Swanson and Others showed the presence of additional dikes as far west as the eastern margin of the Pasco Basin (Figure II-1). The most recent work in areas of dike exposures has been directed toward establishing the association between individual dikes and flows, using comparative chemistry and paleomagnetic techniques as key correlation tools (Price, 1973a, 1973b, 1977; Fruchter and Baldwin, 1975; Swanson and Others, 1975; Kleck, 1976).

Within Washington State, volcanic deposits younger than the Columbia River Basalt Group occur along the western margin of the plateau. Younger basalt flows associated with cinder cones in the Goldendale, Washington area were described by Sheppard in 1967. He informally termed these deposits the Simcoe volcanics. Potassium-argon dates obtained for these volcanics by Kienle and Others (1977a, 1977b) range from 0.9 to 4.5 million years before present. Andesitic flows overlying

Columbia River basalt in the Tieton and lower Naches River drainages were named the Tieton Andesite by Becraft (1950). The Tieton Andesite and younger olivine basalt flows in the vicinity were further described by Swanson (1967). A potassium-argon age of 1 million years before present for the Tieton Andesite was published by Kienle and Others (1977a).

Sedimentary Stratigraphy

Underlying, interlayered with, and overlying Columbia River basalt flows are epiclastic and volcaniclastic sedimentary rocks. Like the basalt, these rocks were first examined by Russell (1893) as part of his reconnaissance study of the Columbia Plateau. Russell (1893) suggested that the sedimentary deposits overlying the basalt were laid down in an extensive Miocene lake and termed them members of the John Day System. Smith (1901) redefined "John Day" sediments exposed near Ellensburg, Washington (and the mouth of the Naches River) as deposits of the Ellensburg Formation. Although Smith's (1901) Ellensburg Formation also included sediments exposed near Pasco, Washington (the White Bluffs area), these suprabasalt sediments were later renamed the Ringold Formation by Merriam and Buwalda (1917). Two decades later, Culver (1937) expanded the Ringold Formation to include post-basalt sediments throughout much of the central Columbia Plateau. Other recognized suprabasalt sedimentary units which were probably included in Russell's (1893) original John Day System are the Hood River Conglomerate (Buwalda and Moore, 1929), the Cowiche Gravel (Smith, 1903a), and the Thorp Gravel (Porter, 1976; Waitt, 1977a, 1979a).

The Ellensburg Formation, as originally defined by Smith (1901) and later by Calkins (1905), included sedimentary units both overlying and interbedded within Columbia River basalt flows. In other studies the lower extent of the formation was defined by Mackin (1961) as the top of the Wanapum Basalt and by Smith (1903a), Waters (1955), and Schmincke (1964b) as the base of the Wanapum Basalt. Waitt (1979a) recently proposed that the definition of the Ellensburg Formation be extended stratigraphically downward to include sedimentary units also interbedded with and underlying Grande Ronde Basalt.

The stratigraphic relationship between sediments and Columbia River basalt flows in the northeastern portion of the Columbia Plateau was originally addressed by Pardee and Bryan (1926). These workers termed the lacustrine and fluvial sediments underlying the Columbia River basalt in the Spokane, Washington area the Latah Formation. Kirkham and Johnson (1929) later expanded the formation to include both sub-basalt and interbedded sedimentary units along the northern and eastern margins of the plateau. In 1969, Hosterman also applied the term to suprabasalt sediments in the Spokane area. Usage of the term "Latah" was further addressed by Griggs in 1976. He suggested that application of the name be restricted to sedimentary units associated within the Columbia River basalt only within the drainage of the Spokane River, thus excluding units outside this area formerly termed "Latah" by Kirkham and Johnson (1929).

Past geologic investigations of the surficial sedimentary deposits of the central and northeastern Columbia Plateau were dominated by a search for the origin of the "Channeled Scablands." In 1923, Bretz first proposed that the complex network of coulees and associated sediments in this area were the result of catastrophic flooding. Bretz's explanation met with much controversy and contemporary workers (Allison, 1933; Hodge, 1934; Flint, 1938b) put forth hypotheses which called for a less "dramatic" origin. However, in 1926, Pardee and Bryan presented evidence which showed that a large volume of water was released to the plateau when a Pleistocene glacial ice dam failed near the Idaho-Montana border. Pardee and Bryan's work (1926), and additional work by Bretz (1959) and Bretz and Others (1956), resulted in general acceptance of the catastrophic flood theory by the early 1960's. However, the timing and number of floods presently remains unresolved (Bretz and Others, 1956; Bretz, 1959; Patton and Baker, 1978; Waitt, 1979b). The regional character of sedimentary units deposited by the catastrophic flood waters have most recently been summarized by Baker (1973) and by Baker and Nummendal (1978).

Loess mantles much of the plateau and was originally described by Russell (1893, 1901), who thought this material was derived from weathering and decomposition of the underlying Columbia River basalt. Calkins (1905) noted the lack of transition between these deposits and basalt and interpreted the Palouse "soils" to be of eolian origin. Fryxell and Cook (1964) determined that the loess consists of at least three to five morphologically distinct units which range in age from mid-Pleistocene, or older, to Holocene.

Volcanic ash derived from Cascade Range volcanoes is interlayed with Pliocene, Pleistocene, and Holocene sediments of the Columbia Plateau (Westgate and Others, 1970). Tephras from Glacier Peak (Fryxell, 1965; Lemke and Others, 1975; Westgate and Evans, 1978), Mount Mazama (Fryxell, 1965; Kittleman, 1973), and Mount St. Helens (Crandell and Mullineaux, 1973; Mullineaux and Others, 1975; Moody, 1977, 1978) have been characterized and dated. These ash horizons have been used as key time stratigraphic marker units.

Although site-specific studies of late Cenozoic sediments are considerable, field studies with a "regional" emphasis are relatively few. Within Washington State, only studies by Grolier and Bingham, (1978), Shannon and Wilson (1973, 1977a, 1977b), and Tabor and Others (1977) have involved geologic mapping of large areas. Absolute dating of sedimentary materials throughout the region has been carried out primarily on a site-specific basis (Shannon and Wilson, 1973, 1977a, 1977b; Waitt, 1979a).

Structures and Tectonics

As stratigraphic studies progressed, so did structural studies of the Columbia Plateau. The first "regional synthesis" of mapped folds, faults, and joints in the Columbia River basalt was compiled by Newcomb (1970). Additional structural information for south-central Washington

was provided by Grolier and Bingham (1971). Since the publication of Newcomb's (1970) and Grolier and Bingham's (1971) work, detailed regional, structural, and tectonic investigations have been conducted by public utility companies in conjunction with nuclear power plant site evaluations (Portland General Electric, 1978; WPPSS, 1974, 1977). These studies have provided significant information concerning the character and age of plateau deformation and have served as a basis for initial tectonic model development (Davis, 1977; Laubscher in WPPSS, 1977; Shannon and Wilson, 1977a, 1977b). Further information concerning the character and timing of deformation within the plateau has been provided by Swanson and Others (1977) and Tabor and Others (1977) as a result of geologic mapping in southeastern and west-central Washington.

Remote Sensing

Regional remote sensing studies have been carried out to identify structures which may have a bearing on the tectonic setting of the Columbia Plateau and contiguous provinces. These studies consisted primarily of an analysis of satellite imagery (ERTS, Landsat). Photolineament maps based on an interpretation of such imagery have been compiled for Idaho (Day and Hall, 1973), Oregon (Lawrence and Carter, 1974), and Washington (Brewer, 1977). An additional analysis of Landsat imagery covering central Washington State was carried out by Glass and Slemmons (in WPPSS, 1977) as part of a tectonic evaluation of the Columbia Plateau and Cascade Range provinces by the Washington Public Power Supply System, Inc. A more detailed remote sensing study of selected structures of this area was also conducted by Glass (in WPPSS, 1977) using aerial photography at a scale of 1:24,000. The results of regional photolineament studies conducted for Washington Public Power Supply System, Inc. have recently been summarized by Slemmons (1979).

Borehole Studies

The primary source of "regional" borehole data is files of drillers' logs maintained by federal and state agencies (U.S. Geological Survey, Washington State Department of Ecology, Washington State Department of Natural Resources, Oregon State Department of Geology and Mineral Industries, and Idaho State Bureau of Mines and Geology). This data base shows only a few boreholes which penetrate basalt and reach "basement" (pre-Columbia River basalt rocks) within the confines of the Columbia Plateau. Of these holes, reliable information is available only for the "Basalt Explorer No. 1 Borehole" in Lincoln County, Washington (Williams, 1961; Brown, 1978), the "Rattlesnake Hills No. 1 Borehole" in Benton County, Washington (Raymond and Tillson, 1968; Gephart and Others, 1979), and the "Condon Borehole" in Gilliam County, Oregon. Although available, the drillers' log from the "Union Gap Borehole" in Yakima County, Washington contains questionable and conflicting entries.

Federal and state agency files contain logs for over 4,000 boreholes in Washington, 1,000 wells in Oregon, and 500 wells in Idaho that penetrate sediments into basalt. Drillers' logs and stratigraphic interval assignments for a number of these wells are discussed by Walters and Grolier (1960),

Griggs (1976), and Grolier and Bingham (1978). However, a "regional" synthesis and evaluation of stratigraphic and structural information which can be derived from available drillers' logs has yet to be completed.

Borehole geophysical investigations within the region have primarily been conducted by Washington State University (Crosby and Anderson, 1971; Bush and Others, 1972; Crosby, 1972; Crosby and Others, 1972; Bush and Morton, 1973; Siems and Others, 1974; Robinette, 1975; Brown, 1978). These studies have provided a geophysical data base which has been used to conduct subsurface correlations of basalt and interbed units based upon their physical properties and apparent chemistries. Geophysical information available for boreholes in southeastern Washington has recently been compiled by Brown (1978).

Geophysical Surveys

Available regional geophysical surveys are divisible into five main categories: (a) aeromagnetic; (b) gravity; (c) seismic; (d) resistivity; and, (e) heat flow. In 1971, a high-altitude aeromagnetic survey of a strip across the northwestern United States was conducted by Zietz and Others (1971) to determine the deep-seated structural character of the area. The results of this survey indicated that the Columbia Plateau is characterized by broad, low-amplitude magnetic anomalies along a pronounced northwest trend (Zietz and Others, 1971). In addition, two low-altitude regional aeromagnetic surveys were performed to specifically detect near-surface structures. Surveys conducted by Weston Geophysical Research (in WPPSS, 1977) defined the locations of several magnetic linears within central Washington State. A second, low-altitude survey published by Swanson and Others (1979c) involved an interpretation of the relationship between aeromagnetic anomalies and folds, faults, dikes, and valley-filling flows within south-central and southeastern Washington.

Bouger gravity maps have been compiled for Washington (Danes, 1969), Oregon (Thiruvathukal and Others, 1970), and Idaho (Eaton and Others, 1978). In general, these maps show that gravity values, lowest in the central portion of the plateau, increase concentrically outward toward the margins of the province. Based on gravity data, Danes (1969) suggested that the plateau is essentially in isostatic equilibrium.

In 1972, Hill made seismic refraction measurements along a 375-mile (600-kilometer) long profile extending due south from the Canadian border across the Columbia Plateau into eastern Oregon. He interpreted these measurements to indicate that the crust under the Columbia Plateau is thinner than the crust under the granitic-metamorphic terrain of northern Washington by as much as 7.5 miles (12 kilometers). Based on these data, Hill (1972) proposed tentative ideas concerning the past and present configuration of the mantle beneath the plateau.

Conclusions concerning the properties of the "crust" beneath the Columbia Plateau were also made by Cantwell and Others (1965) and Cantwell and Orange (1965). Their deep resistivity data collected within eastern Oregon and Washington indicated a major, deep-seated east-west structural

transition in south-central Washington about 12.5 to 24 miles (20 to 40 kilometers) north of the Washington-Oregon border. Cantwell and Others (1965) suggested that this tranistion zone is located in the approximate position of a prominent topographic alignment, termed by Raisz (1945) the Olympic-Wallowa lineament.

Heat flow data available for the western United States has recently been summarized by Blackwell (1978). His map of this area shows a low to moderate heat flow regime for the Columbia Plateau.

REGIONAL STRATIGRAPHY

This section contains a discussion of stratigraphic units present within and contiguous to the Columbia Plateau of eastern Washington. The discussion is divided into four subsections entitled: (a) "Basement" Rocks; (b) Columbia River Basalt Group; (c) Intercalated and Suprabasalt Sediments; and, (d) Late Cenozoic Volcanic Rocks. The contents of these subsections are organized primarily with reference to the regional geologic maps which accompany this report (Plates II-1 through II-19).

"BASEMENT" ROCKS

Along the margins of the plateau, Columbia River basalt flows overlie a diverse and complex assemblage of Precambrian to early Tertiary age units, collectively referred to as "basement" rocks. Within the interior of the province, no "windows" are eroded through the thick basalt cover. Consequently, a direct assessment of the pre-Columbia River basalt history of the plateau area can be made only by studying the "basement" rocks around its perimeter.

The primary emphasis of regional mapping to date has been to define the stratigraphy and structure of the Columbia River Basalt Group and overlying late Cenozoic units. However, the general lithology and distribution of "basement" rocks within a narrow zone surrounding the map area is shown on Plates II-1 through II-10. An examination of these plates shows that, along the western margin of the Columbia Plateau, basalt flows overlie an irregularly eroded, rolling surface comprised of a complex of folded sedimentary and volcanic units (Plates II-3 through II-6 and II-9). To the north, the basalt covers crystalline gneisses, plutonic complexes, and schists which comprise a former surface of moderately low relief (Plates II-1 through II-4). Along the northeastern and eastern margins of the plateau, flows rest upon an irregular landscape comprised of Precambrian metasedimentary rocks of the Northern Rocky Mountains province and Mesozoic intrusive units of the Idaho Batholith province (Plates II-1, II-2, and II-10). To the south, Mesozoic to early Tertiary metamorphic rocks of the Blue Mountains subprovince crop out within deeply dissected portions of the map area (Plate II-10).

COLUMBIA RIVER BASALT GROUP

This section contains a general description of the 5 formations and 14 members recognized within the Columbia River Basalt Group (Swanson and Others, 1979b). This discussion is keyed primarily to the regional stratigraphic chart (Figure II-4), to the table of chemical types (Table II-1), and to generalized outcrop maps included in the text. For a more detailed definition of the distribution of basalt units, the reader is referred to the reconnaissance geologic maps of the Columbia River Basalt Group included as Plates II-1 through II-10.

Imnaha Basalt and Picture Gorge Basalt

The two basal formations of the Columbia River Basalt Group, as recently redefined by Swanson and Others (1979b), are the Imnaha Basalt and Picture Gorge Basalt (Figure II-4). Flows of Picture Gorge Basalt are confined to the vicinity of the John Day Basin in north-central Oregon and were extruded from feeder dikes comprising the Monument swarm (Waters, 1961; Wilcox and Fisher, 1966; Fruchter and Baldwin, 1975) (Figures II-1 and II-5). Outcrops of Imnaha Basalt are confined to southeastern Washington, northeastern Oregon, and adjacent Idaho, where known source dikes are exposed (Taubeneck, 1970; Kleck, 1976) (Figures II-1 and II-5). As such, only flows of the Imnaha Basalt crop out within the map area (Plate II-10).

Flows of Imnaha Basalt are generally coarse grained, plagioclase-phyric, and have compositions similar to one of the first 5 chemical types listed in Table II-1. In the vicinity of the type locality (Taubeneck, 1970; Hooper, 1974; Kleck, 1976; Swanson and Others, 1979b), Imnaha Basalt has a thickness of 1,650 feet (500 meters) and is comprised predominantly of flows of normal polaritylarity (N_0 magnetostratigraphic unit) (Figure II-4). Although Waters (1961) tentatively included what is now defined as Imnaha Basalt in his Picture Gorge Basalt, he noted slight petrographic differences. More recent work (Bond, 1962; Osawa and Goles, 1970; Holden, 1974; Hooper, 1974; Holden and Hooper, 1976; Nathan and Fruchter, 1974; Kleck, 1976; Price, 1977; Reidel, 1978b) has demonstrated that flows of the two newly defined formations not only occur in different areas, but show significant chemical and isotopic differences. In addition, magnetostratigraphic mapping suggests that at least the upper part of the Picture Gorge Basalt in central Oregon is younger than the Imnaha Basalt (Figure II-4) (Swanson and Others, 1979b). The major petrographic, chemical, and paleomagnetic properties of the two formations are summarized in Table II-2.

Grande Ronde Basalt

The Grande Ronde Basalt, the oldest formation of the Yakima Basalt Subgroup (Figures II-4 and II-6) was extruded between 14 and 16.5 million years before present (Watkins and Baksi, 1974). The type locality for this unit is situated in the lower part of the Grande Ronde River Valley, southeasternmost Washington (Camp and Others, 1978; Swanson and Others, 1979b) (Plate II-10). The character of Grande Ronde Basalt

Series	Group	Sub-group	Formation	Member	K-Ar age (m.y.)	Magnetic polarity
MIOCENE	Upper Miocene	COLUMBIA RIVER BASALT GROUP	YAKIMA BASALT SUBGROUP	Saddle Mountains Basalt		
				Lower Monumental Member	6[3]	N
				erosional unconformity		
				Ice Harbor Member		
				basalt of Goose Island	8.5[3]	N
				basalt of Martindale	8.5[3]	R
				basalt of Basin City	8.5[3]	N
				erosional unconformity		
				Buford Member		R
				Elephant Mountain Member	10.5[3]	N,T
				erosional unconformity		
				Pomona Member	12[3]	R
				erosional unconformity		
	Middle Miocene			Esquatzel Member		N
				erosional unconformity		
				Weissenfels Ridge Member		
				basalt of Slippery Creek		N
				basalt of Lewiston Orchards		N
				Asotin Member		N
				local erosional unconformity		
				Wilbur Creek Member		N
				Umatilla Member		N
				local erosional unconformity		
			Wanapum Basalt	Priest Rapids Member		R_3
				Roza Member		T,R_3
				Frenchman Springs Member		N_2
				Eckler Mountain Member		
				basalt of Shumaker Creek		N_2
				basalt of Dodge		N_2
				basalt of Robinette Mountain		N_2
	Lower Miocene		Grande Ronde Basalt		14-16.5[2]	R_2
			Picture Gorge Basalt[4] ?		(14.6-15.8)[1,2]	N_1
						R_1
			Imnaha Basalt[4]			R_1
						T
						N_0
						R_0?

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[1] Information in parentheses refers to Picture Gorge Basalt

[2] Data mostly from Watkins and Baksi (1974)

[3] Data from McKee and Others (1977)

[4] The Imnaha and Picture Gorge Basalts are nowhere known to be in contact. Interpretation of preliminary magnetostratigraphic data suggests that the Imnaha is older.

FIGURE II-4. Regional Columbia River Basalt Group Stratigraphic Nomenclature (after Swanson and Others, 1979b).

TABLE II-1. Average Major Element Compositions for Chemical Types in the Columbia River Basalt Group.

(After Swanson and Others, 1979b)

	1	2	3	4	5	6	7	8
	(7)[1]	(44)	(21)	(68)	(7)	(8)	(4)	(13)
Oxide								
SiO_2	50.99	51.14	51.18	49.53	50.73	50.36	51.46	51.57
Al_2O_3	15.42	15.06	14.06	16.34	17.10	15.54	15.39	13.87
"FeO"[2]	12.24	13.04	14.11	12.38	11.26	11.25	12.46	12.28
MgO	5.94	5.07	4.60	6.06	5.42	6.68	4.86	4.44
CaO	10.11	9.31	8.59	9.15	9.30	10.67	9.45	8.12
Na_2O	2.55	2.58	2.65	2.58	2.45	2.95	3.29	3.36
K_2O	0.53	0.91	1.19	0.93	0.85	0.57	0.74	2.02
TiO_2	1.66	2.24	2.93	2.41	2.32	1.56	1.79	2.71
P_2O_5	0.34	0.42	0.48	0.41	0.38	0.22	0.33	1.39
MnO	0.22	0.22	0.22	0.20	0.19	0.20	0.23	0.24
Total[3]	100.00	99.99	100.00	100.00	100.00	100.00	100.00	100.00

[1]Number of analyses used in computing average.
[2]FeO + Fe_2O_3.
[3]Difference between total and 100 is due to rounding during normalization.

Chemical types defined by method of Wright and Hamilton (1978):

1. Picture Gorge (Imnaha Basalt);
2. American Bar (equivalent to the high-Ti Picture Gorge chemical type of Wright and Others, 1973);
3. Frenchman Springs (Imnaha Basalt);
4. Rock Creek;
5. Fall Creek (Kleck, 1976);
6. High-Mg Picture Gorge (Wright and Others, 1973);
7. Low-Mg Picture Gorge (Wright and Others, 1973);
8. Prineville (recalculated from Uppuluri, 1974).

Table II-1 (continued)

	9	10	11	12	13	14	15	16
	(13)[1]	(8)	(10)	(9)	(20)	(4)	(8)	(35)
Oxide								
SiO_2	53.78	55.94	54.37	50.01	52.13	54.80	52.29	51.19
Al_2O_3	14.45	14.04	15.28	17.08	15.41	13.86	13.21	14.07
"FeO"[2]	11.35	11.77	9.46	10.01	10.66	13.32	14.38	13.91
MgO	5.25	3.36	5.91	7.84	5.92	2.84	4.04	4.39
CaO	9.07	6.88	9.79	11.01	10.18	6.48	7.90	8.48
Na_2O	2.83	3.14	2.80	2.44	3.00	3.18	2.67	2.72
K_2O	1.05	1.99	0.77	0.27	0.68	1.87	1.41	1.22
TiO_2	1.78	2.27	1.17	1.00	1.48	2.46	3.17	3.13
P_2O_5	0.28	0.43	0.29	0.19	0.35	0.93	0.71	0.67
MnO	0.19	0.19	0.16	0.14	0.19	0.26	0.22	0.23
Total[3]	100.01	100.01	100.00	99.99	100.00	100.00	100.00	100.01

[1]Number of analyses used in computing average.
[2]FeO + Fe_2O_3.
[3]Difference between total and 100 is due to rounding during normalization.

Chemical types defined by method of Wright and Hamilton (1978):

9. High-Mg Grande Ronde (one flow);
10. Low-Mg Grande Ronde (one flow);
11. Very high-Mg Grande Ronde (one flow);
12. Robinette Mountain;
13. Dodge;
14. Shumaker Creek;
15. Frenchman Springs (one flow);
16. Roza.

Table II-1 (continued)

Oxide	17 (15)[1]	18 (55)	19 (13)	20 (11)	21 (6)	22 (3)	23 (2)	24 (12)
SiO_2	50.27	50.09	54.70	54.41	50.72	52.12	49.75	54.16
Al_2O_3	13.69	14.31	14.10	14.51	16.23	14.33	15.26	13.84
"FeO"[2]	15.04	13.78	12.63	11.07	9.64	11.64	11.82	12.60
MgO	4.29	5.18	2.71	4.51	8.19	5.58	7.10	3.91
CaO	8.31	8.88	6.14	8.32	10.70	9.64	10.13	7.71
Na_2O	2.67	2.57	3.20	2.69	2.22	2.69	2.32	2.66
K_2O	1.16	1.07	2.68	1.77	0.51	0.87	0.46	1.70
TiO_2	3.55	3.15	2.80	1.95	1.45	2.48	2.42	2.82
P_2O_5	0.81	0.78	0.88	0.56	0.18	0.49	0.55	0.41
MnO	0.21	0.19	0.17	0.21	0.17	0.17	0.21	0.19
Total[3]	100.00	100.00	100.01	100.00	100.01	100.00	100.02	100.00

[1]Number of analyses used in computing average.
[2]FeO + Fe_2O_3.
[3]Difference between total and 100 is due to rounding during normalization.

Chemical types defined by method of Wright and Hamilton (1978):

17. Rosalia;
18. Lolo;
19. Umatilla;
20. Wilbur Creek;
21. Asotin;
22. Slippery Creek;
23. Lewiston Orchards;
24. Esquatzel.

Table II-1 (continued)

Oxide	25 (30)[1]	26 (41)	27 (8)	28 (12)	29 (13)	30 (8)	31 (24)
SiO_2	51.88	51.08	54.46	47.45	48.73	47.50	50.44
Al_2O_3	14.88	13.54	14.29	13.84	13.88	12.50	14.07
"FeO"[2]	10.55	14.75	11.05	15.22	14.41	17.53	13.78
MgO	6.96	4.28	4.85	5.99	5.88	4.41	5.01
CaO	10.67	8.34	8.54	9.71	9.72	8.80	8.67
Na_2O	2.36	2.45	2.75	2.31	2.42	2.44	2.79
K_2O	0.64	1.25	1.39	0.72	0.73	1.23	1.47
TiO_2	1.62	3.52	2.17	3.62	3.30	3.79	2.90
P_2O_5	0.25	0.59	0.35	0.91	0.73	1.54	0.66
MnO	0.17	0.20	0.15	0.23	0.20	0.27	0.21
Total[3]	99.98	100.00	100.00	100.00	100.00	100.01	100.00

[1]Number of analyses used in computing average.
[2]FeO + Fe_2O_3.
[3]Difference between total and 100 is due to rounding during normalization,

Chemical types defined by method of Wright and Hamilton (1978):

25. Pomona;
26. Elephant Mountain;
27. Buford;
28. Basin City;
29. Martindale (Ice Harbor 1);
30. Goose Island (Ice Harbor 2);
31. Lower Monumental.

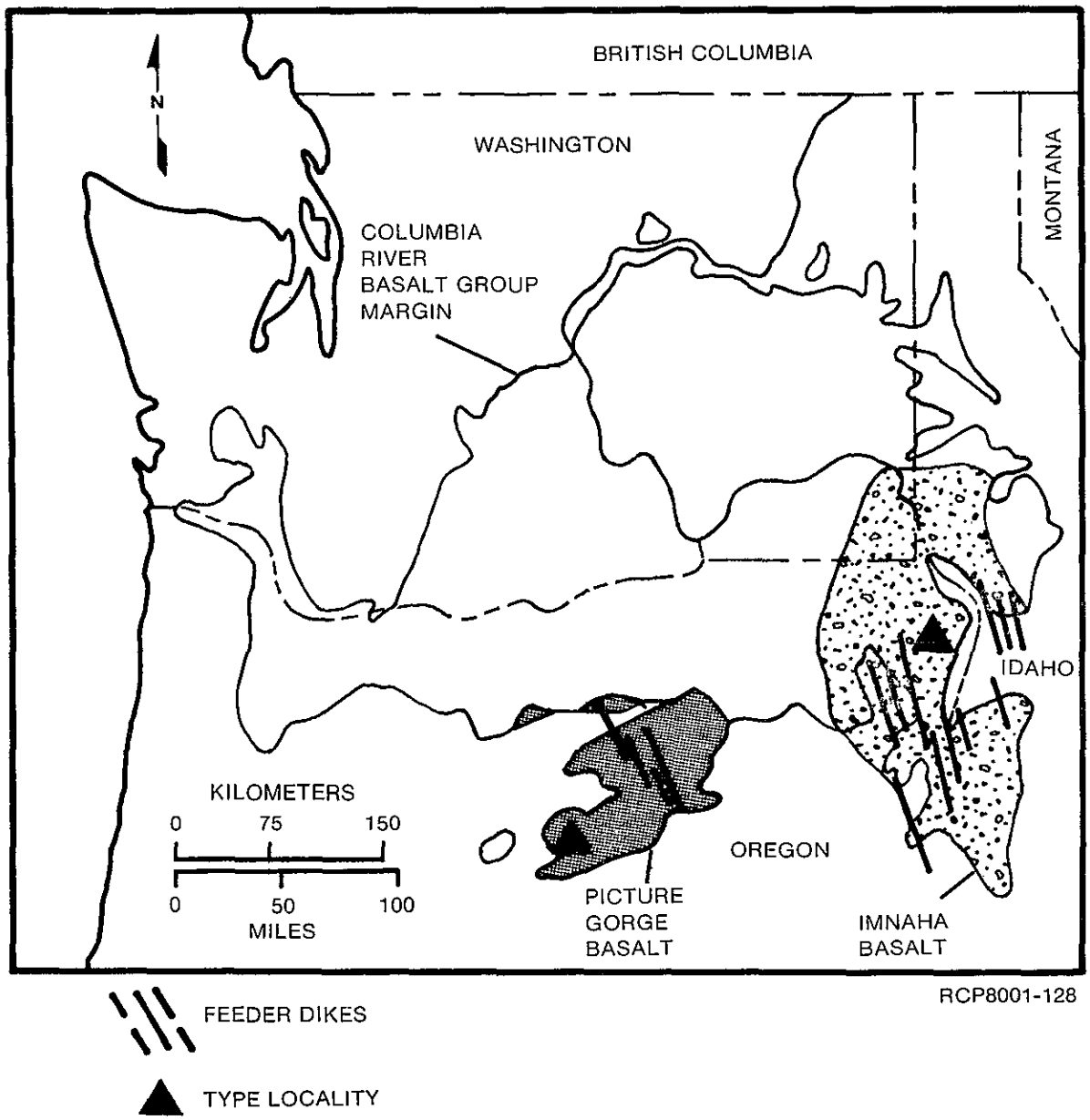

FIGURE II-5. Inferred Original Distribution of Imnaha Basalt and Picture Gorge Basalt (after Swanson and Wright, 1978; Swanson and Others, 1979b).

TABLE II-2. General Properties of Imnaha Basalt and Picture Gorge Basalt.

UNIT NAME AND AGE	TYPE LOCALITY	GENERAL STRATIGRAPHY	OUTCROP CHARACTERISTICS	PETROLOGY	CHEMISTRY (See Table II-1)	MAGNETICS (See Figure II-4)
IMNAHA BASALT	Dug Bar, on Snake River near mouth of Imnaha River; Cactus Mountain quadrangle, Wallowa County, Idaho-Oregon.	Oldest formation within Columbia River Basalt Group; base unconformably overlies pre-Tertiary rocks along rugged erosional unconformity. Imnaha Basalt older than at least upper part of Picture Gorge Basalt. Conformably overlain by Grande Ronde Basalt; no known interbedding of Imnaha Basalt with Grande Ronde Basalt.	Imnaha Basalt found only in northeastern Oregon, adjacent Washington, and Idaho. Feeder dikes present along Imnaha River in extreme northeastern Oregon. Type locality, 14 flows totaling nearly 1,650 feet (500 meters) in thickness. Some flows as much as 396 feet (120 meters) thick as a result of local ponding on irregular, pre-Tertiary surface. Imnaha-Grande Ronde Basalt contact commonly marked by distinct topographic break between grus-covered slopes developed in Imnaha Basalt and bold cliffs developed in Grande Ronde Basalt.	Most flows coarse grained and plagioclase-phyric; zeolite amygdules, secondary minerals, smectitic alteration common.	American Bar, Rock Creek, Picture Gorge, Frenchman Springs (Imnaha), Fall Creek.	Four informal magnetostratigraphic units listed oldest to youngest: R_0; N_0; T; and, R_1. Most flows N_0.
PICTURE GORGE BASALT	Roadcuts along U.S. Highway 26 near its junction with Oregon State Highway 19, SW1/4 sec. 17, NE1/4 sec. 18, NW1/4 sec. 20, T12S, R26W, in Picture Gorge, western Grant County, north-central Oregon.	Unconformably overlies John Day Formation. Conformably underlies Mascall Formation. Locally interlayered and hence coeval, in part, with Grande Ronde Basalt of Yakima Basalt Subgroup; most or all of Picture Gorge Basalt younger than Imnaha Basalt. Picture Gorge subdivided into 3 informal units (listed oldest to youngest): basalt of Twickenham; basalt of Monument Mountain; and basalt of Dayville.	Formation known to crop out only in the John Day Basin, north-central Oregon. Most known feeder dikes occur in John Day Basin and comprise Monument swarm. Type locality comprised of 17 flows, 1,420 feet (430 meters) thick; elsewhere, formation reaches a maximum thickness of 2,640 feet (800 meters).	Sequence of aphyric flows under- and overlain by plagioclase-phyric sequence.	High Mg-Picture Gorge, Low Mg-Picture Gorge; shows significant chemical differences from Imnaha Basalt.	N_1 sequence overlain by R_2 sequence.

IMNAHA BASALT

Primary References:

Bond, 1962
Hooper, 1974
Swanson and Others, 1979b

Additional References:

Camp, 1976
Holden and Hooper, 1976
Hooper and Others, 1976
Hooper and Others, 1979
Kleck, 1976
McDougall, 1976
Nathan and Fruchter, 1974
Price, 1977
Reidel, 1978b

PICTURE GORGE BASALT

Primary References:

Nathan and Fruchter, 1974
Swanson and Others, 1979b
Waters, 1961

Additional References:

Bentley and Cockerham, 1973
Dickinson and Vigrass, 1965
Fruchter and Baldwin, 1975
Lindsley, 1960
Lindsley and Others, 1971
Osawa and Goles, 1970
Robinson, 1966
Swanson, 1967
Watkins and Baksi, 1974

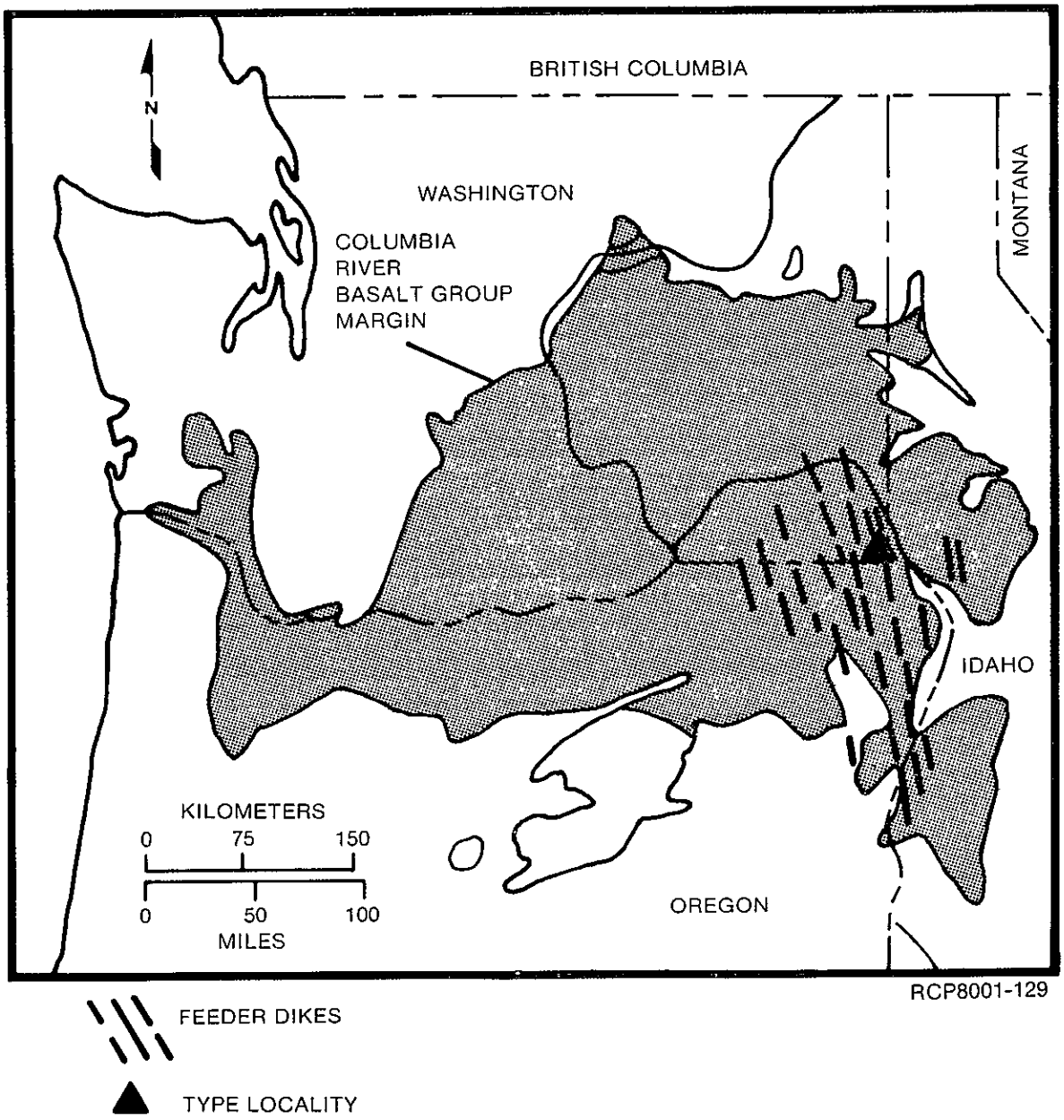

FIGURE II-6. Inferred Original Distribution of Grande Ronde Basalt (Shaded Area) (after Swanson and Others, 1979b).

flows in the vicinity of the type locality has been discussed in detail by Camp (1976), Price (1977), Reidel (1978b), and Ross (1978). These studies, along with other studies listed in Table II-3 and data included in Chapter III of this report, provide a comprehensive description of this formation. The chemical, petrographic, paleomagnetic, and stratigraphic properties of Grande Ronde Basalt are summarized in Table II-3.

The Grande Ronde Basalt is the most areally extensive unit of the Columbia River Basalt Group and underlies most of the Columbia Plateau (Figure II-6). The formation is also the most voluminous of the units, comprising approximately 85 percent of the basalt group (Swanson and Wright, 1978). In the map area (Plates II-1 through II-10), Grande Ronde Basalt is largely covered by younger flows, except along the margins of the plateau. However, the formation does crop out in the more deeply eroded parts of the central portion of the area, such as within valleys of major drainages, along floors of coulees, and within water gaps breaching anticlinal structures (Swanson and Others, 1979a). Known feeder dikes for the Grande Ronde Basalt (Taubeneck, 1970; Price, 1977; Swanson and Others, 1977) are exposed within the southeastern portion of the map area (Figure II-6; Plate II-10).

The known thickness of the Grande Ronde Basalt ranges from tens of feet (meters), along the margins of the Columbia Plateau, to more than 3,300 feet (1,000 meters) within the Pasco Basin, the approximate center of the Columbia Plateau (Raymond and Tillson, 1968; ARHCO, 1976). Along the edge of the plateau the thickness of the formation varies considerably, owing to the relief of the pre-basalt surface. Within the plateau, the thickest exposures of the Grande Ronde Basalt are generally composed of 30 to 40 flows. However, it is proposed that the formation, as a whole, may be comprised of hundreds of flows extruded from an equivalent number of vents located in the eastern portion of the plateau (Swanson and Wright, 1978; Swanson and Others, 1979a).

Most Grande Ronde Basalt flows are fine grained, aphyric, black, and dense. Only rare plagioclase and clinopyroxene phenocrysts are visible in hand specimen, although microphenocrysts of those minerals are common in thin section. Olivine has a volume of less than 0.5 percent and occurs only as a groundmass constituent (Swanson and Others, 1979b). Plagioclase-phyric flows within the sequence, because of their anomalous character, serve as local stratigraphic horizons, especially within the southeastern portion of the plateau (Gibson, 1969; Camp, 1976; Price, 1977; Reidel, 1978b).

Grande Ronde Basalt flows have a continuous range in chemical composition within a field defined as Grande Ronde chemical type (Myers, 1973; ARHCO, 1976; Swanson and Others, 1979b) (Table II-1). In general, Grande Ronde Basalt flows can be divided into two chemical subtypes, low-MgO Grande Ronde and high-MgO Grande Ronde (Table II-1). Within localized areas of the plateau, chemical "breaks" between sequences of flows having low-MgO and high-MgO Grande Ronde chemistries have been used for correlation and mapping purposes (Myers, 1973; Camp, 1976; Price, 1977; Reidel, 1978b; Beeson and Moran, 1979).

TABLE II-3. General Properties of Grande Ronde Basalt.

AGE	TYPE LOCALITY	GENERAL STRATIGRAPHY	OUTCROP CHARACTERISTICS	PETROGRAPHY	CHEMISTRY (See Table II-1)	MAGNETICS (See Figure II-4)
14.0-16.5 million years before present	Prominent west-trending ridge extending from NW1/4 sec. 23 across the N1/3 sec. 22 to the NE1/4 sec. 21, T7N, R46E, Black Butte quadrangle, in the lower part of the Grande Ronde River Valley, Asotin County, Washington.	Contact between Imnaha Basalt and Grande Basalt everywhere conformable; no evidence of break in time; no known interbedding of two units. Intertonguing of Picture Gorge Basalt with Grande Ronde Basalt present in north-central Oregon; two formations are, in part, coeval. Top of Grande Ronde Basalt generally well defined by zone of weathering and/or sedimentary interbed separating formation from overlying Wanapum or Saddle Mountains Basalt. However, interbedding of Grande Ronde and Wanapum Basalt flows present in Pomeroy, Washington area. Grande Ronde Basalt flows commonly interbedded with sedimentary material of Ellensburg and Latah Formations near plateau margin. Grande Ronde Basalt sequence has not been formally subdivided; informal chemical and magnetostratigraphic units recognized.	Most widespread formation in Columbia River Basalt Group. Grande Ronde Basalt underlies virtually all of Columbia Plateau in Washington, although covered by younger rocks in most of area. Grande Ronde type locality, 34 flows totaling 2,739 feet (830 meters) in thickness. Elsewhere thickness of formation varies considerably depending upon basalt topography and amount of erosion. Thickest known exposure 3,300 feet (1,000 meters) in Pasco Basin. Grande Ronde Basalt flows are predominantly cliff-formers and range in thickness from less than 3.3 feet (1 meter) to greater than 330 feet (100 meters). Generally, flows thinner and flow-top breccia more common near major vent areas. Flows range from those with well-developed colonnades and entablatures to those with no such recognizable subdivisions. Known Grande Ronde Basalt feeder dikes found in Chief Joseph swarm, northeast Oregon and adjacent Washington and Idaho.	Predominantly aphyric to very sparsely phyric, fine-grained tholeiitic basalt. Flows contain rare plagioclase microphenocrysts and plagioclase-clinopyroxene clots visible in both hand specimen and thin section; olivine generally absent as phenocrysts, but commonly present in small amounts (less than 0.5 percent) in groundmass. Only rarely are flows highly plagioclase-phyric.	Continuous range in chemical compostion within field defined as Grande Ronde chemical type. Known chemical breaks between high-MgO and low-MgO Grande Ronde Basalt flows recognized within southeastern portion of plateau and Pasco Basin area. Grande Ronde-Wanapum Basalt contact can generally be recognized by TiO_2 "break;" Grande Ronde Basalt generally has lower TiO_2 content than Wanapum Basalt.	Four informal magnetostratigraphic units (listed oldest to youngest): R_1; N_1; R_2; and N_2.

Primary References:

ARHCO, 1976
Camp and Others, 1976
Swanson and Others, 1979b

Additional References:

Baksi and Watkins, 1964
Bentley and Cockerham, 1973
Bentley, 1977a, 1977b
Bond, 1962
Camp, 1976
Choniere and Swanson, 1979
Diery and McKee, 1969
Gibson, 1969
Gray and Kittleman, 1967
Hammond and Others, 1977
Hogenson, 1964
Holden and Hooper, 1976
Holmgrem, 1969
Hooper and Others, 1976
Hooper and Others, 1979
Jackson, 1975
Kleck, 1973
Lindsley, 1960
Nathan and Fruchter, 1974
Newcomb, 1966, 1970
Price, 1974, 1977
Price and Others, 1973
Raymond and Tillson, 1968
Reidel, 1978b
Siems and Others, 1974
Smith, 1901
Stout, 1961
Swanson, 1967
Swanson and Wright, 1978
Swanson and Others, 1975
Swanson and Others, 1976
Swanson and Others, 1977
Tabor and Others, 1977
Taubeneck, 1970
Thayer and Brown, 1966
Waters, 1961
Watkins and Baksi, 1974
Wright and Others, 1973

To date, the only consistent "regional" subdivisions of the Grande Ronde Basalt are four magnetostratigraphic units (defined on the basis of dominant magnetic polarity) (Swanson and Wright, 1976). These units, listed in ascending order, are termed reversed-one (R]), normal-one (N_1), reversed-two (R_2), and normal-two (N_2) (Figure II-4). This magnetic stratigraphy, first determined from detailed and reconnaissance mapping in southeastern Washington (Swanson and Others, 1977), has been found to hold throughout the area geologically mapped for this study (Plates II-1 through II-10).

Examination of the reconnaissance geologic map set (Plates II-1 through II-10) reveals that the oldest of the four units, R_1, is exposed only at the base of canyons within the southeasternmost portion of the map area (Figure II-7; Plate II-10). With the exception of this area, exposures of N_1 flows are also limited to relatively deep canyons within the western portion of the plateau (Figure II-8). Surface exposures of Grande Ronde Basalt within the map area primarily belong to the two upper magnetic intervals, R_2 and N_2 (Figures II-9 and II-10; Plates II-1 through II-10). As such, the R_2-N_2 contact serves as an important regional stratigraphic horizon.

Magnetostratigraphic units shown on the map set (Plates II-1 through II-10) serve as an important framework for conducting more detailed studies of Grande Ronde Basalt throughout the plateau. Several such studies have already been completed within the tri-state area of Washington, Oregon, and Idaho (Camp, 1976; Price, 1977; Reidel, 1978b; Ross, 1978) and within the western portion of the plateau (Beeson and Moran, 1979; Swanson and Others, 1979a). These studies provide additional insight into the stratigraphic character of Grande Ronde Basalt. The results of such studies show that "groups" of Grande Ronde Basalt flows can be correlated for several tens of miles (kilometers) on the basis of chemical and paleomagnetic data. For example, in the southeastern portion of the plateau, the horizon between a high-MgO Grande Ronde Basalt flow sequence, overlain by a low-MgO Grande Ronde Basalt flow sequence, can be traced throughout the tri-state area. This chemical horizon consistently occurs one to two flows below the R_1-N_1 magnetic "break." A "mappable" chemical horizon is also present within the southwestern part of the plateau, where a sequence of flows of high-MgO Grande Ronde chemistry overlies a sequence of flows of low-MgO Grande Ronde chemistry (Nathan and Fruchter, 1974; Taylor, 1976; ARHCO, 1976; WPPSS, 1977; Beeson and Moran, 1979; Swanson and Others, 1979a, 1979b; also see Chapter III). This horizon occurs within the N_2 magnetic interval. With further study, such "chemical units" within the Grande Ronde Basalt may prove to have "regional" stratigraphic significance.

Detailed studies of Grande Ronde Basalt within the tri-state area (Camp, 1976; Price, 1977; Reidel, 1978b; Ross, 1978) have shown the presence of distinctive Grande Ronde Basalt flows, herein termed "through-running" flows. These flows crop out within deep canyons cut into the basalt by the Snake, Grande Ronde, and Salmon Rivers. Such flows are identifiable by a combination of physical properties (topographic expression, weathering characteristics, jointing habits), petrography, chemistry,

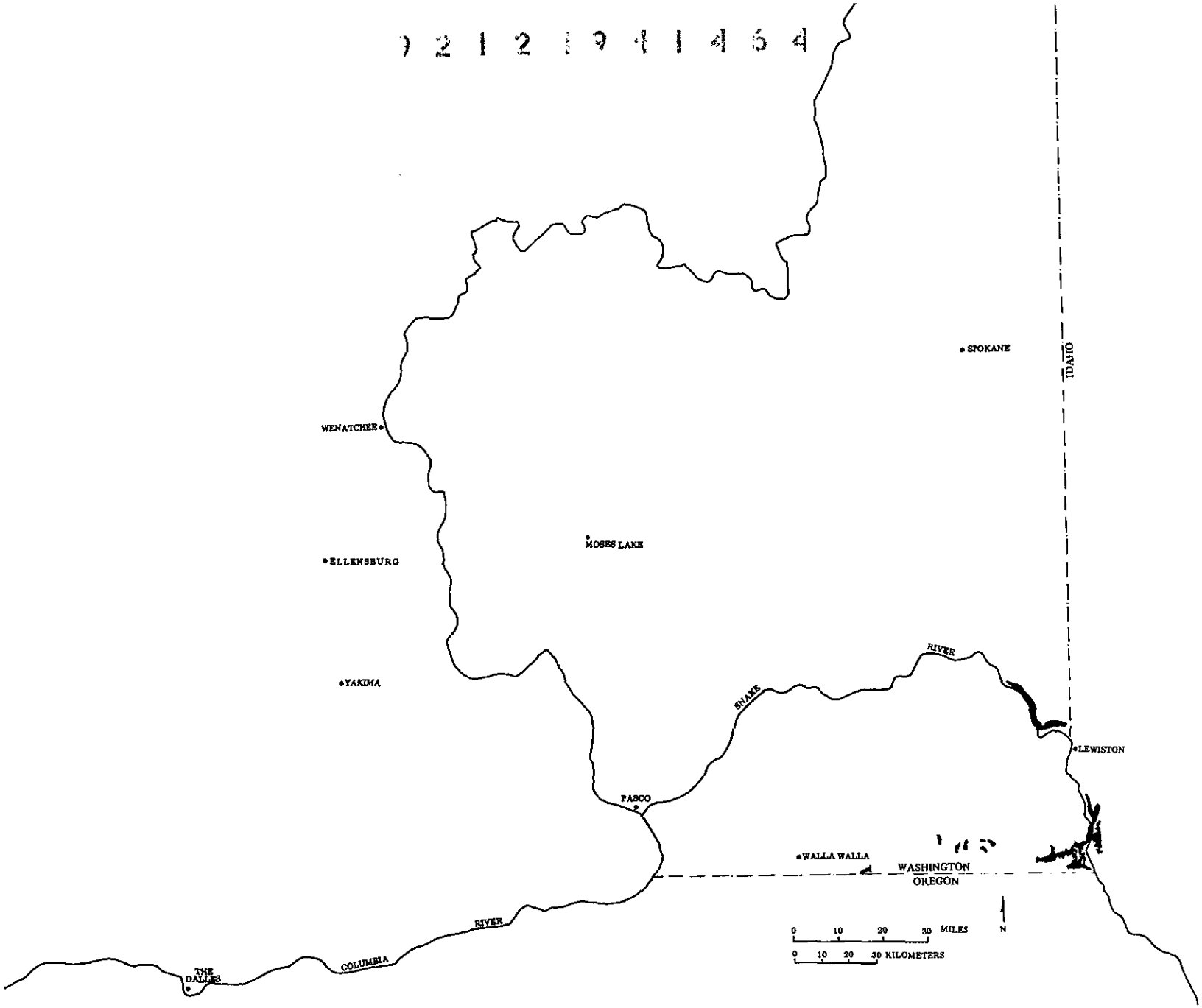

FIGURE II-7. Generalized Outcrop Distribution of R_1 Grande Ronde Basalt, Eastern Washington (after Swanson and Others, 1979a).

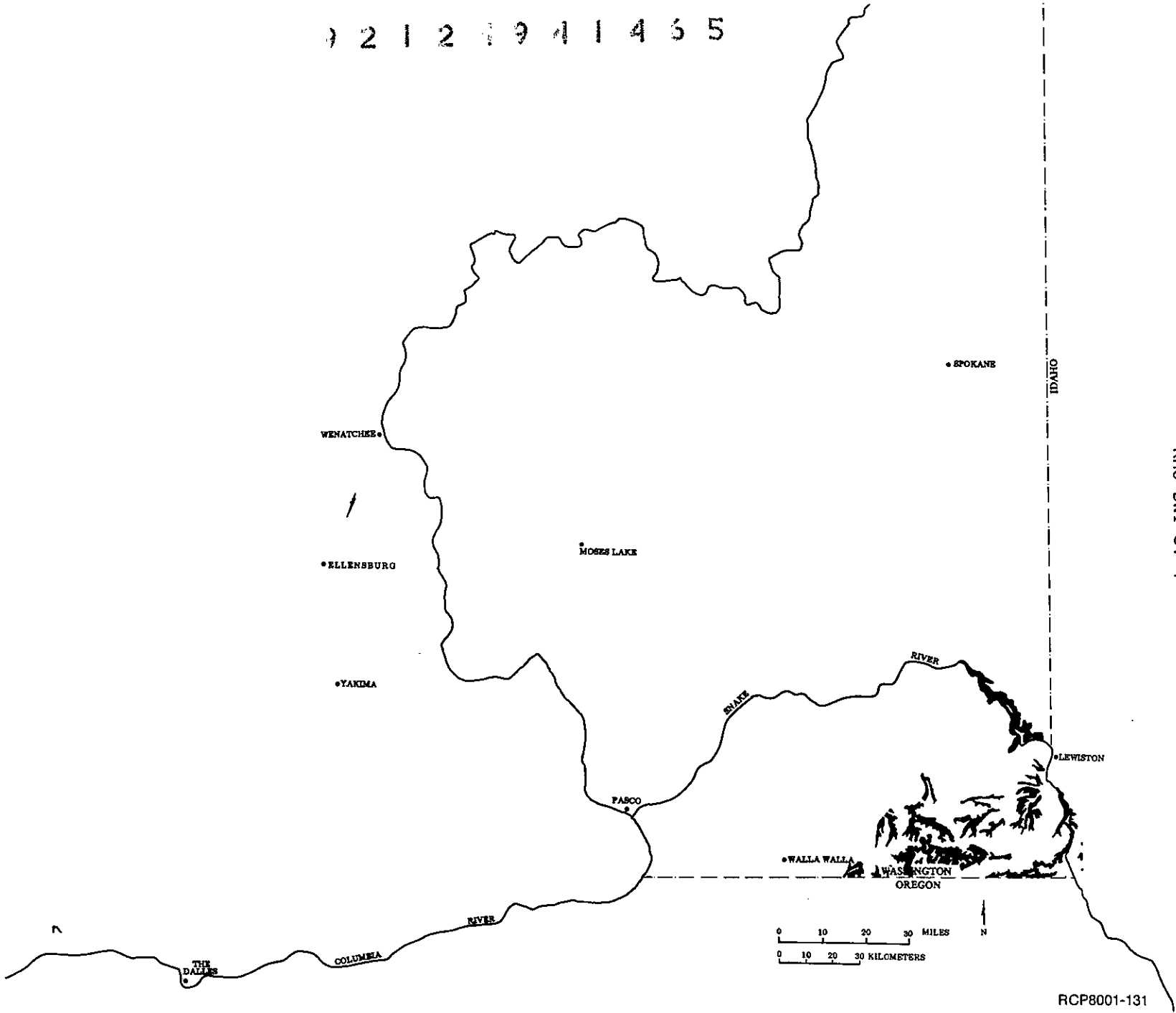

FIGURE II-8. Generalized Outcrop Distribution of N_1 Grande Ronde Basalt, Eastern Washington (after Swanson and Others, 1979a).

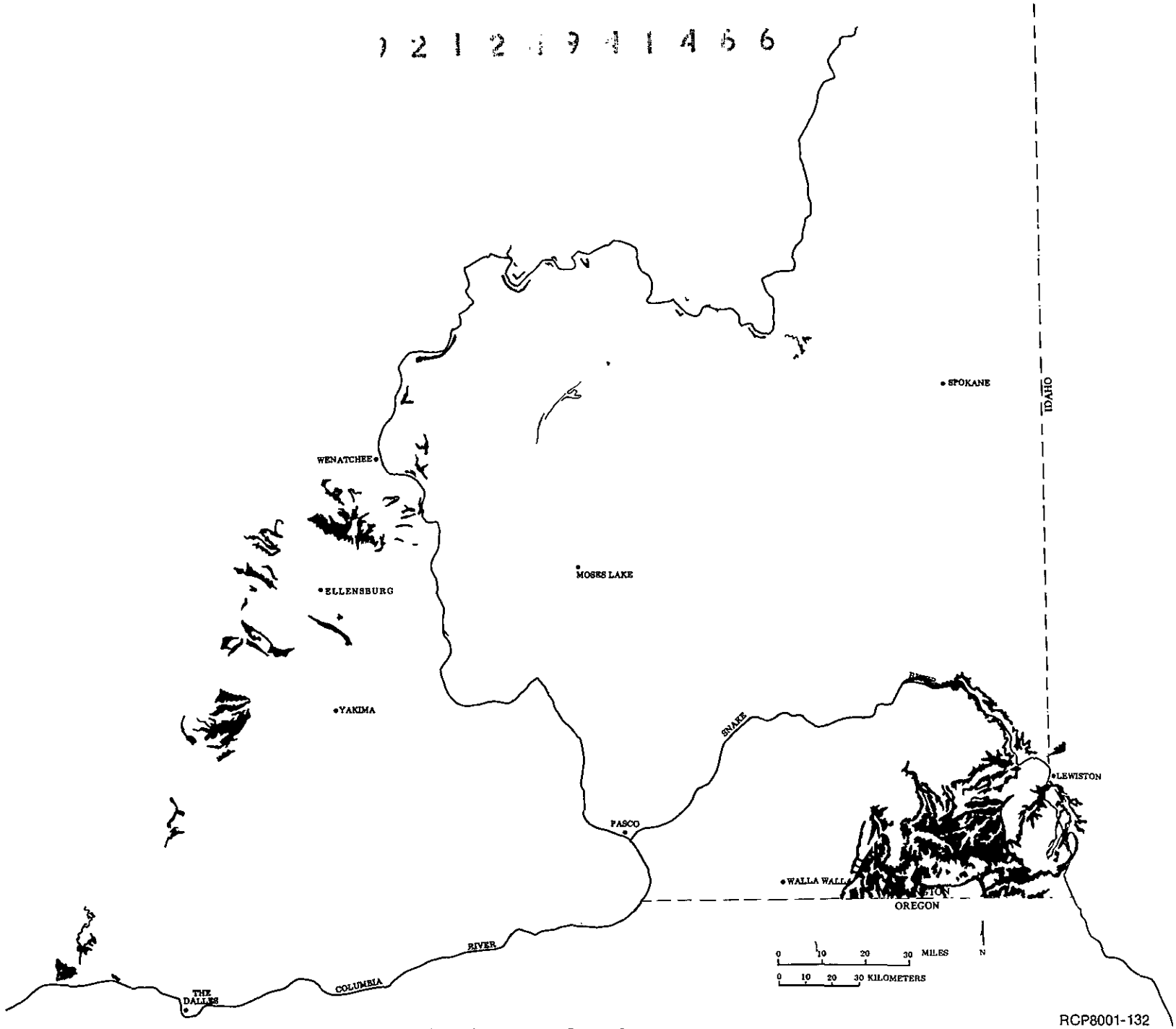

FIGURE II-9. Generalized Outcrop Distribution of R_2 Grande Ronde Basalt, Eastern Washington (after Swanson and Others, 1979a).

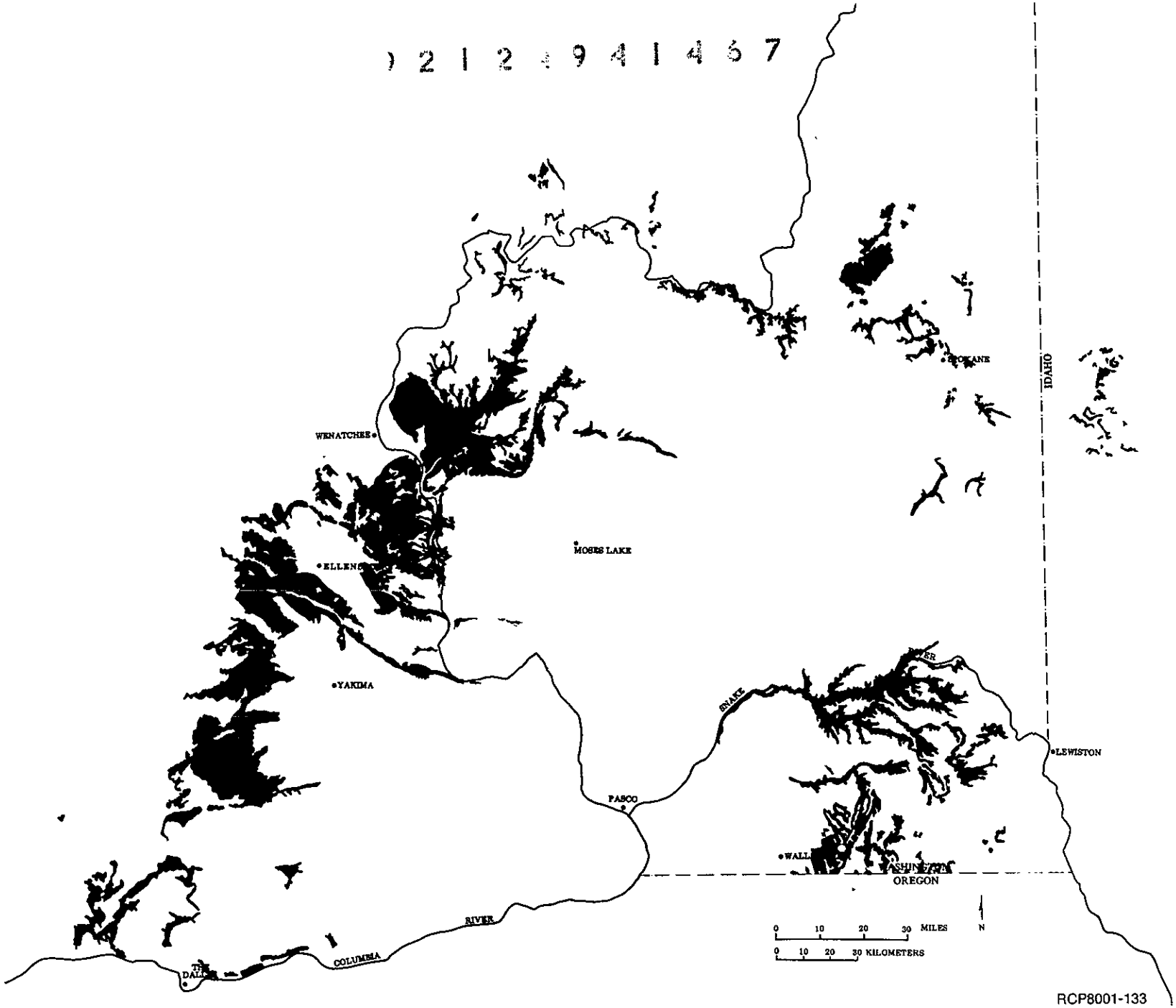

FIGURE II-10. Generalized Outcrop Distribution of N_2 Grande Ronde Basalt, Eastern Washington (after Swanson and Others, 1979a).

and paleomagnetics, and have been named on an informal basis (Table II-4). They generally have a known areal extent of over 100 square miles (250 square kilometers) and a thickness of over 100 feet (30 meters). Other widespread Grande Ronde Basalt flows exposed within the western part of the plateau have been described by Swanson (1967). Studies by Rockwell Hanford Operations (Chapter III of this report) have also shown the presence of "through-running" Grande Ronde Basalt flows within the Pasco Basin.

The contact of Grande Ronde Basalt with underlying Imnaha Basalt is well exposed in the tri-state area (Plate II-10). The contact between the two formations is conformable, with no evidence of a major time break (Bond, 1962; Holden, 1974; Camp, 1976; Price, 1977; Reidel, 1978b; Swanson and Others, 1979b). Magnetostratigraphic mapping shows that flows of the oldest known Grande Ronde Basalt magnetic units (R_1) overlie flows of the youngest known Imnaha Basalt magnetic unit (N_0) (Figure II-4) (Swanson and Others, 1979b).

The contact between Grande Ronde Basalt and Picture Gorge Basalt flows is exposed only in central Oregon, outside of the plateau area discussed in this report. However, the relationship between these two formations has been studied in some detail by Nathan and Fruchter (1974). They have shown that upper flows of the Picture Gorge Basalt interfinger with lower Grande Ronde Basalt flows of the N_1 magnetic unit. Interfingering of Grande Ronde Basalt and Picture Gorge Basalt indicates that the two formations are, in part, coeval. Consistent with this interpretation are potassium-argon dates for the two formations, which indicate an age of about 16 million years before present for both (Watkins and Baksi, 1974).

The contact between Grande Ronde Basalt and Wanapum Basalt is commonly marked by a zone of weathering or a thin sedimentary interbed (Mackin, 1961; ARHCO, 1976; Swanson and Others, 1979b). The contact is also distinguished by a change in chemistry; Grande Ronde Basalt flows generally contain significantly less TiO_2 (0.5 to 1.0 percent less) than do overlying Wanapum Basalt flows (Table II-1). This horizon, detectable using borehole geophysical logging techniques, has also been termed the "TiO_2 discontinuity" (Siems and Others, 1974; ARHCO, 1976; Brown, 1978). However, the contact between the two formations is not marked by a change in magnetic polarity. In fact, interfingering of Grande Ronde and Wanapum Basalt flows near Pomeroy, Washington (Plate II-10) has been noted by Swanson and Others (1977 and 1979b). Swanson and Others (1977 and 1979b) have interpreted this relationship to indicate that the interval between eruption of the Grande Ronde Basalt and Wanapum Basalt occurred within one magnetic polarity interval, the N_2, and probably lasted no more than a few tens of thousands of years.

Wanapum Basalt

The Wanapum Basalt is the middle formation of the Yakima Basalt Subgroup (Figure II-4) (Swanson and Others, 1979b). Its type locality is designated as the area of nearly continuous exposure along the east

TABLE II-4. Named Grande Ronde Basalt Flows within the Canyons of the Salmon, Snake, and Grande Ronde Rivers and the Lewiston Basin Area.

GRANDE RONDE MAGNETOSTRATIGRAPHIC UNIT	SALMON RIVER CANYON AND SNAKE RIVER CANYON	GRANDE RONDE RIVER CANYON	LEWISTON BASIN
R_2	High P_2O_5, K_2O, Zr, Ba, flows[5]	Meyer Ridge flow[3,4,5] Troy Flow-Table Mtn. Flow[4,6] High-P_2O_5, K_2O, Zr, Ba flows[5]	Meyer Ridge flow[3,4]
N_1	Johns Creek flow[1,2,5] Low TiO_2, P_2O_5 flows[5]	Mud Creek flow[6]	Couse Creek flow[3]
R_1	Center Creek flow[1,2,5] Rogersburg flows[3,4,5] High-MgO Low-P_2O_5, Zr, Ba flows[5] High-TiO_2 flows[3,5] Graves Creek flow[1,2]	Center Creek flow(s) Rogersburg flows[3,4,5] High-MgO Low-P_2O_5, Zr, Ba flows[5] High-TiO_2 flows[3,4,5]	Rogersburg flows[3]

[1]Bond, 1962

[2]Holden, 1974

[3]Camp, 1976

[4]Price, 1977

[5]Reidel, 1978b

[6]Ross, 1978

side of the Columbia River near Wanapum Dam, east-central Washington (Figure II-11). The Wanapum Basalt in the vicinity of the type locality was first described by Mackin (1961) and later in more detail by Myers (1973). Additional references which contain a description of this formation are listed in Table II-5.

The Wanapum Basalt is the second-most voluminous of the basalt formations, comprising an estimated 15 percent of the Columbia River Basalt Group. Although its volume is considerably less than that of the Grande Ronde Basalt, the Wanapum Basalt is the most extensively exposed of the 5 formations and covers 80-90 percent of the central part of the plateau (Figure II-11) (Swanson and Wright, 1978; Swanson and Others, 1979b).

Wanapum Basalt is comprised primarily of flows which are generally medium grained, olivine-bearing, and slightly to moderately plagioclase-phyric. Most Wanapum Basalt flows have relatively "high" FeO and TiO_2 contents and are of Frenchman Springs, Rosalia, or Lolo chemical type (Table II-1). Known feeder dikes for Wanapum Basalt are exposed within the southeastern part of the plateau (Figure II-11) (Price, 1977; Swanson and Others, 1977).

Wanapum Basalt currently includes four recognized members: Eckler Mountain; Frenchman Springs; Roza; and, Priest Rapids (listed oldest to youngest) (Swanson and Others, 1979b). All but the Eckler Mountain Member cover large parts of the map area (Plates II-1 through II-10). Petrographic, chemical, and paleomagnetic properties which distinguish these four members are discussed briefly in the remainder of this section and are summarized within Table II-5.

Eckler Mountain Member. The Eckler Mountain Member is the oldest, but most recently defined (Swanson and Others, 1977, 1979b), of the four Wanapum Basalt subdivisions (Figures II-4 and II-12). The member includes flows of normal magnetic polarity overlying the Grande Ronde Basalt and underlying the Frenchman Springs Member. The Eckler Mountain Member contains flows of three different petrographic and chemical types, informally termed the basalt of Robinette Mountain, the basalt of Dodge, and the basalt of Shumaker Creek (listed from oldest to youngest) (Swanson and Others, 1979b). Distinctive properties of these three informal subdivisions are included in Table II-5. Within the map area the Eckler Mountain Member is most extensively exposed within southeastern Washington (Figure II-12; Plate II-10) although isolated outcrops of the member (i.e., basalt of Dodge) occur in the northeastern part of the area (St. Maries River drainage) (Figure II-12; Plate II-1) (Swanson and Others, 1979a, 1979b). Suspected and confirmed Eckler Mountain Member vents have been found within both outcrop areas (Price, 1973a, 1973b, 1974; Swanson and Others, 1975, 1977, 1979a, 1979b).

TABLE II-5. General Properties of Wanapum Basalt.

UNIT NAME	TYPE LOCALITY	GENERAL STRATIGRAPHY	OUTCROP CHARACTERISTICS	PETROLOGY	CHEMISTRY (See Table II-1)	MAGNETICS (See Figure II-4)
WANAPUM BASALT	East side of Columbia River near Wanapum Dam, from Sand Hollow in sec. 28, T17N, R23E, south to top of section near Vantage Substation above Wanapum Dam in sec. 16, T16N, R23E, Vantage and Beverly quadrangles, Grant County, Washington.	Wanapum Basalt subdivided into four members (listed oldest to youngest): Eckler Mountain; Frenchman Springs; Roza; and Priest Rapids. On local scale, Wanapum Basalt overlies Grande Ronde Basalt conformably or with local disconformities, except for interbedded relation in Pomeroy, Washington area; on a regional scale, Wanapum disconformably overlies progressively older parts of Grande Ronde Basalt eastward from the center of the plateau.	Prominent saprolite marks Grande Ronde-Wanapum Basalt contact in southeastern Washington and adjacent Oregon and Idaho; Vantage Member of Ellensburg Formation marks contact across much of western part of Columbia Plateau. Contact between Wanapum and Saddle Mountains Basalt generally conformable; saprolite or sediments of Ellensburg Formation commonly occur along contact. Contacts between four Wanapum Basalt members conformable, although sedimentary interbeds separate them in places. Wanapum Basalt dikes and vents recognized in eastern and central parts of Columbia Plateau.	Sequence of generally medium-grained, olivine-bearing, commonly slightly to moderately plagioclase-phyric flows.	Seven chemical types represented; in general, relatively high "Fe" and "Ti" flows.	Normal, transitional, and reversed members.
ECKLER MOUNTAIN MEMBER	South and southeast side of Eckler Mountain about 10.6 miles (17 kilometers) southeast of Dayton, Columbia County, Washington in north halves of secs. 26 and 27, T9N, R40E, Eckler Mountain quadrangle.	Member informally subdivided into three units listed from oldest to youngest as: basalt of Robinette Mountain; basalt of Dodge; and basalt of Shumaker Creek. Member occurs between typical flows of Grande Ronde Basalt and Frenchman Springs Member; only basalt of Robinette Mountain and Dodge exposed at type locality. Flows of member overlie well-developed saprolite in most places, but are themselves somewhat weathered and locally overlain by a saprolite.	Total thickness of member in vicinity of type locality 66-82 feet (20-25 meters). Known Eckler Mountain Member dikes occur in eastern part of plateau; projected members of Chief Joseph swarm.	Coarse-grained, plagioclase and olivine-phyric sequence capped by aphyric sequence.	Three chemical types represented; chemistry of Eckler Mountain Member bears more resemblance to Grande Ronde Basalt than to Wanapum Basalt.	Normal-two (N_2).
BASALT OF ROBINETTE MOUNTAIN	Roadcuts on Robinette Mountain near power line crossing in NE1/4 SW1/4 sec. 22, T9N, R39E, Robinette Mountain quadrangle, Columbia County, Washington.	Informal unit of Eckler Mountain Member. Overlain by basalt of Dodge at type locality.	Inferred areal extent minimum of 70 square miles (180 square kilometers). Nowhere have two or more Robinette Mountain flows been found in contact. Prominent cliff-former throughout much of outcrop area. Maximum exposed thickness, 60 feet (21 meters). At least one feeder dike located in southeast Washington.	Coarse-grained, has distinctive coarsely diktytaxitic texture; contains abundant olivine, but only very rare, small plagioclase phenocrysts.	Robinette Mountain chemical type; highest Al_2O_3, lowest K_2O and TiO_2 contents of any known flow in Yakima Basalt Subgroup.	Normal-two (N_2).
BASALT OF DODGE	Roadcut along Highway 127, SW1/4 NE1/4 sec. 16, T12N, R40E, Hay quadrangle, 1 mile (1.6 kilometers) from intersection of Highways 127 and 12 at Dodge, Garfield County, Washington.	Middlemost informal unit of Eckler Mountain Member. Overlies basalt of Robinette Mountain at type locality. Locally interbedded with Frenchman Springs Member southeast of Walla Walla, Washington.	Most widespread unit of Eckler Mountain Member. Occurs principally in two major outcrop areas: Blue Mountains east and south of Walla Walla, Washington; and in a northwest-trending belt located in southeastern Washington-northeastern Oregon. Member possibly represented in lower St. Joe and St. Maries River drainages. Generally consists of 1 flow, but locally comprised of as many as 4 flows; maximum thickness about 132 feet (40 meters); flow(s) shows grussy weathering at low elevations, at higher elevations form cliffs. Presumable feeder dikes occur in Blue Mountains in Washington, Little Sheep Creek east of Enterprise, Oregon.	Coarse grain size and moderately abundant large phenocrysts and glomerocrysts of plagioclase; smectitic alteration common; olivine present, but most altered to clay.	Dodge chemical type. Similar in composition to some very high-MgO Grande Ronde Basalt flows.	Normal-two (N_2).
BASALT OF SHUMAKER CREEK	Roadcuts at head of Shumaker Creek, extreme southeast corner of sec. 11, T7N, R45E, Black Butte quadrangle, Asotin County, Washington.	Inferred uppermost unit of Eckler Mountain Member. At type locality, unit overlies basalt of Dodge. Precise age relation of basalt of Shumaker Creek to Frenchman Springs Member unknown, although Shumaker Creek tentatively considered to be older.	Distribution of Shumaker Creek unit poorly known; locally overlies Dodge flows. In outcrop, comprised of one or two flows. Feeder dike(s) unidentified.	Fine-grained and aphyric; similar in appearance to Grande Ronde Basalt.	Shumaker Creek chemical type; lower in MgO and higher in P_2O_5 than low-MgO Grande Ronde; higher in alkalis and lower in MgO than Dodge chemical type.	Normal-two (N_2).

Table II-5 (continued)

UNIT NAME	TYPE LOCALITY	GENERAL STRATIGRAPHY	OUTCROP CHARACTERISTICS	PETROLOGY	CHEMISTRY (See Table II-1)	MAGNETICS (See Figure II-4)
FRENCHMAN SPRINGS MEMBER	Frenchman Springs Coulee, secs. 19-21 and 29-30, T18N, R23E, Grant County, south-central Washington.	Member rests on Grande Ronde Basalt except in parts of southeastern Washington and northeastern Oregon, where it overlies and is locally interbedded with Eckler Mountain Member. Saprolite or arkosic to subarkosic siltstone and sandstone occur on pre-Frenchman Springs surface in many places. Thin, discontinuous subarkosic and tuffaceous interbeds occur between some Frenchman Springs flows in central and western parts of plateau. Squaw Creek Member of Ellensburg Formation, a diatomite bed, overlies member at type locality.	Most extensive member of Wanapum Basalt; flows occur throughout central portion of plateau and in Willamette Valley of western Oregon; member generally thins away from central plateau; eastern limit in southeastern Washington about 117°25' west. South-central Washington member consists of as many as 9 flows, generally 3-6. Devils Canyon, at least 9 flows totaling 627 feet (190 meters) in thickness present. Feeder dikes occur in Blue Mountains, southwest of Walla Walla, Washington; along Snake River upstream from Walker, Washington; and possibly in Clearwater Embayment.	Most flows contain scattered glomerophyric clots of plagioclase generally unequally distributed throughout a flow. A few flows contain large phenocrysts of olivine. Some aphyric flows in eastern part of plateau.	All flows of Frenchman Springs chemical type; in most places, "TiO_2 discontinuity" marks contact between Grande Ronde Basalt and member.	Normal-two (N).
ROZA MEMBER	Exposure on east side of Yakima River opposite Roza Station; 1,500 feet (460 meters) elevation, SE1/4 sec. 16, T15N, R19E, Wymer quadrangle, south-central Washington.	Includes one or more flows between the Frenchman Springs and Priest Rapids Members. Overlies progressively older flows eastward from the central Columbia Plateau; member near its eastern margin overlies R_2 Grande Ronde Basalt.	Occurs across much of the Columbia Plateau in north-central Oregon along Columbia River; has not been recognized farther south. Member has not been found east of 117°10' west and does not occur in Idaho. Westernmost known exposure in Mosier syncline west of Mosier, Oregon, Columbia River Gorge. Member generally consists of no more than 2 flows whose total thickness is about 165 feet (50 meters) at any site. Erupted from narrow linear vent system more than 94 miles (150 kilometers) long in southeastern Washington-northeastern Oregon.	Characterized by numerous plagioclase phenocrysts, mostly single crystals; phenocrysts evenly distributed throughout flow.	Member slightly richer in MgO, but otherwise chemically similar to most flows of Frenchman Springs chemical type.	Transitional (T), Reversed-three (R_3).
PRIEST RAPIDS MEMBER	Exposures along Columbia River in the area upstream from Priest Rapids Dam in central Washington; type locality now mostly covered by water.	Includes all basalt flows above Roza Member and below Umatilla Member of Saddle Mountains Basalt.	One of most widespread Columbia River basalt units. Well exposed in Horse Heaven Hills, north Grand Coulee; present in Spokane area, far up St. Joe and St. Maries River drainages; present in Oregon along Columbia River valley.	Invariably contains small olivine phenocrysts and commonly small plagioclase phenocrysts or glomerophyric clots of plagioclase and olivine.	Lolo chemical type common in central and southeastern Columbia Plateau area; Rosalia chemical type common in northeastern and northern parts of the plateau.	Reversed-three (R_3).

Primary Reference:

Swanson and Others, 1979b

Additional References:

Wanapum Basalt

Bentley, 1977b, 1979b
Bingham and Grolier, 1966
Hammond and Others, 1977
Holmgrem, 1967
Mackin, 1961
Swanson and Others, 1975
Swanson and Others, 1976
Swanson and Others, 1977
Waters, 1961
Wright and Others, 1973

Eckler Mountain Member

Camp, 1976
Choniere and Swanson, 1979
Griggs, 1976
Kleck, 1976
Price, 1977
Ross, 1978
Swanson and Others, 1975
Swanson and Others, 1977

Frenchman Springs Member

Beeson and Moran, 1979
Bentley, 1977
Bingham and Grolier, 1966
Bingham and Walters, 1965
Camp, 1976
Hammond and Others, 1977
Kienle and Others, 1977
Mackin, 1961
Rietman, 1966
Siems and Others, 1974
Swanson and Others, 1975
Swanson and Others, 1977
Swanson and Wright, 1976
Wright and Others, 1973

Roza Member

Bentley, 1977
Bingham and Grolier, 1966
Bingham and Walters, 1965
Choniere and Swanson, 1979
Diery and McKee, 1969
Hammond and Others, 1977
Lefebure, 1970
Mackin, 1961
Swanson and Others, 1975
Swanson and Others, 1977

Priest Rapids Member

ARHCO, 1976
Bentley, 1977
Bingham and Grolier, 1966
Bingham and Walters, 1965
Bond, 1962
Brown, 1975
Bryan, 1927
Griggs, 1976
Hammond and Others, 1977
Laval, 1956
Myers, 1973
Schmincke, 1967a
Wright and Others, 1973

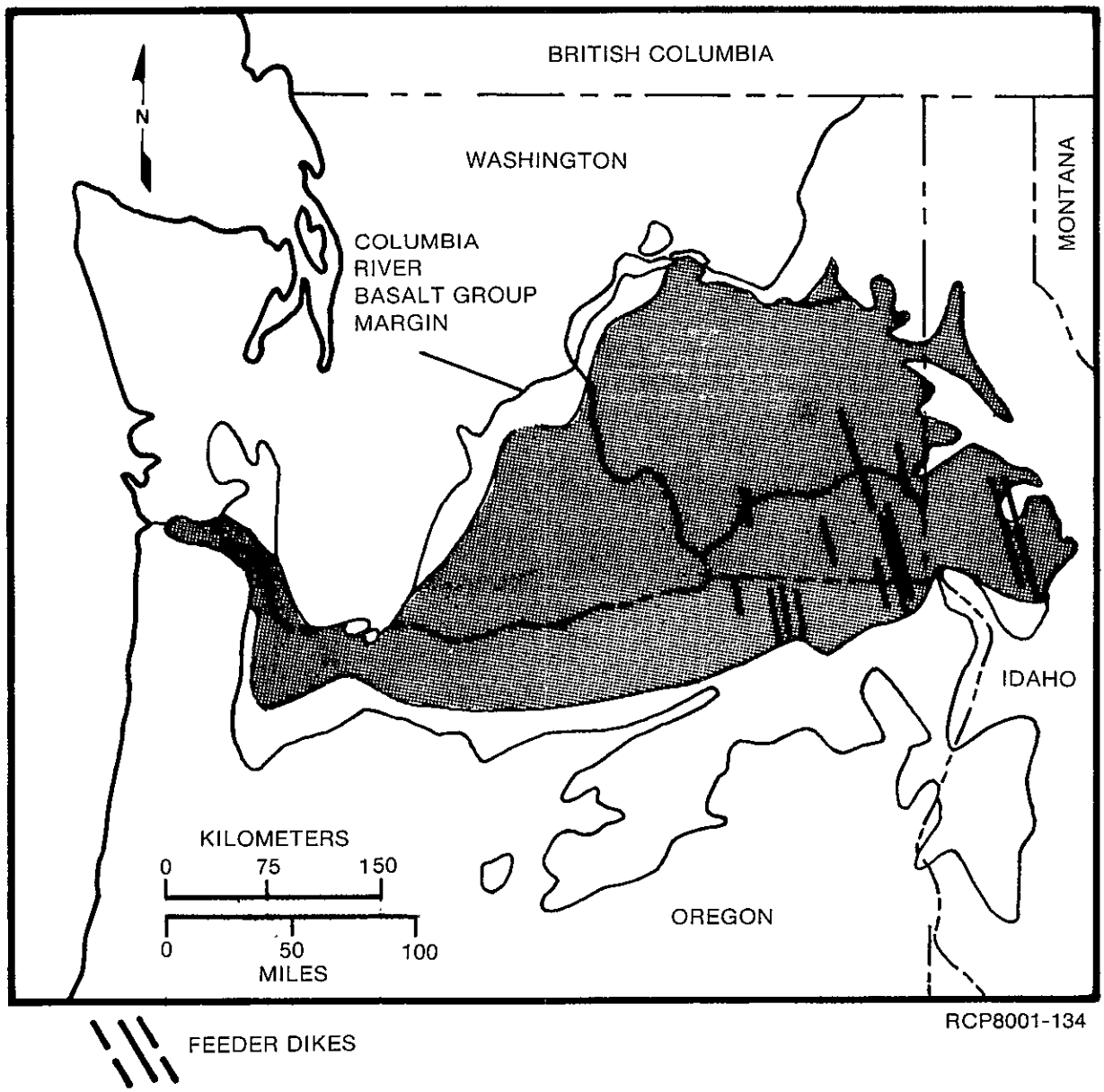

FIGURE II-11. Inferred Original Distribution of Wanapum Basalt (Shaded Area) (after Swanson and Wright, 1978; Swanson and Others, 1979b).

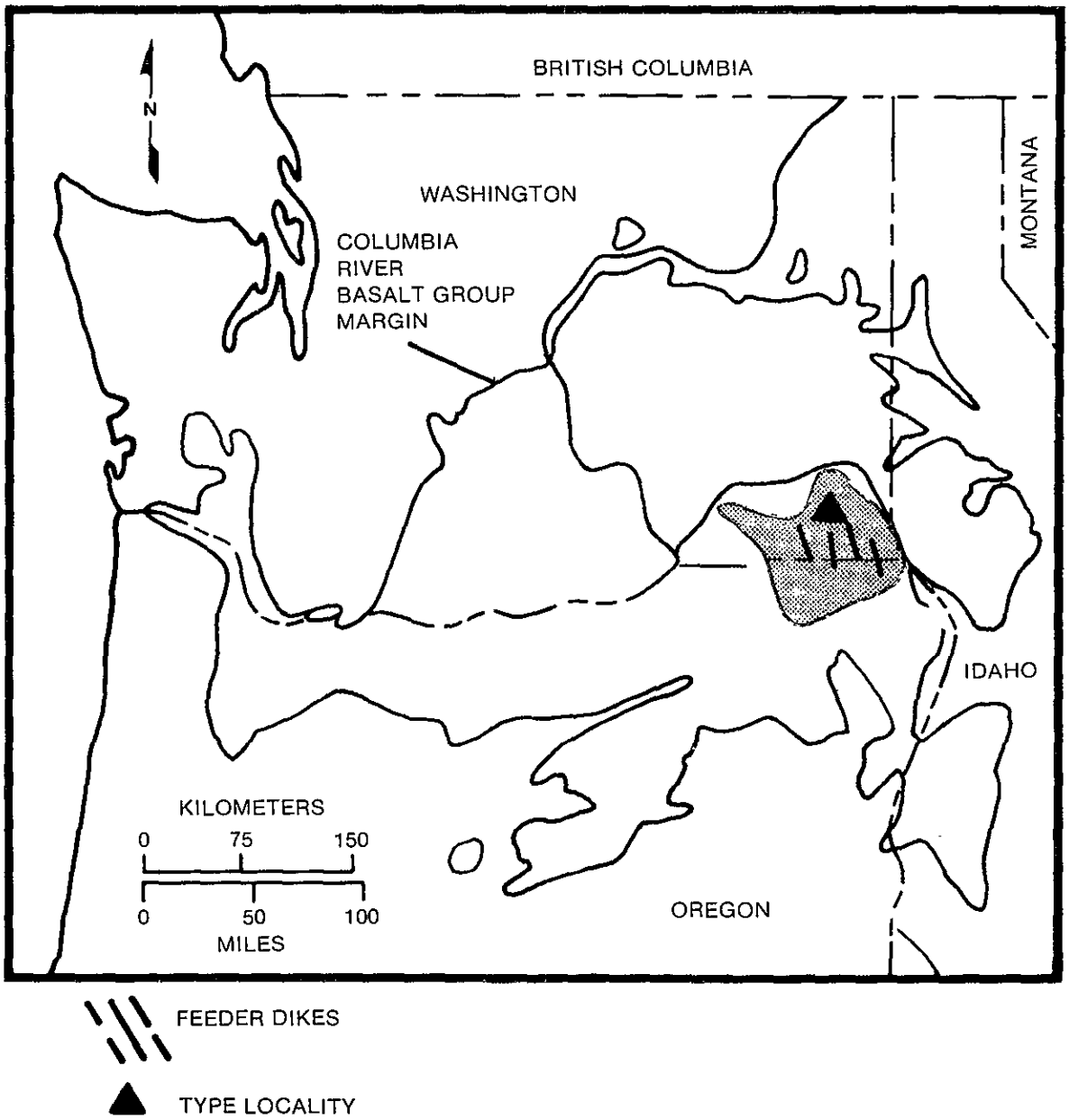

FIGURE II-12. Inferred Original Distribution of Eckler Mountain Member (after Swanson and Others, 1979b).

Frenchman Springs Member. The Frenchman Springs Member occurs throughout the southeastern, central, and western part of the plateau (Figure II-13) and is the most widespread and voluminous of the Wanapum Basalt subunits. Flows of this normally magnetized member, numbering as many as 15, are of Frenchman Springs chemical type (Table II-1) and typically contain scattered glomerophyric clots of plagioclase (Table II-5). Local interflow abundance of these glomercrysts varies and Frenchman Springs flows within the central and western parts of the plateau have been subdivided into as many as 6 informal units on the basis of relative phenocryst content (Myers, 1973; ARHCO, 1976; Bentley, 1977; Bentley in WPPSS, 1977; Bentley in Swanson and Others, 1979a). However, regionally consistent petrographic horizons within the Frenchman Springs Member are unconfirmed (Swanson and Others, 1979a); hence, the member has not been subdivided on the reconnaissance geologic maps (Plates II-1 through II-10). Dikes of the Frenchman Springs Member are exposed along the Snake River near Walker, Washington and in north-central Oregon (Figure II-13) (Swanson and Others, 1979b).

Regional reconnaissance mapping conducted for this study (Swanson and Others, 1979a) has served to further extend the previously known western limit of the Frenchman Springs Member. The western margin of the member has been established as a south-southwest line from Tampico (T12N, R16E) to Grayback Mountain (T6N, R13E), but an outlier in the upper Klickitat drainage suggests that the member originally covered much of the upper Toppenish Creek Basin (Plates II-6 and II-9). In the Grayback Mountain area, intracanyon flows of the Frenchman Springs Member partly fill a canyon eroded into a structural high in possible R_2 Grande Ronde Basalt (Anderson in Swanson and Others, 1979a). Regional field studies (Swanson and Others, 1979a) have further served to show that major unconformities due to erosion or pre-flow topography exist at the top of the Frenchman Springs Member throughout much of the map area.

Roza Member. The Roza Member is exposed throughout the central and western portions of the Columbia Plateau and has served as one of the most important stratigraphic marker units since the completion of early Columbia River basalt stratigraphic studies (Mackin, 1961; Bingham and Grolier, 1971; Lefebure, 1970). The generalized outcrop distribution of this member is shown in Figure II-14. The Roza Member typically is comprised of one or two flows which are abundantly plagioclase-phyric and of transitional magnetic polarity (Swanson and Others, 1979b) (Table II-5). Studies (Swanson and Others, 1977; Price, 1977; Hooper in Swanson, 1978) have shown that Roza lava was extruded from a 3-mile (5-kilometer) wide by 94-mile (150-kilometer) long north-northwest-trending linear vent system located in Figure II-14. Distribution of this member, in relation to its vent system, indicates a westward paleoslope was present during early Wanapum Basalt time (Swanson and Others, 1975, 1977).

Regional reconnaissance mapping conducted for this study (Swanson and Others, 1979a) served to establish the distribution of the Roza Member in more detail (Figure II-14). The Roza Member was found to have an irregular western margin, possibly reflecting early structurally controlled

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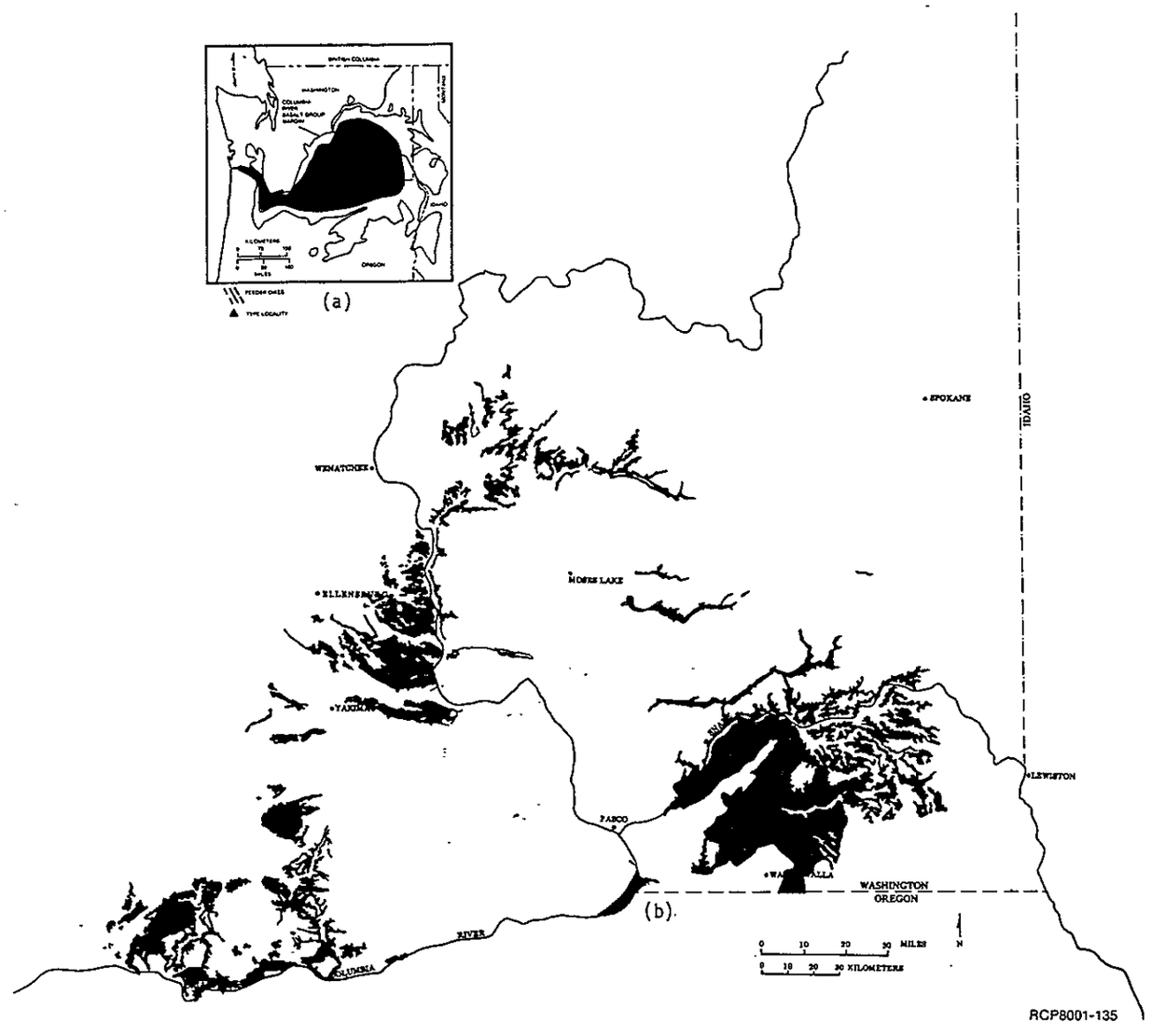
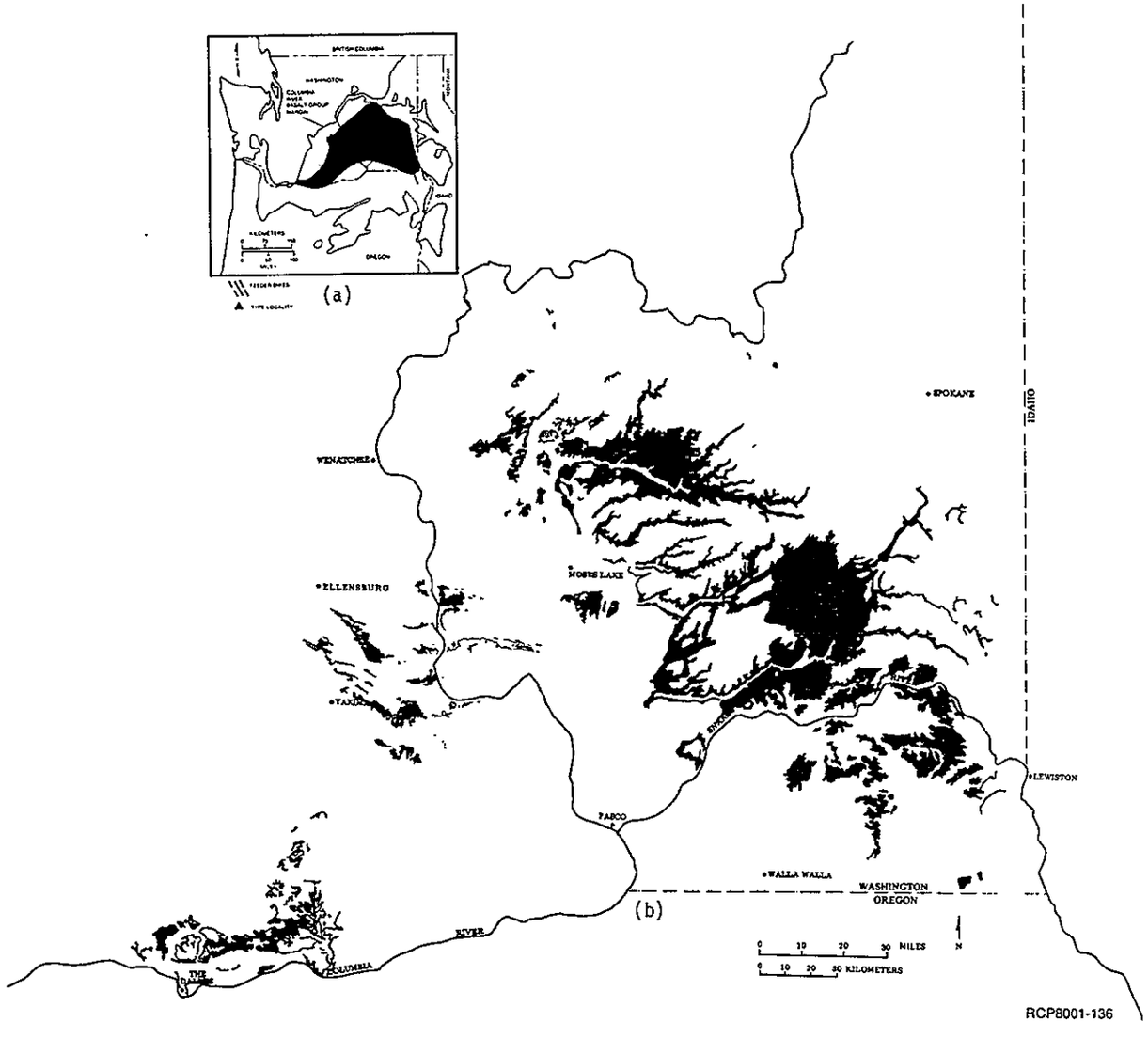


(a) Inferred original distribution (after Swanson and Wright, 1979b); (b) Outcrop distribution, Eastern Washington (after Swanson and Others, 1979a).

FIGURE II-13. Inferred Original Distribution and Generalized Outcrop Distribution of Frenchman Springs Member.



(a) Inferred distribution (after Swanson and Others, 1979b); (b) Outcrop distribution, Eastern Washington (after Swanson and Others, 1979a).

FIGURE II-14. Inferred Original Distribution and Generalized Outcrop Distribution of Roza Member.

topography. In general, the western margin of the unit follows a southwest trend from Yakima, Washington to near Mosier, Oregon (Swanson and Others, 1979a) (Plates II-6 and II-9). In the west-central part of the plateau (Grand Coulee area, Plate II-4), the Roza Member was observed to pinch out south of the Columbia River. Mapping also served to show that circular or ring structures near Odessa, Washington (as defined by McKee and Stradling, 1970) continue eastward into an area of Roza vents in the McCall-Revere area (Plate II-4) (Swanson and Others, 1979a).

Priest Rapids Member. The Priest Rapids Member (Figure II-4) was named by Mackin (1961) for three to four flows in the vicinity of Priest Rapids Dam, south-central Washington (Figure II-15). The member is the youngest subdivision of Wanapum Basalt and the youngest Columbia River basalt unit occurring throughout the northeastern part of the Columbia Plateau (Figure II-15) (Swanson and Others, 1979a). The reversely magnetized flows of the Priest Rapids Member are generally medium grained and contain small, scattered olivine and plagioclase phenocrysts. Compositionally, Priest Rapids flows are of either Rosalia or Lolo chemical type (Swanson and Others, 1979b) (Table II-1). Flows of Rosalia chemical type, with more abundant FeO and TiO_2 than those of Lolo chemical type, predominate throughout the northern and northeastern portions of the map area. Priest Rapids flows of Lolo chemical type, occurring within the southeastern part of the plateau, are younger than flows of Rosalia chemical type (Swanson and Others, 1979a, 1979b). The general properties of the Priest Rapids Member are summarized in Table II-5.

Reconnaissance mapping served to further refine the outcrop extent of the Priest Rapids Member (Figure II-15). The mapping has shown that the western margin of the Priest Rapids Member follows approximately the same line as the Roza Member, but is slightly more extensive to the west--on the order of 0.5 to 2 miles (1 to 3 kilometers) (Swanson and Others, 1979a). The Frenchman Springs flows and the Roza flows do not extend as far north as Priest Rapids flows; hence, along the northern margin of the plateau, the Priest Rapids Member rests directly on, but commonly with intervening sediments, N_2 Grande Ronde Basalt (Plates II-1, II-3, and II-4). The known eastern and southern extent of the member lies beyond the map area.

Saddle Mountains Basalt

Saddle Mountains Basalt is the youngest formation in the Columbia River Basalt Group and is comprised of 10 recognized members (Figure II-4). Saddle Mountains Basalt flows in the vicinity of the type locality, an anticlinal ridge located in south-central Washington (Figure II-16), have been described by Mackin (1961), Bingham and Grolier (1966), and Schmincke (1967c). These references, and more recent publications listed in Table II-6, contain a description of Saddle Mountain Basalt flows.

The Saddle Mountains Basalt was extruded about 6 and 13.5 million years before present, predominantly from fissures located in the east and east-central part of the Columbia Plateau (Swanson and Others, 1979b) (Figure II-16). Despite the 7-million year accumulation period of this

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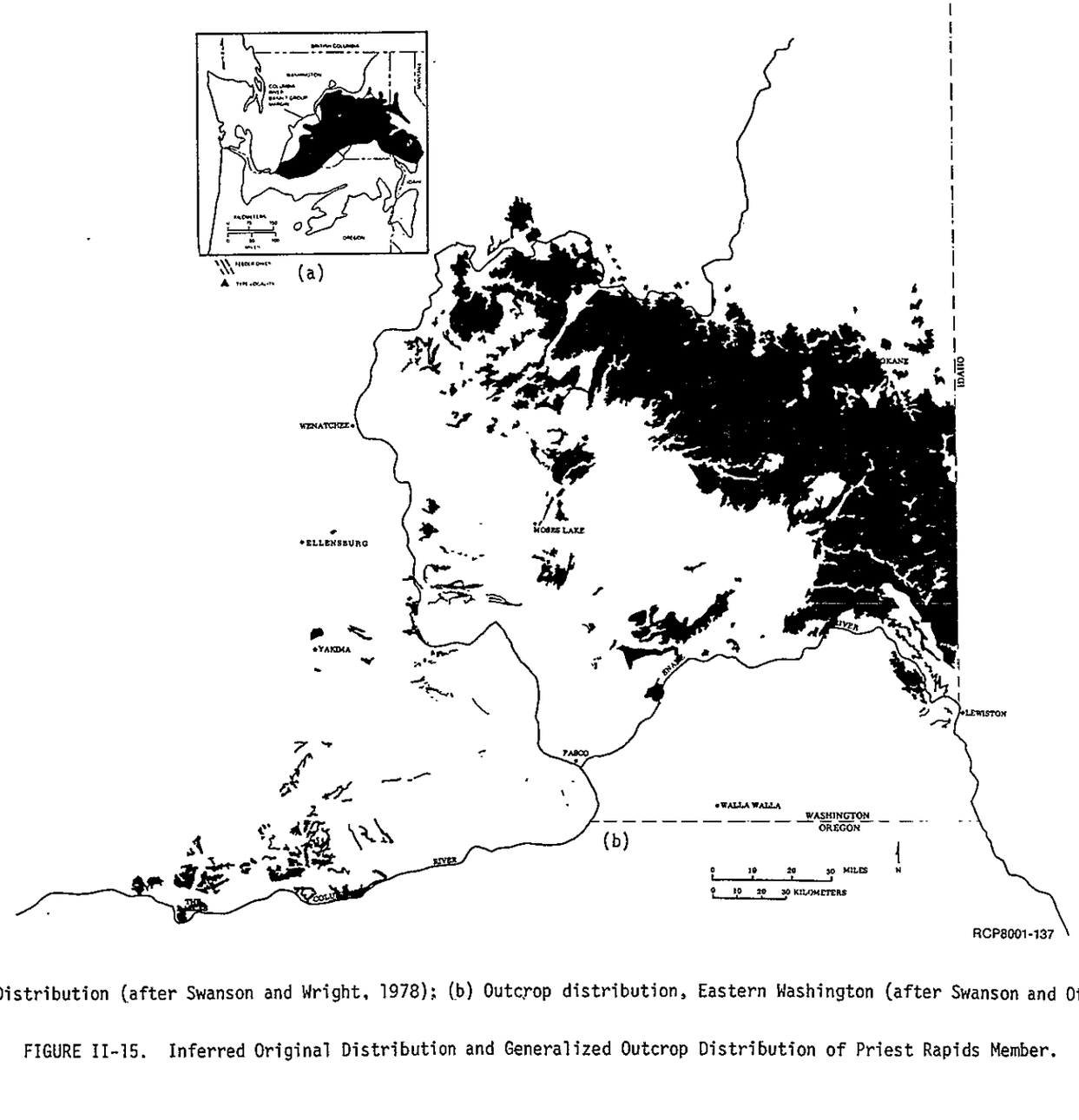

(a) Inferred Original Distribution (after Swanson and Wright, 1978); (b) Outcrop distribution, Eastern Washington (after Swanson and Others, 1979a).

FIGURE II-15. Inferred Original Distribution and Generalized Outcrop Distribution of Priest Rapids Member.

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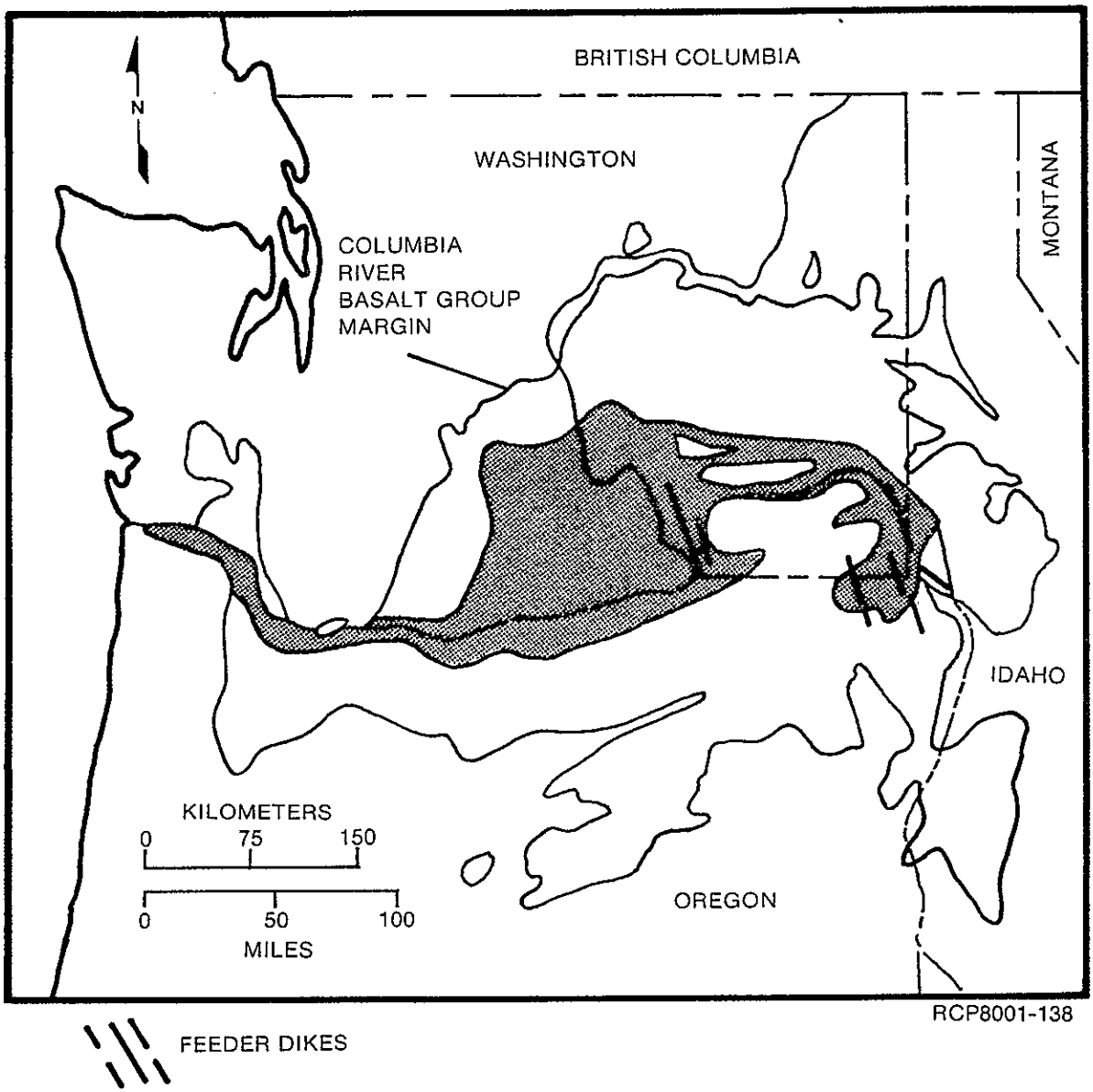

FIGURE II-16. Inferred Original Distribution of Saddle Mountains Basalt (after Swanson and Others, 1979b).

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TABLE II-6. General Properties of Saddle Mountains Basalt.

UNIT NAME AND AGE	TYPE LOCALITY	GENERAL STRATIGRAPHY	OUTCROP CHARACTERISTICS	PETROLOGY	CHEMISTRY (See Table II-1)	MAGNETICS (See Figure II-4)
SADDLE MOUNTAINS BASALT	Southeast of Sentinel Gap, Beverly quadrangle, west-central part of Columbia Plateau.	Formation includes all flows younger than Priest Rapids Member. Formation subdivided into 10 members (listed oldest to youngest): Umatilla; Wilbur Creek; Asotin; Weissenfels Ridge; Esquatzel; Pomona; Elephant Mountain; Buford; Ice Harbor; and Lower Monumental. Flows erupted during period of waning volcanism, deformation, canyon cutting, and development of thick, but local, sedimentary deposits between flows.	Wilbur Creek, Asotin, Weissenfels Ridge, and Buford Members occur principally in Lewiston Basin and lower Grande Ronde River drainage; Wilbur Creek and Asotin Members also found as intracanyon flows toward central and western parts of Columbia Plateau. Esquatzel and Lower Monumental Members occur chiefly as intracanyon flows along ancestral Snake River. Umatilla, Pomona, Elephant Mountain, and Ice Harbor Members cover relatively wide areas and occur locally as intracanyon flows. Nine of ten members erupted from fissures near eastern margin of plateau in southeastern Washington, adjacent Oregon, and Idaho.	Members exhibit diverse petrography.	Contains by far the greatest chemical diversity of any formation.	Normal, reversed, transitional.
UMATILLA MEMBER	Natural exposures and cuts along abandoned railroad 0.6 mile (1 kilometer) west of north abutment of McNary Dam, extreme SE1/4SE1/4SE1/4 sec. 4, T5N, R28E, Umatilla quadrangle, Benton County, Washington.	At type locality, member overlies Mabton Member of Ellensburg Formation; underlies Pomona Member at Sillusi Butte overlooking type locality. Unit recognized in drill cores from Pasco Basin, Walla Walla Basin.	Occurs throughout much of extreme south-central Washington as sheet-like flow; occurs as intracanyon flow along Yakima Ridge; assumes valley-filling character in Blue Mountains. Occurs as sheet-like flow in Uniontown Plateau and extreme southeastern Washington, northeastern Oregon. At type locality, member is 328 feet (100 meters) thick; includes 2 flows or flow units. Puffer Butte vent area and source dike exposed in NW1/4 sec. 3, T6N, R45E, Field Springs quadrangle, along north wall of Grande Ronde Valley near Shumaker Canyon.	Very fine grained; consistently finer than other Columbia River basalt flows. Small plagioclase and olivine phenocrysts rare.	Umatilla chemical type. Characterized by lower CaO and higher K_2O and total alkalies than others flows. Barium content of over 3,000 parts per million.	Normal (N).
WILBUR CREEK MEMBER	Roadcuts along Wilbur Creek, sec. 9 and SW1/4SW1/4 sec. 4, T14N, R44E, Ewartsville quadrangle, about 4.4 miles (7 kilometers) west of Pullman, Whitman County, Washington.	Named for basalt flows between the Umatilla and Asotin Members on the Uniontown Plateau and in the Lewiston Basin of southeastern Washington. Tentatively correlated with canyon-filling flow in Warden-Othello area in central part of Columbia Plateau; intracanyon flow within and west of Pasco Basin.	Member consists of at least 2 flows totaling at least 148 feet (45 meters) in thickness. Unit generally less than 66 feet (20 meters) thick. Source dike(s) have not been found; assumed to be near Lewiston Basin - Uniontown Plateau area, as flows moved from there down a canyon draining westward.	Sparsely plagioclase-phyric; fine grained.	Wilbur Creek chemical type. Compositionally similar, but contains more P_2O_5 than Grande Ronde chemical type.	Normal (N).
ASOTIN MEMBER	Roadcuts along Cloverland Grade, NE1/4 SE1/4 sec. 26 and NW1/4 and SW1/4 of the SW1/4 sec. 25, T10N, R45E, Asotin quadrangle, 3 miles (5 kilometers) southwest of Asotin, Asotin County, extreme southeastern Washington.	Flow occurring between the Wilbur Creek and Weissenfels Ridge Members in the Lewiston Basin of Washington and Idaho. Sedimentary deposits lie above and below member at type locality and elsewhere in Lewiston Basin. Member occurs as an invasive flow. Possibly correlative with Huntzinger flow in central part of plateau; Huntzinger occurs between probable correlatives of Wilbur Creek and Esquatzel Members in core holes in Pasco Basin; elsewhere, Huntzinger fills a channel and its stratigraphic relations often obscure.	Occurs chiefly in that part of Lewiston Basin in western Idaho. Occurs on Uniontown Plateau, where it fills a valley eroded into underlying flows. Similar flow near Lind and La Crosse, Washington may be remnant of member that flowed down a valley from Uniontown Plateau. Sedimentary deposits above and below member easily erodible, often leading to development of prominent cliff. Potential source dikes present in Joseph Canyon, extreme southeastern Washington, northeastern Oregon.	Sparsely olivine and plagioclase-phyric.	Asotin chemical type; major element chemistry similar to Robinette Mountain; contains more MgO and Al_2O_3 and less FeO than Pomona chemical type.	Normal (N).

Table II-6 (continued)

UNIT NAME AND AGE	TYPE LOCALITY	GENERAL STRATIGRAPHY	OUTCROP CHARACTERISTICS	PETROLOGY	CHEMISTRY (See Table II-1)	MAGNETICS (See Figure II-4)
WEISSENFELS RIDGE MEMBER	Roadcuts along Weissenfels Ridge, Asotin County, Washington in NW1/4 sec. 24 and NE1/4 sec. 23, T9N, R46E, Captain John Rapids quadrangle.	Flows between underlying Asotin Member and overlying Elephant Mountain Member in Lewiston Basin of Washington and Idaho. Informally subdivided into 2 units (listed in ascending order): basalt of Lewiston Orchards; and basalt of Slippery Creek.	Comprised of three of more basalt flows. At type locality, member at least 112 feet (34 meters) thick. Inferred location of source dikes, eastern Columbia Plateau.	Plagioclase and olivine-phyric.	Lewiston Orchards and Slippery Creek chemical types.	Normal (N).
BASALT OF LEWISTON ORCHARDS	Above sedimentary interbed in roadcuts at 1,245 feet (380 meters) elevation along Thain Road, sec. 8, T35N, R5W, Lewiston Orchards North quadrangle.	Lowermost informal subdivision of Weissenfels Ridge Member.	Occurs chiefly in that part of Lewiston Basin in western Idaho. At type locality, consists of 1 flow 121 feet (37 meters) thick; elsewhere averages 33-49 feet (10-15 meters) thick. Definite feeder dike not recognized.	Rather coarse grained and sparsely plagioclase-phyric; olivine visible in hand specimen.	Lewiston Orchards chemical type; relatively rich in MgO and poor in K_2O.	Normal (N).
BASALT OF SLIPPERY CREEK	Head of Slippery Creek, NE1/4 sec. 21, T7N, R46E, Black Butte quadrangle, Washington.	Uppermost informal subdivision of Weissenfels Ridge Member.	Basalt of Slippery Creek covers most of plateau surface in extreme southeastern Washington south of Asotin Creek and north of Anatone, Washington. Averages about 33 feet (10 meters) in thickness. Definite feeder dike not recognized.	Contains moderately abundant plagioclase phenocrysts; much groundmass olivine visible with hand lens.	Slippery Creek chemical type.	Normal (N).
ESQUATZEL MEMBER	Hillslope 0.6 (1 kilometer) north of Mesa, north side Esquatzel Coulee, elevation between 730-790 feet (223-241 meters), NW1/4 NW1/4 sec. 25, T13N, R30E, Mesa quadrangle, Franklin County, south-central Washington.	Esquatzel Member rests with erosional unconformity on Priest Rapids Member and is overlain by Pomona Member at type locality. Probably equivalent to Gable Mountain flows of Pasco Basin.	Remnants of one or more intracanyon flows correlated with type Esquatzel occur along an ancestral Snake River Canyon from Devils Canyon upstream to mouth of New York Gulch, 32 miles (52 kilometers) distance. Member averages 33 feet (10 meters) in thickness, but reaches 164 feet (50 meters) in some canyon-filling remnants. Source not found with certainty; distribution of member suggests located in eastern plateau at head of ancestral Snake River.	Contains phenocrysts and glomerophyric clots of plagioclase and clinopyroxene; distribution of phenocrysts irregular.	Esquatzel chemical type.	Normal (N).
POMONA MEMBER 12 Million Years Before Present	Roadcuts along Canyon Road (old Highway 97) and a nearby quarry, near Pomona, Yakima County, south-central Washington.	At type locality, member interbedded with volcaniclastic rocks of Ellensburg Formation. Esquatzel Member contains youngest flows known to underlie Pomona; Elephant Mountain Member contains oldest flows known to overlie Pomona.	Member covers much of southwestern part of plateau from Saddle Mountains in south-central Washington to northern Oregon; extends west along Columbia River as far as Mosier, Oregon and may have reached the Pacific Ocean. Member consists in most places of a single flow, averaging 99 feet (30 meters) thick. Present as intracanyon remnants along ancestral Snake River canyon from Asotin, Washington to Pasco Basin. Source dike(s) inferred in eastern plateau; possible feeder dike located in Wapshilla Creek, Lower Salmon Canyon, Idaho.	Sparsely phyric; small wedge-shaped plagioclase phenocrysts, together with scattered clinopyroxene and olivine; may contain clots of plagioclase, pyroxene, and olivine.	Pomona chemical type.	Reversed (R).

Table II-6 (continued)

UNIT NAME AND AGE	TYPE LOCALITY	GENERAL STRATIGRAPHY	OUTCROP CHARACTERISTICS	PETROLOGY	CHEMISTRY (See Table II-1)	MAGNETICS (See Figure II-4)
ELEPHANT MOUNTAIN MEMBER 10.5 Million Years Before Present	Exposures near Elephant Mountain (chiefly in secs. 22 and 27, T12N, R20E, Elephant Mountain quadrangle), on Rattlesnake Ridge about 10 miles (16 kilometers) southeast of Yakima, Yakima County, Washington.	Includes Ward Gap flow in south-central Washington and Wenaha flow in lower Grande Ronde River drainage, southeastern Washington, northeastern Oregon.	Only slightly less extensive than Pomona Member in south-central Washington and adjacent Oregon; did not extend through Columbia Gorge. Only two flows known to occur in member west of Columbia River; three or more flows east of river in Washington. Occurs as sheet-like flow in Lewiston Basin; appears to spill into ancestral Snake River canyon west of Clarkston, Washington. Sheet-like exposures average 90 feet (30 meters) thick; intracanyon remnants along Asotin Creek and Snake River reach 492 feet (150 meters) thick. Two possible source dikes occur in extreme southeastern Washington and adjacent Oregon and Idaho.	Nearly aphyric, generally fine grained.	Elephant Mountain chemical type.	Transitional (T), Normal (N).
BUFORD MEMBER	About 5 miles (8 kilometers) northeast of Flora, Oregon, in quarry east of Highway 3 at 4,044 feet (1,225 meters) elevation in NE1/4NE1/4 sec. 2, T5N, R44E, Flora quadrangle, Wallowa County, extreme northeastern Oregon.	Judged by stratigraphic relations in Grande Ronde Valley to be post-Elephant Mountain in age. Age relationship of Buford to Ice Harbor and Lower Monumental Members unclear--Buford believed to be older than both based on lack of intracanyon remnants. Youngest known basalt on plateau surface of extreme southeastern Washington, northeastern Oregon.	Flow extends north and west from Buford Creek; restricted to southeastern Washington, northeastern Oregon. Everywhere consists of one flow, generally 66-99 feet (20-30 meters) thick. Distribution suggests source in extreme southeastern Washington or adjacent parts of Idaho or Oregon; tentative feeder dike identified in lower Grande Ronde Valley.	Fine to medium grained; very sparsely plagioclase and olivine-phyric.	Major element chemistry similar to some flows in Grande Ronde Basalt, except has generally lower Na_2O for a given MgO content.	Reversed (R).
ICE HARBOR MEMBER 8.5 Million Years Before Present	Quarry on south side of Snake River 1.6 miles (2.6 kilometers) west of Ice Harbor Dam, SE1/4 NE1/4 sec. 22, T9N, R31E, Humorist quadrangle, Walla Walla County, southeastern Washington.	Flows and minor tephra younger than Elephant Mountain Member. Subdivided into three informal units (listed oldest to youngest): basalt of Basin City; basalt of Martindale; and basalt of Goose Island. Product of youngest known eruptive activity in central Columbia Plateau.	Occurs as narrow belt of outcrops separated by younger alluvial deposits extending about 56 miles (90 kilometers) north-northwest from near Washington-Oregon border. Member generally about 49 feet (15 meters) thick; nowhere more than 99 feet (30 kilometers) thick. Many dikes and vent areas located along elongate north-northwest trending belt of major outcrops.	Plagioclase and olivine-phyric.	Comprised of 3 distinct chemical types.	Normal (N)-reversed (R)-normal (N) sequence.
BASALT OF BASIN CITY	Named for Basin City, community 7 miles (11 kilometers) west of Mesa, Franklin County, Washington.	Inferred lowermost informal subdivision of Ice Harbor Member. Occurs stratigraphically above Elephant Mountain Member and below basalt of Goose Island.	Occupies narrow "graben" cutting the Elephant Mountain Member.	Sparsely phyric flows with olivine and plagioclase phenocrysts and glomerocrysts.	Basin City chemical type.	Normal (N).
BASALT OF MARTINDALE	Railroad siding on north side of Snake River in Franklin County about 2 miles (3 kilometers) downstream from type locality of Ice Harbor Member.	At type locality, occurs above Elephant Mountain Member and below basalt of Goose Island in a shallow syncline. Inferred middlemost subdivision of Ice Harbor Member. Relationship of basalt of Martindale to basalt of Basin City uncertain; field relations suggest Basin City older.	Martindale most extensive of Ice Harbor units. About 49 feet (15 meters) thick and markedly columnar. Sourced by north-northwest trending vent area.	Contains single phenocrysts and glomerocrysts of clinopyroxene, plagioclase, and olivine.	Martindale chemical type.	Reversed (R).
BASALT OF GOOSE ISLAND	Named for small island near type locality of member.	Uppermost informal subdivision of Ice Harbor Member. Occurs above basalt of Martindale at type locality.	Sourced by north-northwest trending vent area.	Sparsely phyric with respect to plagioclase, magnetite, and rarely olivine.	Goose Island chemical type.	Normal (N).

Table II-6 (continued)

UNIT NAME AND AGE	TYPE LOCALITY	GENERAL STRATIGRAPHY	OUTCROP CHARACTERISTICS	PETROLOGY	CHEMISTRY (See Table II-1)	MAGNETICS (See Figure II-4)
LOWER MONUMENTAL MEMBER 6 Million Years Before Present	Roadcut 0.6 mile (1 kilometer) south of Lower Monumental Dam in NW1/4SE1/4 sec. 3, T12N, R34E., Lower Monumental quadrangle. Walla Walla, County, southeastern Washington.	Overlies poorly consolidated river gravel 262 feet (80 meters) above present Snake River just south of Lower Monumental Dam. Field relations show Lower Monumental Member partly filled an ancestral Snake River canyon eroded into rocks as young as Elephant Mountain Member. Lower Monumental Member inferred to be younger than Ice Harbor Member as it occurs within canyon appearing to be eroded into Ice Harbor Member.	Many remnants of one or more intracanyon flows occur along present course of Snake River from type locality upstream to mouth of Asotin Creek, extreme southeastern Washington. At type locality, member about 100 feet (30 meters) thick. Member averages 82 feet (25 meters) thick; locally thickens up to about 198 feet (60 meters). Feeder dike inferred to be located in eastern part of plateau; member produced by youngest known volcanic activity in plateau.	Nearly aphyric; moderately abundant microphenocrysts of olivine can be seen with hand lens.	Similar to Lolo chemical type, but has slightly higher Na_2O and K_2O contents.	Normal (N).

Primary References:

ARHCO, 1976
Bingham and Grolier, 1966
Swanson and Others, 1977
Swanson and Others, 1979b

Additional References:

Saddle Mountains Basalt

Camp, 1976
Laval, 1956
McDougall, 1976
McKee and Others, 1977
Schmincke, 1967a
Swanson and Others, 1975
Swanson and Wright, 1976
Wright and Others, 1973

Umatilla Member

ARHCO, 1976
Bush and Others, 1972
Laval, 1956
Ledgerwood and Others, 1973
Myers, 1973
Price, 1974
Price, 1977
Rietman, 1966
Schmincke, 1967c
Waters, 1961

Wilbur Creek Member

ARHCO, 1976
Camp, 1976
Goff, 1977
Grolier, 1965
Swanson and Others, 1977

Asotin Member

ARHCO, 1976
Byerly and Swanson, 1978
Camp, 1976
Ledgerwood and Others, 1973
Mackin, 1961
Myers, 1973
Swanson and Others, 1977
Ward, 1976

Weissenfels Ridge Member

Camp, 1976
Price, 1977

Esquatzel Member

ARHCO, 1976
Choiniere and Swanson, 1979
Swanson and Others, 1977

Pomona Member

Schmincke, 1967a, 1967b
Snavely and Others, 1973
Swanson and Others, 1977
Swanson and Wright, 1976
Waters, 1955

Elephant Mountain Member

ARHCO, 1976
Camp, 1976
Choiniere and Swanson, 1979
McKee and Others, 1977
Rietman, 1966
Ross, 1978
Schmincke, 1967a
Shannon and Wilson, 1973a, 1973b
Swanson and Others, 1975
Swanson and Others, 1977
Walker, 1973
Waters, 1955

Buford Member

Price, 1977
Ross, 1978
Swanson and Others, 1977

Ice Harbor Member

ARHCO, 1976
Choniere and Swanson, 1979
Helz, 1978
Helz and Others, 1976
Ledgerwood and Others, 1973
McKee and Others, 1977
Myers, 1973
Swanson and Others, 1975
Swanson and Others, 1977
Wright and Others, 1973

Lower Monumental Member

Camp, 1976
Choniere and Swanson, 1979
McKee and Others, 1977

formation, it comprises less than 1 percent of the total volume of the Columbia River Basalt Group. Saddle Mountains time was not only marked by waning volcanism, but by the development of thick, local, sedimentary deposits between flows, and by accelerated folding and canyon cutting (Swanson and Wright, 1978). Consequently, the contact between Saddle Mountains Basalt flows and older basalt units is generally a regional disconformity with local angular and erosional unconformities delineating areas of earlier ridge or basin development.

Flows of the Saddle Mountains Basalt have been subdivided into 10 members, listed from oldest to youngest as: Umatilla; Wilbur Creek; Asotin; Weissenfels Ridge; Esquatzel; Pomona; Elephant Mountain; Buford; Ice Harbor; and, Lower Monumental (Figure II-4) (Swanson and Others, 1979b). Members of Saddle Mountains Basalt display the greatest petrographic, chemical, and paleomagnetic variability of any formation of the Columbia River Basalt Group. Therefore, the character of the Saddle Mountains Basalt is better discussed on a member rather than a formation basis. The member description is keyed, for the most part, to the regional reconnaissance geologic maps of the Columbia River Basalt Group (Plates II-1 through II-10). For ease of discussion, generalized outcrop maps of the most widely distributed Saddle Mountains Basalt members are included in the text. The general properties of all 10 members are summarized in Table II-6.

Umatilla Member. The Umatilla is the oldest and one of the most widespread Saddle Mountains Basalt members. The member was first described in the south-central portion of the plateau by Laval (1956) and later by Schmincke (1967c). In subsequent studies, Gibson (1969) and Price (1973a, 1973b) described a Umatilla-like flow and source dike in southeastern Washington and northeastern Oregon. In 1974, Price suggested that lava extruded from this vent reached as far west as the Pasco Basin. Recent mapping for the Rockwell Hanford Operations' regional geology program (Swanson, 1978) has shown that these two areas are indeed connected across northern Oregon by remnants of the Umatilla Member filling a former broad, shallow valley. This outcrop pattern (Figure II-17) indicates that Umatilla lava was extruded from its feeder dikes in southeastern Washington-northeastern Oregon, "channeled" westward along this broad valley, and spilled forth to form the sheet-like Umatilla flow now covering much of southcentral Washington (Figure II-15). As such, the Umatilla Member provides the earliest evidence of extensive erosion and canyon cutting within the eastern portion of the Columbia Plateau during Columbia River basalt time. The western margin of the Umatilla Member was mapped between Wiley City (T9N, R17E) and the area just east of Satus Pass (T9N, RME); the Umatilla fills an ancient canyon eroded into Priest Rapids on lower Logy Creek (T8N, R18E) (Plate II-6) (Swanson and Others, 1979a).

Petrographically, the Umatilla Member is usually aphyric, fine grained, black, and dense. Its very even grain size helps distinguish it from fine grained, but microphyric, Frenchman Springs basalt. Chemically, the member is one of the most distinctive units of the Columbia River Basalt Group (Table II-1). It has a lesser CaO and MgO content and greater alkali (Na_2O and K_2O) and barium content than any other flow of the Yakima Basalt Subgroup. Distinctive properties of the normally-magnetized Umatilla Member are summarized in Table II-6.

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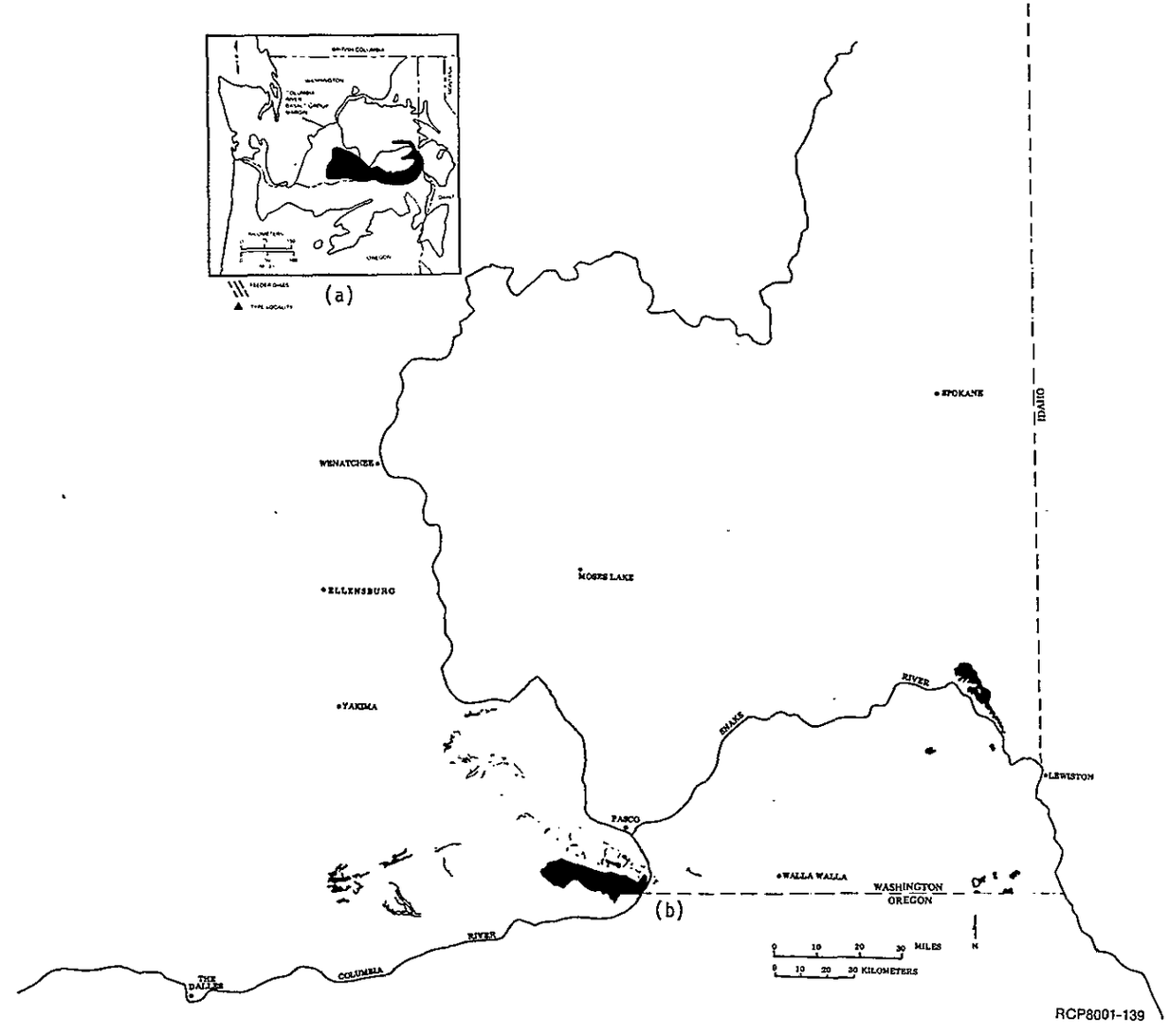

(a) Inferred original distribution (after Swanson and Others, 1979b); (b) Generalized outcrop distribution, Eastern Washington (after Swanson and Others, 1979a).

FIGURE II-17. Inferred Original Distribution and Generalized Outcrop Distribution of Umatilla Member.

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Wilbur Creek Member. The Wilbur Creek Member (Figure II-4) was formally named by Swanson and Others (1979b). The outcrop pattern of this member (Figure II-18) suggests that it was erupted in the eastern part of the province and flowed westward down an ancestral valley system (Swanson and Others, 1975, 1977, 1979b). Within south-central Washington, the Wilbur Creek Member is expressed predominantely as intracanyon or valley-filling remnants (Plates II-7 and II-10) which have a distinct aeromagnetic signature (Swanson and Others, 1979c). The normally magnetized Wilbur Creek Member is fine grained and has sparse phenocrysts of plagioclase less than 0.25-inch (5 millimeters) long. The composition of the Wilbur Creek chemical type is tabulated in Table II-1.

Asotin Member. The Asotin Member (Figure II-4) was first described in the Lewiston Basin area by Camp (1976). The character of the member and associated feeder dikes exposed along the southern margin of the basin (within the lower Grande Ronde River Valley) was subsequently discussed by Price (1977). Concurrent regional studies (Swanson and Others, 1977) showed the presence of isolated remnants of the Asotin Member located to the west of the type locality. The overall outcrop pattern of the Asotin Member, as discussed by Price (1977) and Swanson and Others (1977, 1979a, 1979b) suggests that the Asotin lava, upon extrusion in the Lewiston Basin area, advanced down valleys and gorges leading to the central part of the plateau (Figure II-19). Intracanyon and intravalley remnants of an Asotin-like flow, the Huntzinger, occur as far west as the Pasco Basin area (Ledgerwood and Others, 1973; Ward, 1976) (Plates II-7 and II-10). The character of the Huntzinger flow is discussed in Chapter III of this report.

Petrographically, the Asotin Member is fine grained and contains sparse phenocrysts of plagioclase and olivine. The member is chemically distinct in the eastern part of the plateau, containing more MgO, CaO, and Al_2O_3 than most other Columbia River basalt flows (Table II-1). The distinctive properties of the normally magnetized Asotin Member are summarized in Table II-6.

Weissenfels Ridge Member. The Weissenfels Ridge Member (Figure II-4) was introduced by Swanson and Others (1979b), and currently includes three or more basalt flows described by Camp (1976) and Price (1977) in the Lewiston Basin area. The normally magnetized flows of this member are informally subdivided into two units, the basalt of Lewiston Orchards (Camp, 1976) and the basalt of Slippery Creek (Camp, 1976; Price, 1977; Reidel, 1978b). Potential source dikes for both units have been identified within the outcrop area (Price, 1974, 1977; Swanson and Others, 1979b) (Figure II-20; Plate II-10). The petrographic and chemical properties of the basalt of Lewiston Orchards and the basalt of Slippery Creek are summarized in Table II-6.

Recent mapping by Swanson and Others (1979a) has shown the presence of one or two flows, possibly equivalent to the Weissenfels Ridge Member, in the Lamont-Sprague area southwest of Spokane, Washington (Plate II-1). These flows, informally termed the basalt of Sprague Lake, fill a shallow ancient valley eroded into the Priest Rapids Member.

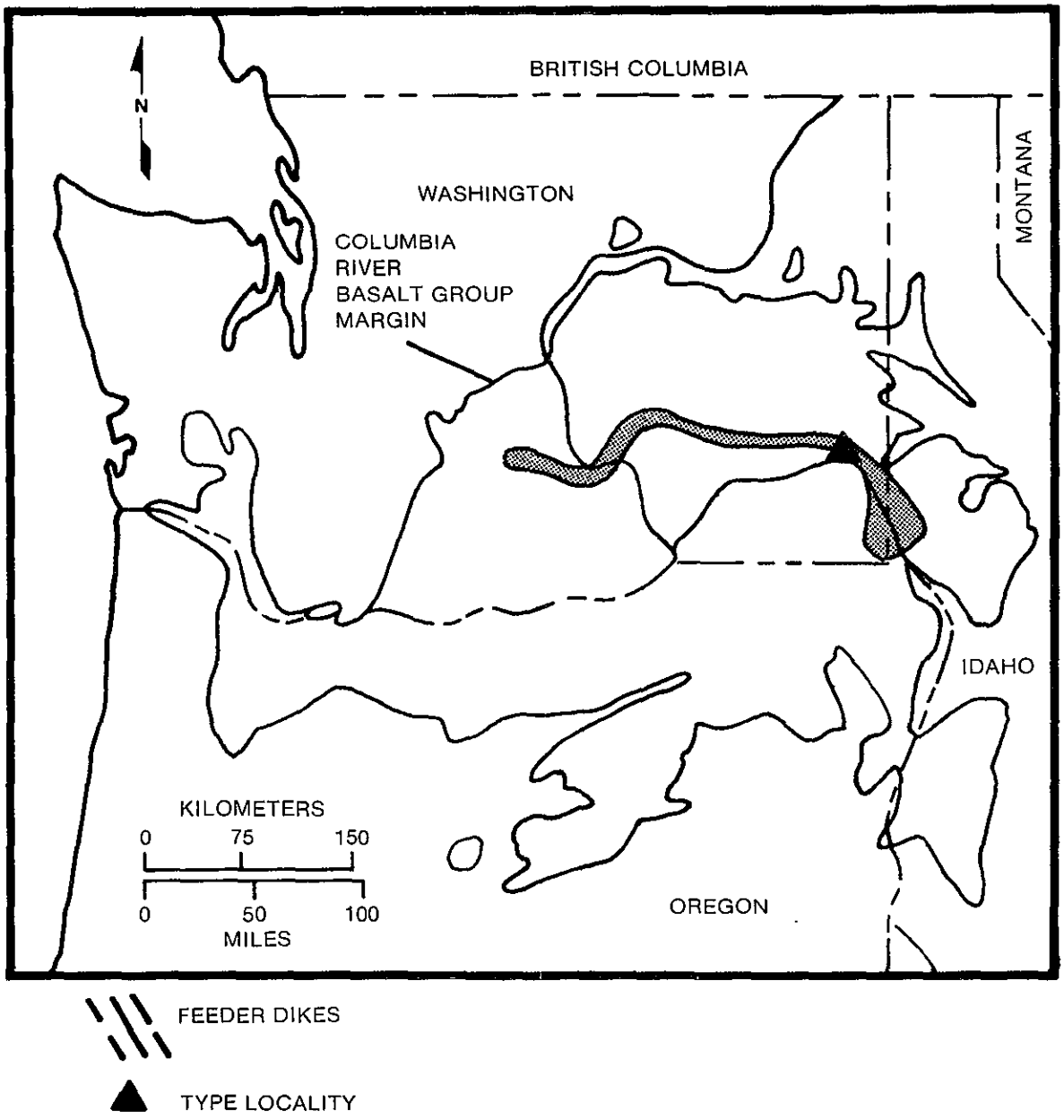


FIGURE II-18. Inferred Original Distribution of Wilbur Creek Member (after Swanson and Others, 1979b).

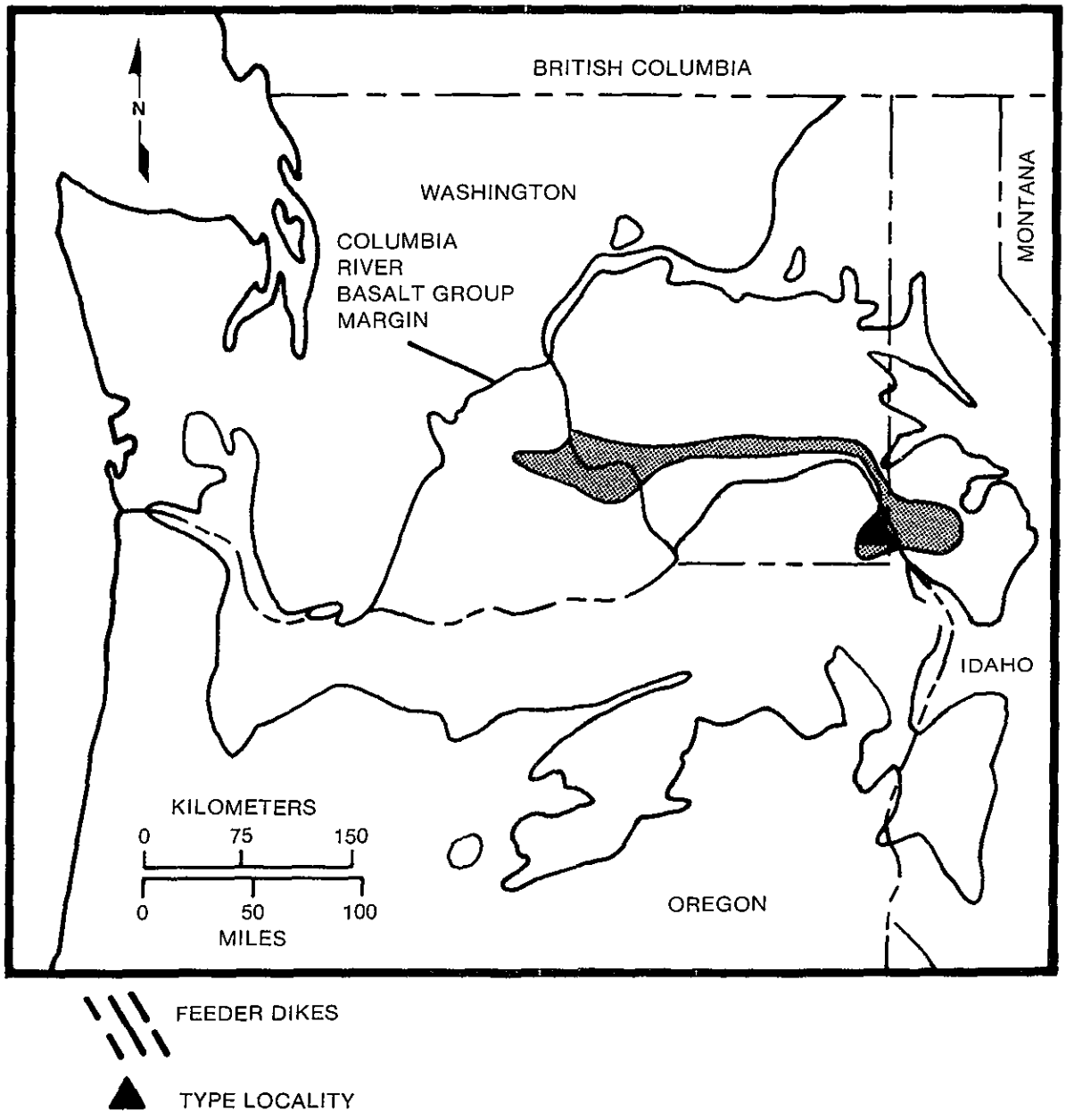


FIGURE II-19. Inferred Original Distribution of Asotin Member (after Swanson and Others, 1979b).

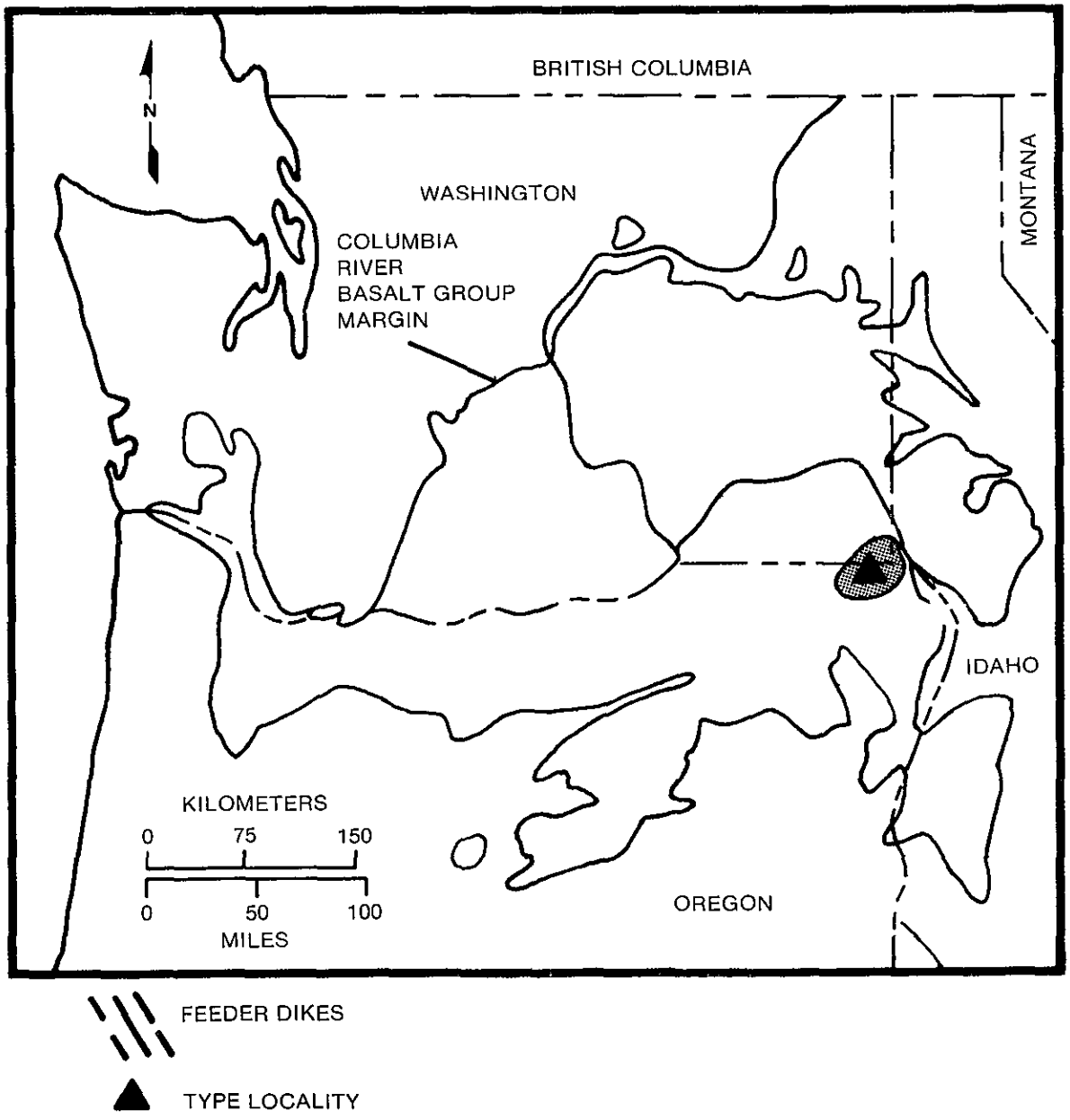


FIGURE II-20. Inferred Original Distribution of Weissenfels Ridge Member (after Swanson and Others, 1979b).

Esquatzel Member. The Esquatzel Member was introduced by Swanson and Others (1979b) for one or more flows occurring in Esquatzel Coulee near Mesa, Washington (Plate II-7). These normally magnetized flows have a distinct petrography characterized by strongly zoned plagioclase phenocrysts and clinopyroxene phenocrysts less than 0.25 inch (5 millimeters) in diameter (Swanson and Others, 1979b). Other distinguishing properties of the member are summarized in Table II-6.

The inferred original distribution of the Esquatzel Member is shown in Figure II-21. This pattern suggests that the Esquatzel was erupted within an ancestral Snake River drainage and flowed down-canyon to enter an ancestral drainage of the Columbia River within the vicinity of the current Pasco Basin. Distribution of the Esquatzel Member, and the older Wilbur Creek and Umatilla Members, suggests that the dominant stream drainage was westward within the eastern half of the Columbia Plateau during early and middle Saddle Mountains time (Swanson and Others, 1977, 1979a, 1979b).

Pomona Member. The Pomona Member (Figure II-4) was first defined and described by Schmincke (1967c) as an extensive sheet-like flow occurring throughout south-central Washington. Later work by Swanson and Others (1976) showed the presence of nearly 50 intracanyon remnants of the Pomona Member along an ancestral Snake River canyon extending as far east as the Lewiston Basin (Figure II-22). A possible source for the Pomona has been identified in western Idaho by Reidel (1978b). Based on the known distribution of the member, Pomona lava presumably was extruded in western Idaho 12 million years ago (McKee and Others, 1977), advanced down an ancestral Snake River canyon, and spread out within the south-central portion of the plateau (Figure II-22) (Swanson and Wright, 1976; Swanson and Others, 1977). A "tongue" of the lava continued down the ancestral Columbia River Gorge to solidify into the Pomona Member present within the westernmost extremity of the Columbia Plateau (Figure II-22) (Snavely and Others, 1973). As such, the Pomona Member is one of the most extensive and voluminous Saddle Mountains Basalt flows, covering an estimated area of 6,800 square miles (17,680 square kilometers) and having an estimated volume of 125 cubic miles (600 cubic kilometers) (Swanson and Wright, 1978).

In the region, the Pomona Member consists of one principal cooling unit characterized by small, commonly wedge-shaped, plagioclase phenocrysts (less than 0.20 inch [5 millimeters] long), and scattered clinopyroxene and olivine phenocrysts (Schmincke, 1967c). The reversely magnetized member is chemically distinct, containing more CaO and MgO and less TiO_2 than other Columbia River basalt flows (Table II-1), with the exception of the Asotin Member. Characteristic properties of the Pomona Member are summarized in Table II-6.

Elephant Mountain Member. Early studies of the Elephant Mountain Member (Figure II-4) were carried out in south-central Washington by Waters (1955) and by Schmincke (1967c). Subsequent studies by Walker (1973) and by Ross (1978) showed the presence of an Elephant Mountain-like flow, named the Wenaha, in northeastern Oregon. Based on regional mapping in southeastern Washington, Swanson and Wright (1976) suggested that the

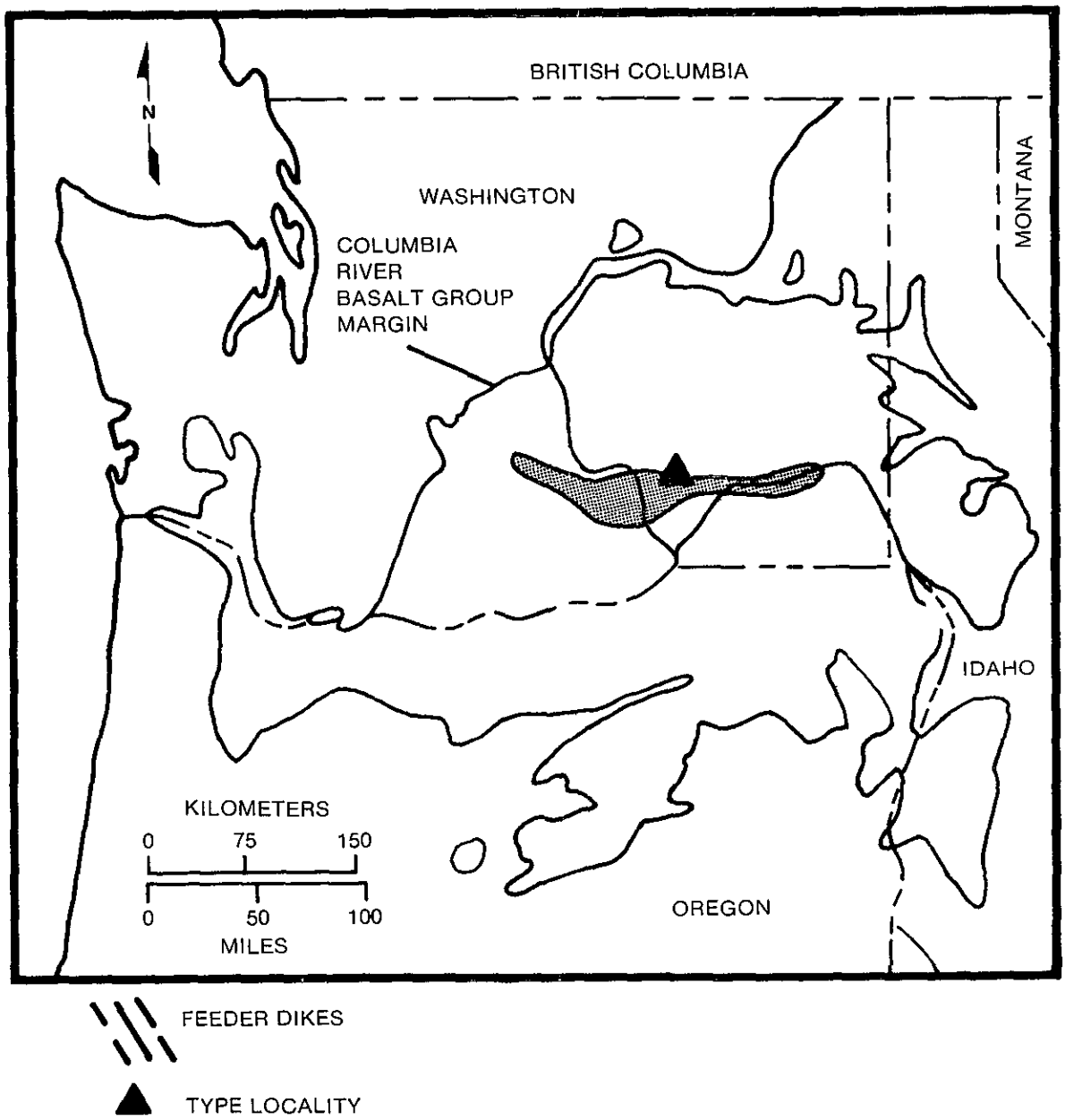
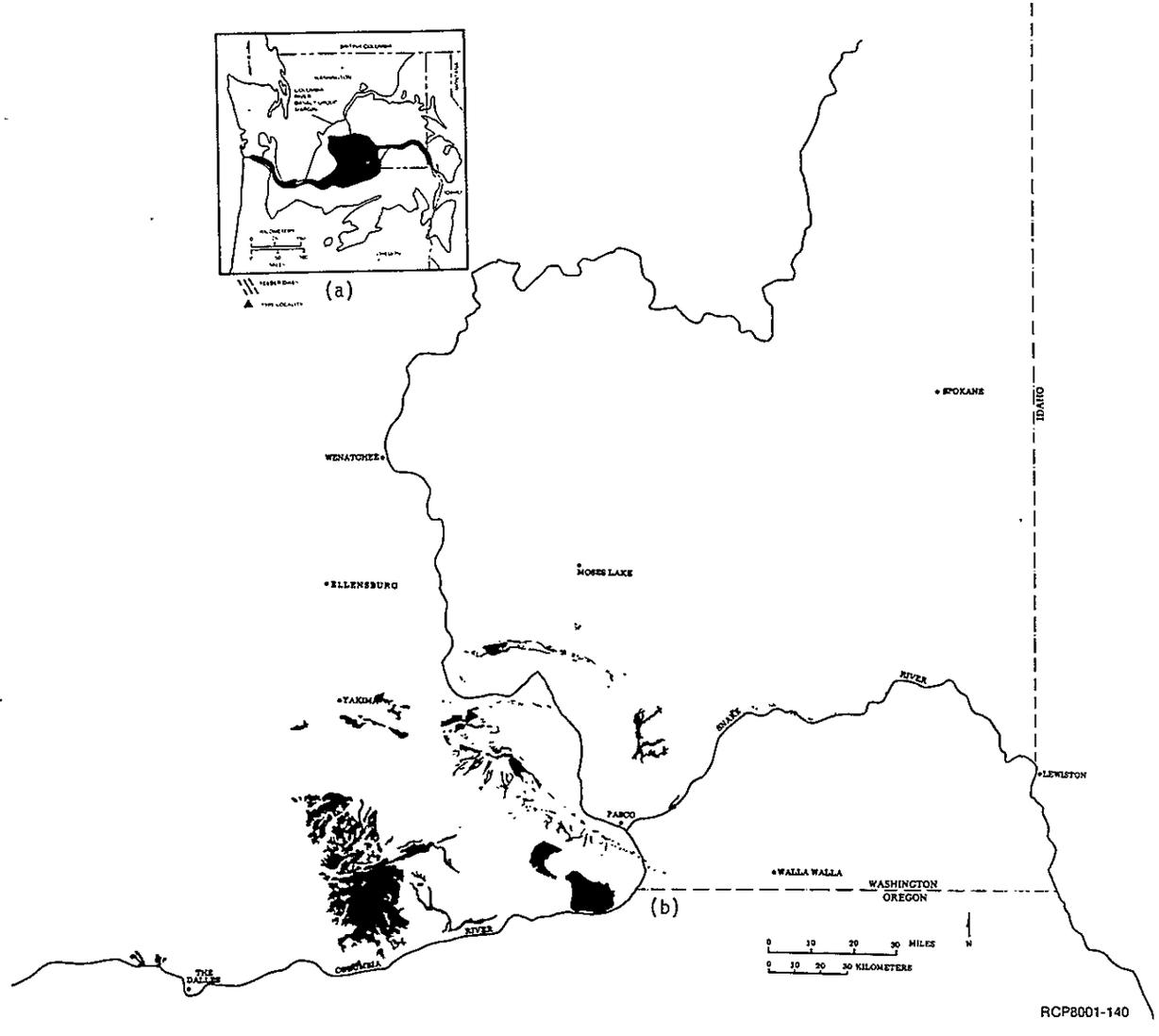


FIGURE II-21. Inferred Original Distribution of Esquatzel Member (after Swanson and Others, 1979b).



(a) Generalized Distribution (after Swanson and Wright, 1978); (b) Generalized outcrop distribution, Eastern Washington (after Swanson and Others, 1979a).

FIGURE II-22. Inferred Original Distribution and Generalized Outcrop Distribution of Pomona Member.

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Elephant Mountain Member, like the Pomona Member, was erupted in the eastern part of the plateau and flowed down an ancestral Snake River Canyon to reach the interior of the province. As such, the Elephant Mountain Member covered approximately the same area as the Pomona Member, although it did not advance west of the Cascade Range (Figure II-23) (Swanson and Wright, 1978). Recent mapping by Swanson and Others (1979a) has shown that the western margin of the member extends from Black Rock Valley (T12N, R22E), past Elephant Mountain to Toppenish Mountain, and from there due south to just east of Roosevelt, Washington (T3N, R20E) (Plates II-6 and II-9). Dikes of the Elephant Mountain Member have been identified in the eastern part of the plateau by Ross (1978) and by Reidel (1978b) (Figure II-23a).

The Elephant Mountain Member is stratigraphically the youngest of the "widespread" Saddle Mountains Basalt units. The unit is comprised of from one to three flows which are of transitional to normal polarity (Rietman, 1966). The member is non-porphyritic and generally fine-grained (Schmincke, 1967c; Ross, 1978) and is characterized by a relatively high TiO_2 content (ARHCO, 1976; Ross, 1978) (Table II-1). Distinctive properties of the Elephant Mountain Member are summarized in Table II-6.

Buford Member. The Buford Member (Figure II-4) was first defined and described in northeastern Oregon by Walker (1973). Subsequent work by Price (1977) and Ross (1978) further served to detail the character, distribution, and stratigraphic placement of this post-Elephant Mountain unit. Outcrops of the reversely magnetized Buford Member appear to be restricted to the lower Grande Ronde Valley (Figure II-24; Plate II-10). Here, the member is the youngest known Columbia River basalt unit (Price, 1977; Ross, 1978). Potential source dikes for the member have been identified in the vicinity of the type locality (Price, 1977).

Petrographically, the Buford Member is fine to medium grained, with sparse plagioclase and olivine phenocrysts (Walker, 1973; Price, 1977; Ross, 1978). Chemically, the major element composition of the member is similar to Grande Ronde Basalt (Table II-1). However, the Buford Member has generally less Na_2O for a given MgO content (Swanson and Others, 1979b). The distinctive properties of the Buford Member are summarized in Table II-6.

Ice Harbor Member. The Ice Harbor Member (Figure II-4) includes flows and minor tephra units along the lower Snake River younger than the Elephant Mountain Member (Swanson and Others, 1975, 1977, 1979b; Helz, 1978; Helz and Others, 1976). Potassium-argon dates for this member indicate an age of 8.5 million years before present (McKee and Others, 1977). The Ice Harbor Member is restricted in distribution to the eastern and southern part of the Pasco Basin (Chapter III) and lower Walla Walla River area along the strike of a north-northwest-trending linear vent system (Swanson and Others, 1975) (Figure II-25; Plate II-7). Recent mapping (Swanson and Others, 1979a) has shown that this vent system is the westernmost known member of the Chief Joseph swarm.

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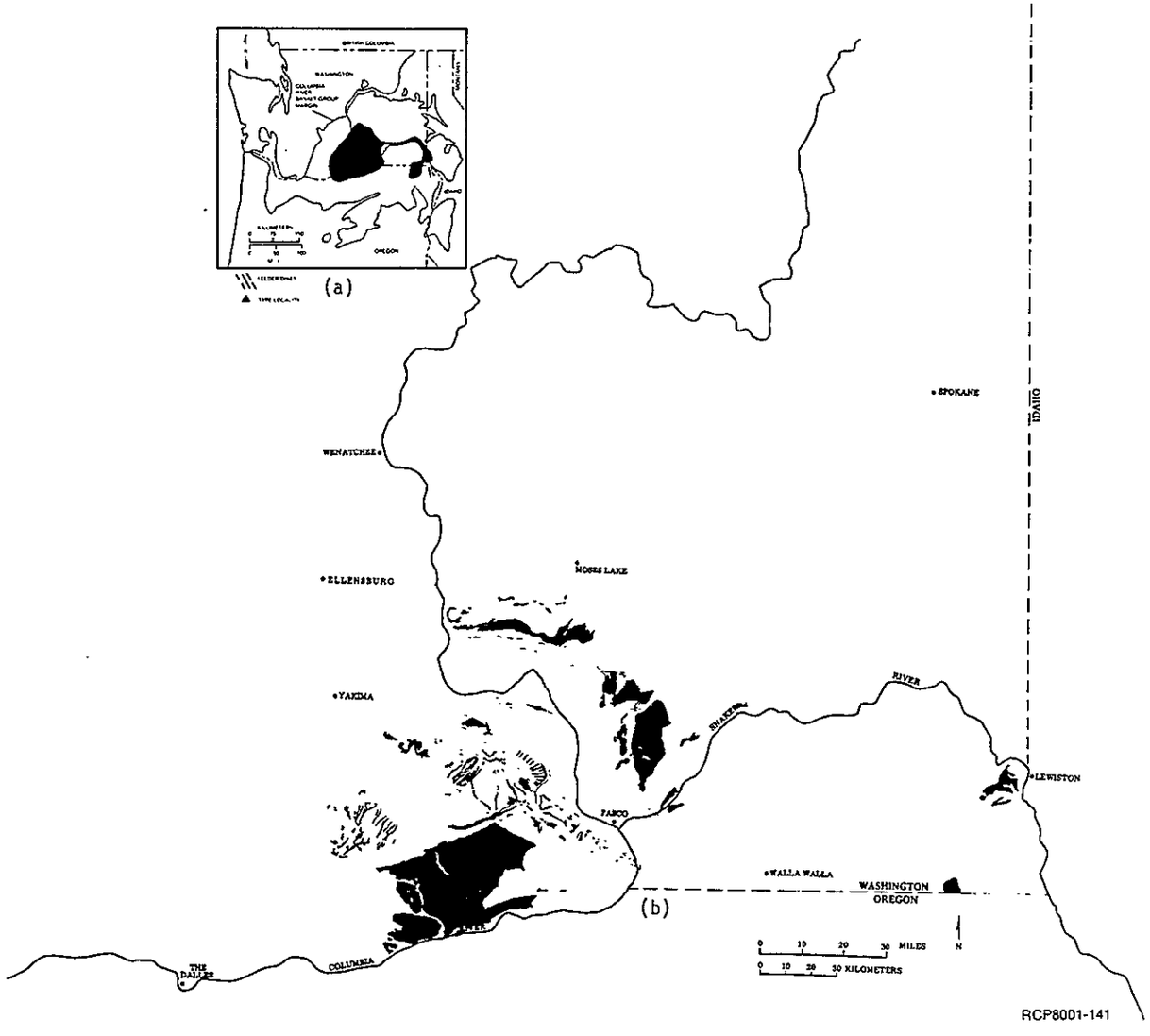

(a) Inferred Original Distribution (after Swanson and Others, 1979b); (b) Generalized Distribution, Eastern Washington (after Swanson and Others, 1979a).

FIGURE II-23. Inferred Original Distribution and Generalized Outcrop Distribution of Elephant Mountain Member.

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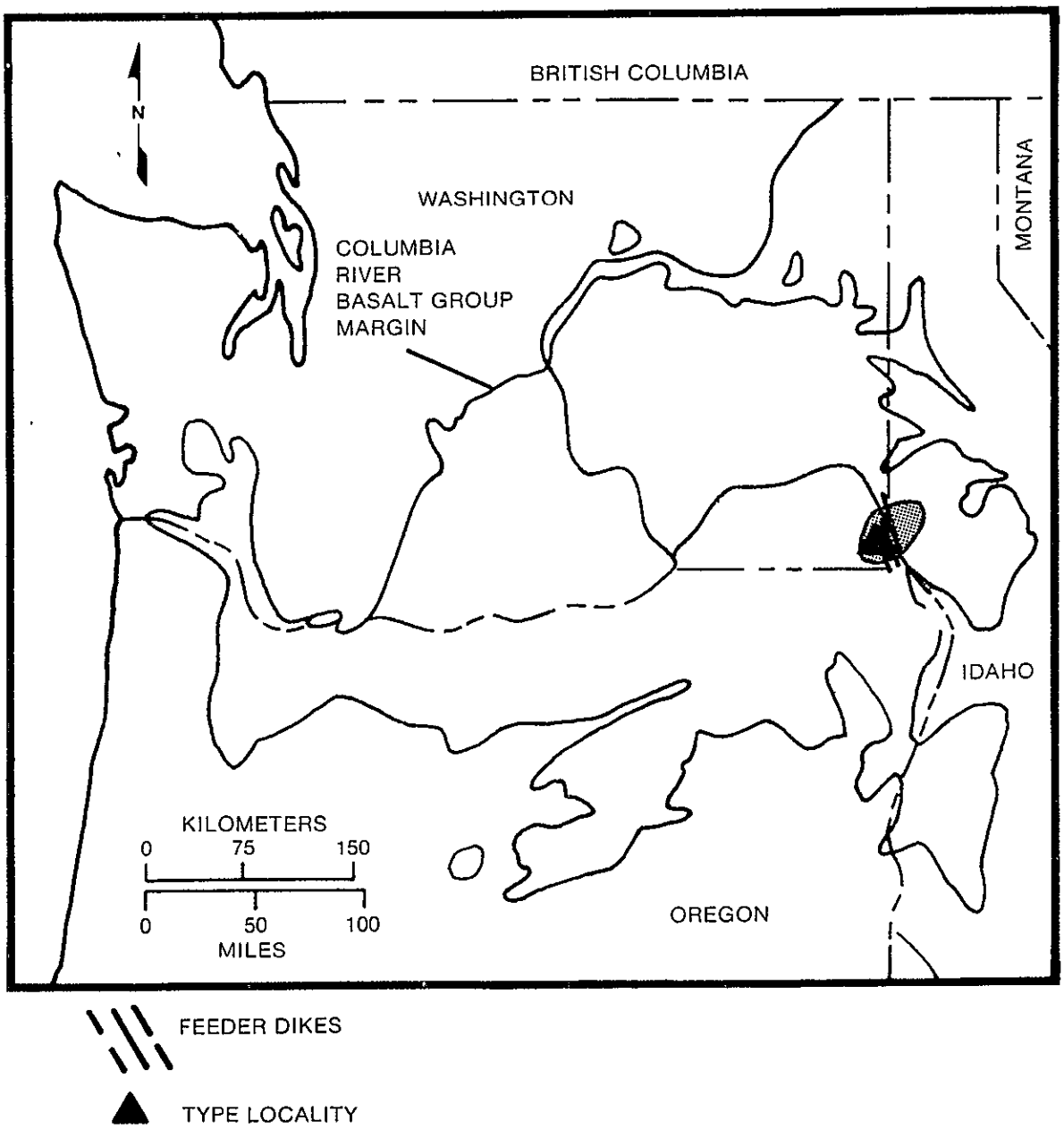

FIGURE II-24. Inferred Original Distribution of Buford Member (after Swanson and Others, 1979b).

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The Ice Harbor Member has been subdivided by Swanson and Others (1979b) into three informal units, listed from oldest to youngest as: basalt of Basin City; basalt of Martindale; and basalt of Goose Island (Figure II-4). Although all three informal units are plagioclase and olivine-phyric, they are characterized by different chemistries and magnetic polarities. Distinctive petrographic, chemical, and paleomagnetic properties of the informal units of the Ice Harbor Member are summarized in Table II-6.

Lower Monumental Member. The Lower Monumental Member (Figure II-4) has a potassium-argon age of 6 million years before present (McKee and Others, 1977) and is the youngest known member of the Columbia River Basalt Group (Swanson and Others, 1979b). Outcrops of this member are confined to the present-day Snake River Canyon between the Lower Monumental Dam area, southeastern Washington, and Lewiston, Idaho (Figure II-26; Plates II-7 and II-10) (Swanson and Others, 1978, 1979b). Although Lower Monumental feeder dikes have not been found, the intracanyon character of the member implies that Lower Monumental lava was erupted in the eastern part of the plateau and flowed down the Snake River Canyon as far west as the type locality (Swanson and Others, 1978, 1979b), (Figure II-26).

Petrographically, the Lower Monumental Member contains moderately abundant microphenocrysts of plagioclase and olivine. This normally magnetized member has a composition similar to the Lolo chemical type, but has a slightly greater content of Na_2O and K_2O (Camp, 1976; Swanson and Others, 1979b) (Table II-1). Characteristic properties of the Lower Monumental Member are summarized in Table II-6.

INTERCALATED AND SUPRABASALT SEDIMENTS

Intercalated and suprabasalt sedimentary deposits of south-central and southeastern Washington are described within this section. The discussion of these rocks is drawn mostly from a report prepared by Rigby and Othberg (1979) to accompany the regional late Cenozoic sediment map (Plates II-11 through II-19). A generalized summary of sedimentary map units is given in Table II-7. The most widespread of these units are discussed below.

Ellensburg Formation

The Ellensburg Formation (Russell, 1893; Smith, 1903a; Mackin, 1961; Schmincke, 1964b, 1967c; Waitt, 1979a) includes weakly lithified clastic and volcaniclastic sediments which occur within the western and central portion of the Columbia Plateau. Units of the formation underlie, interfinger, and overlie flows of the Yakima Basalt Subgroup. Because of this stratigraphic relationship, Ellensburg deposits are recorded on both the Columbia River Basalt Group map (Plates II-1 through II-10) and the late Cenozoic sediment map (Plates II-11 through II-19). Future work will include an integration of Ellensburg stratigraphic data acquired from both mapping projects.

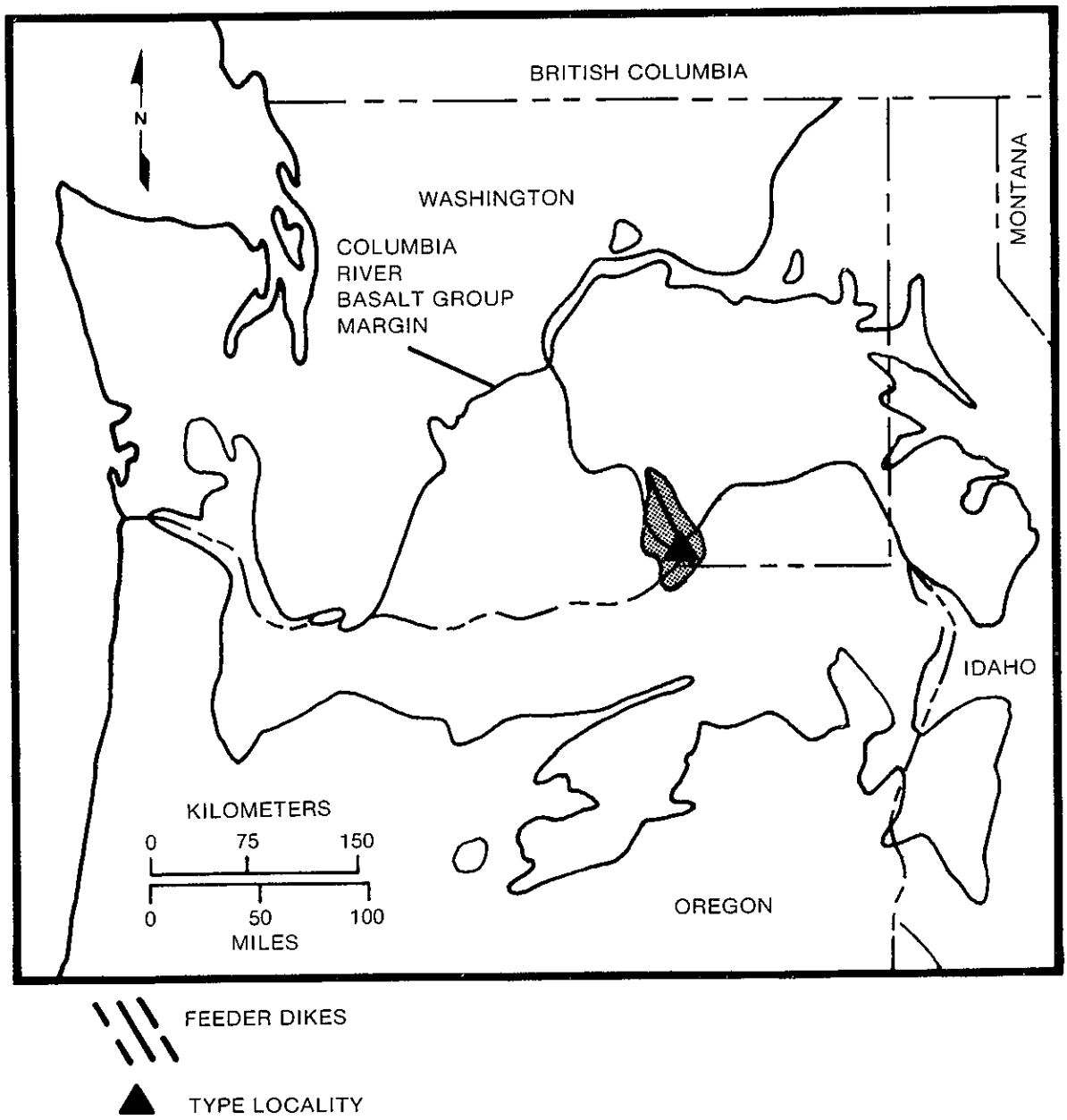


FIGURE II-25. Inferred Original Distribution of Ice Harbor Member (after Swanson and Others, 1979b).

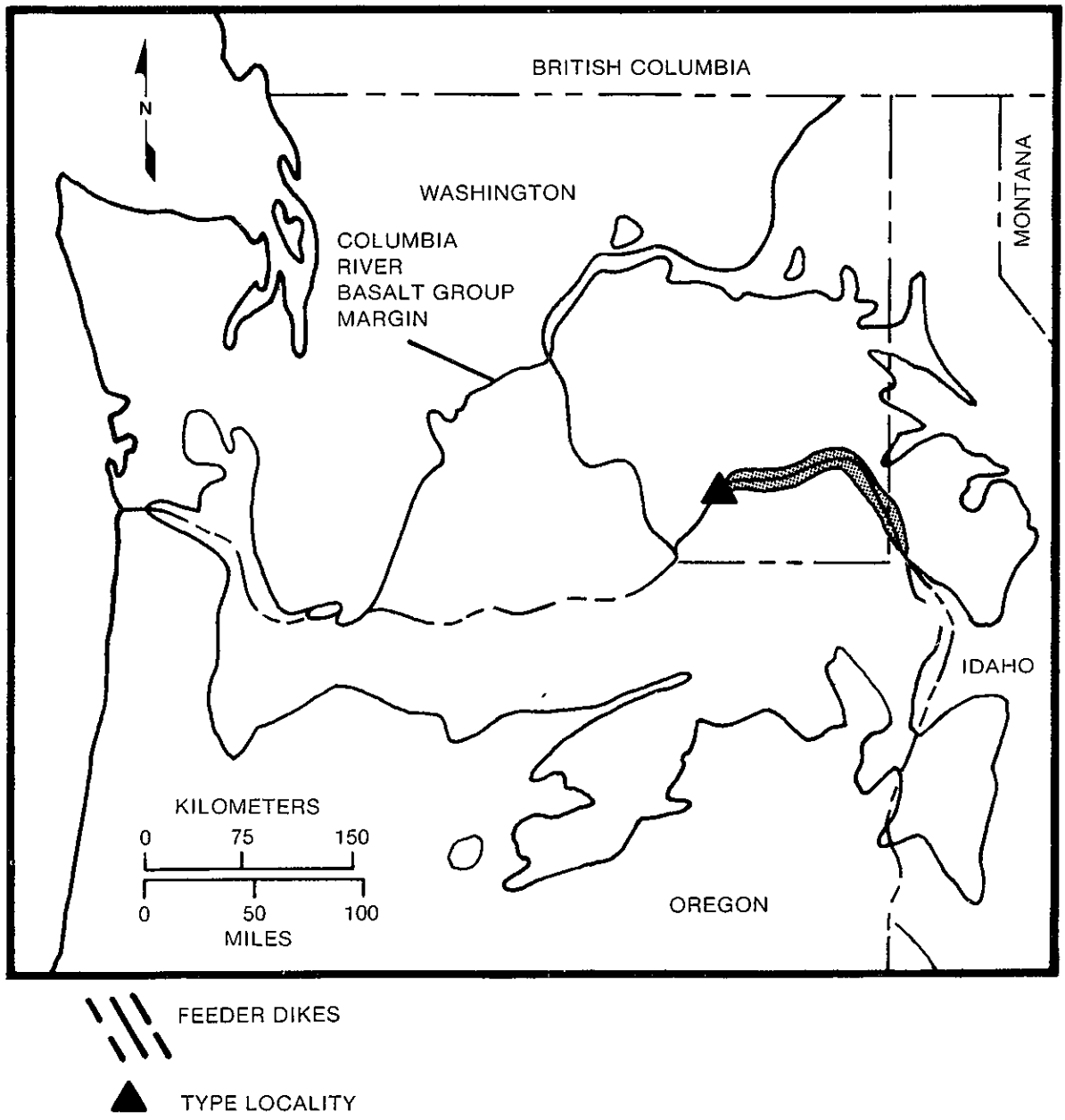


FIGURE II-26. Inferred Original Distribution of Lower Monumental Member (after Swanson and Others, 1979b).

On the Columbia River Basalt Group map (Plates II-4 through II-9), interbedded and suprabasalt Ellensburg deposits have been subdivided into three units, informally termed "subarkosic deposits," "volcaniclastic deposits," and "conglomerate of Snipes Mountain." The "conglomerate of Snipes Mountain" has been assigned to this formation on the basis of its interbedded relationship with an Ellensburg-type dacitic lahar at the east end of Toppenish Ridge (Plate II-6) (Bentley in Swanson and Others, 1979a). A more complete description of these three Ellensburg subdivisions is included in the map explanation on Plate II-8. Deposits of the "subarkosic" and "conglomerate" units are interpreted to define the course of the ancestral Columbia River (Swanson and Others, 1979a).

Only the distribution of suprabasalt Ellensburg deposits is recorded on the late Cenozoic sediment map accompanying this report. A generalized outcrop distribution map of these deposits, compiled from Plates II-14 through II-18 and II-19, is shown in Figure II-27. In general, suprabasalt Ellensburg deposits crop out on the flanks of anticlinal ridges in the Kittitas Valley, Wenas Valley, and the Yakima Valley, where they are folded with the underlying basalt (Rigby and Othberg, 1979). The sediments of this formation are moderately to poorly lithified fluvial sand and gravel with some lahar deposits. Two facies are recognized, a fluvial "sandstone facies" and a "gravel facies." The sandstone facies is composed of white to reddish-brown sand, silt, and clay, and the gravel facies is composed of andesite, dacite, pumice, and basalt clasts representing a mixture of fluvial and lahar deposits. The Ellensburg deposits, thicker and coarser grained in the far western portion of the Columbia Plateau, reflect a Cascade Range source area.

Latah Formation

The Latah Formation (Table II-7) includes sedimentary units associated with Grande Ronde Basalt and Wanapum Basalt within the Spokane River drainage, including parts of the lower St. Joe and Coeur d'Alene River drainages (Griggs, 1976) (Plates II-1 and II-11). Latah sediments occur stratigraphically below basalt flows and as interbedded units. Outcrops commonly are 5 to 20 feet (1.5 to 6 meters) thick with the thickest exposure less than 100 feet (30 meters) (Griggs, 1976). Latah sediments are best developed between Grande Ronde Basalt and the Priest Rapids Member (Swanson and Others, 1979a, 1979b).

The Latah Formation is composed mostly of poorly indurated, finely laminated siltstone, with some claystone, fine-to coarse-grained sandstone, and conglomerate. Plant fossils are abundant in much of the fine-grained strata (Chaney and Axelrod, 1959). The lithologic and mineralogic composition of Latah sediments reflects a "basement" rock source area (Griggs, 1976; Rigby and Othberg, 1979).

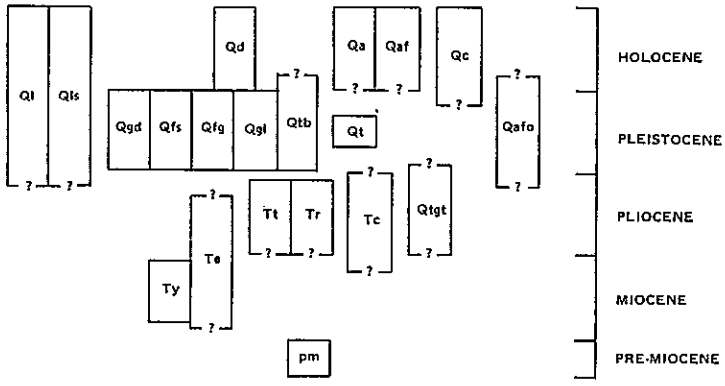
Gravels of the Ancestral Columbia River

This informal unit (Table II-7) originally introduced by Williams (1916), includes gravels thought to be deposited by the ancestral Columbia River (Rigby and Othberg, 1979). The gravels are composed primarily of well-rounded quartzite pebbles, with minor amounts of

TABLE II-7. Summary Description of Late Cenozoic Map Units.

(After Rigby and Othberg, 1979)

CORRELATION OF MAP UNITS



DESCRIPTION OF UNITS

Qd	DUNE SAND - Active and stabilized dunes of predominantly fine to medium sand: mostly quartz and basalt grains reworked from older sedimentary deposits.
Qa	ALLUVIUM - Primarily stream deposits of silt, sand, and gravel in floodplains, terraces, and valley bottoms. Includes local lacustrine, paludal, and eolian deposits in depressions.
Qaf	ALLUVIAL FAN DEPOSITS - Primarily unconsolidated sand and gravel on alluvial fans. Surface is relatively undissected and exhibits little or no petrocalcic soil development (caliche).
Qc	COLLUVIUM - Primarily angular to subangular basaltic debris accumulated at the base of steep slopes and cliffs. Includes talus and talus cones formed by active and inactive rockfall.
Qls	LANDSLIDE DEPOSITS - Unstratified and poorly sorted clay, silt, sand, and gravel deposited by rotational and translational slides and flows.
Ql	LOESS - Loess deposits consisting of eolian silt and fine sand up to 246 feet (75 meters) in thickness. Generally not mapped where less than approximately 6.5 feet (2 meters) thick. Locally contains multiple petrocalcic horizons and tephra beds.
Qafo	OLDER ALLUVIAL FAN DEPOSITS - Primarily semi-consolidated gravel or fanglomerate. Surface of fans is dissected and capped by well-developed petrocalcic soils (caliche).
Qfs	CATASTROPHIC FLOOD SLACKWATER SEDIMENTS - Rhythmically bedded and graded silt, sand, and gravel deposited by lower energy slackwaters or catastrophic floods and (or) surges of catastrophic floods. Includes the Touchet beds.
Qfg	CATASTROPHIC FLOOD GRAVELS - Predominantly coarse gravel and sand deposited by higher energy waters of catastrophic floods.
Qtb	TERRACE AND BAR DEPOSITS, UNDIFFERENTIATED - Glaciofluvial, fluvial, and ice-contact stratified silt, sand, and gravel deposits of various lithologies in terraces and bars in the valleys of the Columbia, Okanogan, and Spokane Rivers and tributaries. Includes deposits of the Great Terrace.
Qgl	GLACIOLACUSTRINE TERRACE DEPOSITS - Silt, sand, and gravel deposited in glacial lakes that formed along the Columbia, Okanogan, and Spokane Rivers and their tributaries. Includes deposits of the Nespelem Terrace. Surface of the terraces may exhibit local modifications by fluvial and catastrophic floodwaters.
Qgd	GLACIAL DEPOSITS - Till, outwash, and ice-contact stratified deposits in moraines, till plains, and melt-water channels and terraces.
Qt	TIETON ANDESITE - Andesitic flow of the lower Naches River drainage.
QTgt	GRAVEL OF THE TERRACE REMNANTS - Gravel and coarse sand in remnants of high fluvial terraces and alluvial fans within the Yakima River drainage basin. Includes the Cowiche gravel. Age uncertain, but may be in part correlative with Thorp Gravel, Ellensburg Formation, Ringold Formation, and gravels of ancestral Columbia River (Tc).
Tt	THORP GRAVEL - Fluvial (?) gravel in dissected high terraces and alluvial fans in the Kittitas Valley. Probably correlative with the upper Ringold Formation.
Tr	RINGOLD FORMATION - Fluvial and lacustrine clay, silt, sand, conglomerate, and fanglomerate of diverse composition. Includes a cap of thick, well-developed petrocalcic soil (caliche). May be correlative with the uppermost Ellensburg Formation.
Tc	GRAVEL OF ANCESTRAL COLUMBIA RIVER - Predominantly well-rounded pebble gravel. Columbia River provenance indicated by a dominance of quartzite pebbles.
Te	ELLENSBURG FORMATION - Primarily weakly lithified fluvial and laharic deposits. Base undefined. Mapped only where they overlie the Yakima Basalt Subgroup. Dominated by dacitic, andesitic, and pumiceous clasts.
Ty	YAKIMA BASALT SUBGROUP - Lava flows of the Saddle Mountains, Wanapum, and Grande Ronde Formations. Includes sedimentary interbeds of the Ellensburg and Latah Formations, local colluvium, caliche, and widespread, thin loess.
pm	PRE-MIOCENE ROCKS, UNDIFFERENTIATED - Primarily Precambrian through Mesozoic metamorphic and plutonic rocks, and early Tertiary sedimentary and volcanic rocks.

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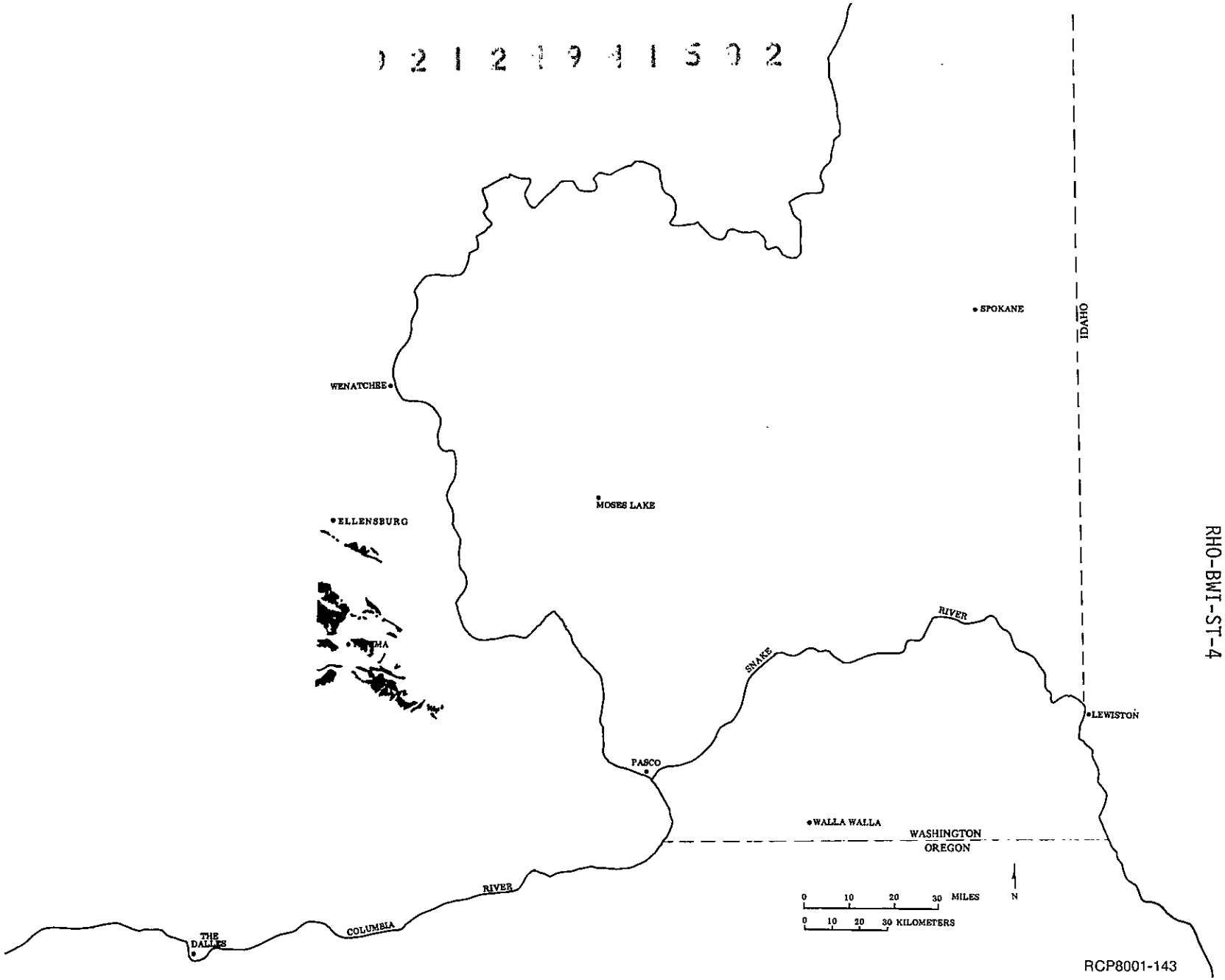

FIGURE II-27. Generalized Outcrop Distribution of Suprabasalt Ellensburg Formation, Eastern Washington (after Rigby and Othberg, 1979).

granite, gneiss, and basalt components. Deposits of this unit are limited in extent and are confined, for the most part, to higher elevations on ridges of the Yakima Fold Belt subprovince (Rattlesnake, Toppenish, Umtanum, Yakima, and Horse Heaven Ridges). At present, these gravels are considered to be Pliocene in age. However, their age, origin, and stratigraphic affinity have yet to be established with certainty. Rigby and Othberg (1979) considered the "Snipes Mountain Conglomerate" to be a member of this unit, rather than a subunit of the Ellensburg Formation as proposed by Swanson and Others (1979a).

Ringold Formation

Sediments assigned to the Ringold Formation are exposed within the Pasco and Quincy Basins (Rigby and Othberg, 1979) (Plates II-13, II-15, and II-16). A generalized outcrop distribution map of the deposits of this formation is included as Figure II-28. Two major facies of the Ringold Formation are exposed within the area, a "fine sand and silt" facies, and a "gravel and conglomerate" facies. The "conglomerate" facies crops out only at the base of the White Bluffs, located within the Pasco Basin. The presence in the Ringold Formation of vertebrate fossils, relict soil horizons, and current-bedding structures, indicates a fluvial/flood plain origin (Gustafson, 1978) for the unit. Available paleontologic (Gustafson, 1973, 1978) and paleomagnetic data (Packer and Johnston, 1979) suggest that Ringold sediments were deposited during the Gilbert paleomagnetic epoch, 3.3 to 5.1 million years before present. As such, the Ringold Formation may be correlative with the uppermost Ellensburg Formation.

Thorp Gravel

These suprabasalt gravels within the Kittitas Valley were originally referred to as the Thorp Drift by Porter (1976). They were later renamed the Thorp Gravel by Waitt (1979a). The unit (Table II-7), restricted to the western part of the Columbia Plateau, occurs as high terraces along the Yakima River and its tributaries in the Kittias Valley (Rigby and Othberg, 1979). Deposits of the Thorp Gravel are composed of moderately weathered, weakly cemented, well-rounded gravel. The sediments contain significant amounts of basaltic detritus derived from the Yakima Ridge and granitic and volcanic detritus derived from the Cascade Range (Rigby and Othberg, 1979). Fission track dates on tephra from the Thorp Gravel indicate a Pliocene age of approximately 3.7 million years before present (Waitt, 1979a).

Glacial Deposits

Glacial deposits (Table II-7), which include till, ice-contact-stratified drift, and outwash deposits, are present in the northern and in the far western portions of the Columbia Plateau. The most extensive glacial deposits occur within the northwestern portion of the map area (Plate II-14). Here, the plateau was overridden by the Okanogan Lobe of the Cordilleran Ice Sheet. The terminal position of this late Wisconsinan (approximately 15,000 to 20,000 years before present) glacial ice sheet is marked by the Withrow moraine (Easterbrook, 1976). The moraine area

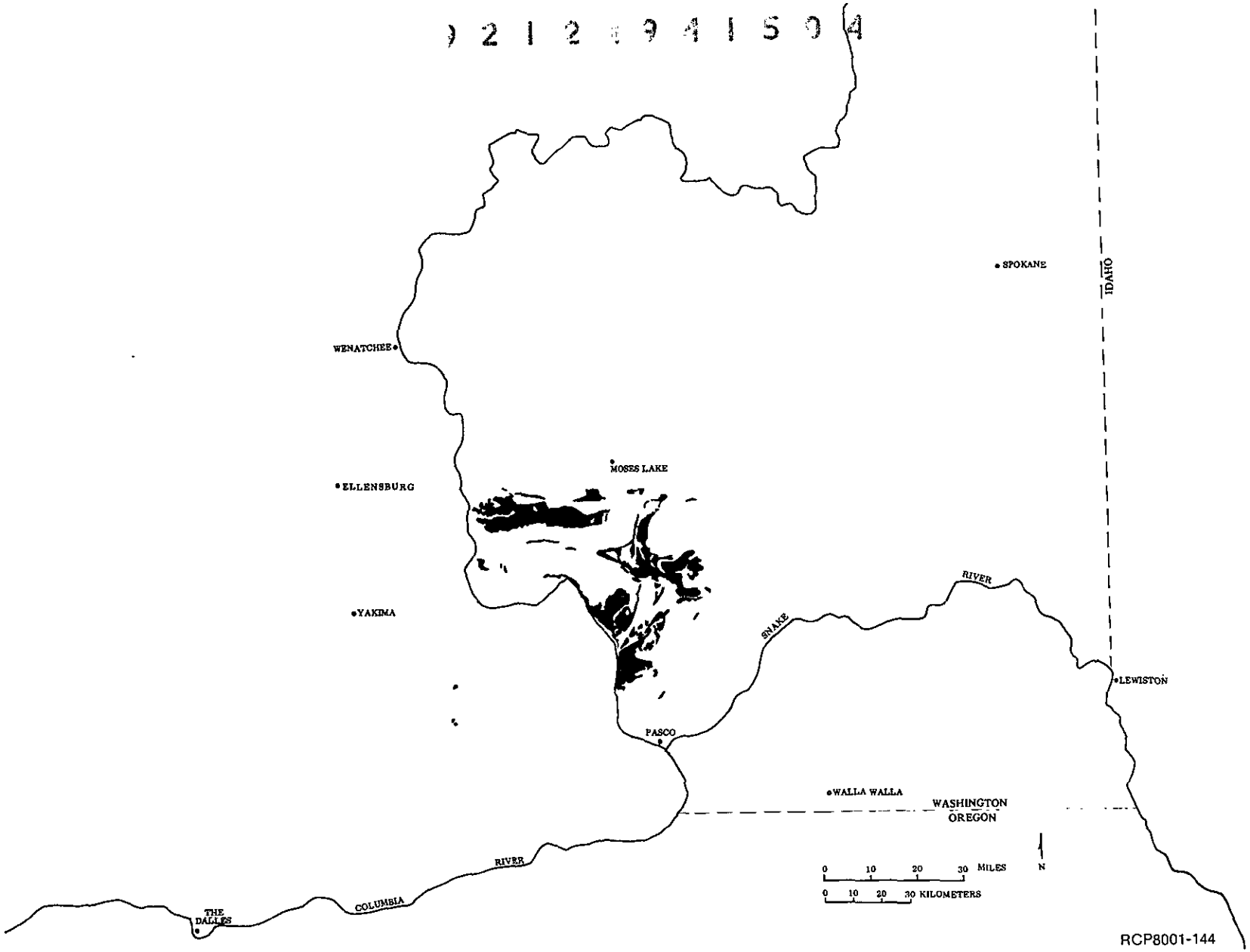

FIGURE II-28. Generalized Outcrop Distribution of Ringold Formation, Eastern Washington (after Rigby and Othberg, 1979).

is characterized by eskers, ground moraine deposits, and large basalt erratics, referred to as "haystack" rocks. Glacial drift, a product of Wisconsinan-age alpine glaciation, occurs in the Kittitas, Wenatchee, and Chelan Valleys (Rigby and Othberg, 1979).

Catastrophic Flood Deposits

Catastrophic flood deposits (Table II-7) are widespread in the Columbia Plateau. These sediments were deposited when ice dams in western Montana and northern Idaho were breached and massive volumes of water spilled abruptly across eastern and central Washington. The timing and number of such floods presently remains unresolved (Bretz and Others, 1956; Bretz, 1959; Patton and Baker, 1978; Waitt, 1979b). The majority of the sediments deposited by these floods are late Pleistocene in age, with the last major flood sequence dated at about 13,000 years before present (Mullineaux and Others, 1977). However, flood deposits have been found in the south-central portion of the plateau which are interpreted to be pre-Wisconsinan in age (Patton and Baker, 1978). Old flood gravels in the Pasco Basin were dated at approximately 200,000 years before present using the thorium/uranium method (see Appendix A) (Tallman and Others, 1978). Within the map area, catastrophic flood deposits are divided into two main facies, termed the "flood gravel" facies and the "slackwater" facies (Rigby and Othberg, 1979).

Flood Gravel Facies. The flood gravel facies is composed of poorly sorted, sub-rounded to angular clasts which locally display foreset bedding. In general, their distribution is limited to: (a) floors and sides of scabland channels; (b) depositional basins into which these channels emptied (primarily the Quincy and Pasco Basins); (c) Columbia River Gorge below Wallula Gap; and, (d) Snake River Canyon (as far up as Lewiston, Idaho). Within the scabland channels and along the Columbia River, this facies occurs principally as flood bar deposits (Baker, 1973; Rigby and Othberg, 1979).

Also included in this unit are sand and gravel deposits which originated from the Pleistocene-age Lake Bonneville floods(s). Bonneville flood sediments were transported to the plateau via the Snake River drainage, and are presently thought to be confined to the Snake River Canyon (Rigby and Othberg, 1979).

Slackwater Facies. This facies includes the rhythmically bedded and graded silt, sand, and minor gravel deposits originally referred to by Flint (1938a) as the Touchet Beds. In general, deposits of the slackwater facies are limited to peripheral areas of the Pasco and Quincy Basins, and to tributary valleys such as the Touchet and Walla Walla (Rigby and Othberg, 1979). Slackwater conditions occurred at those localities during impoundment of floodwaters due to "hydraulic" damming," primarily at Wallula Gap. Locally, slackwater deposits contain ice-rafted erratics, ash beds, clastic dikes, and minor gravel-filled channels. At several localities, slackwater deposits approach a thickness of 300 feet (100 meters) (Rigby and Othberg, 1979). In the Walla Walla Valley, a thick deposit displays 40 separate rhythmite cycles and Waitt (1979b) has proposed that each of these cycles record a catastrophic flood event. Also included within this unit are minor deposits in the Snake River Canyon thought to be associated with Lake Bonneville catastrophic flood(s) (Rigby and Othberg, 1979).

Loess Deposits

Loess (Table II-8), comprised of wind-deposited fine sand and silt, mantles much of the Columbia Plateau in varying thicknesses. All loess, regardless of age, is shown on the late Cenozoic sediment map (Plates II-11 through II-19) as one unit. However, loess deposits of at least four different ages are recognized (Richmond and Others, 1965).

The two oldest loess units have been correlated with pre-Bull Lake glaciation (pre-Illinoian or older than 125,000 years before present [Pierce and Others, 1976]) (Richmond and Others, 1965). The units are dark reddish-orange in color and are best exposed in deep "cuts" in the Palouse Hills area of eastern Washington.

The next oldest loess unit is referred to as the Palouse Formation and comprises most of the Palouse Hills. The Palouse Formation is divided into at least three morphologically distinct units and has been defined as Bull Lake (Illinoian) in age (Richmond and Others, 1965). The eolian nature of the Palouse Formation is demonstrated by: (a) the predominant southwest-northeast alignment of the Palouse Hills, parallel to the direction of the prevailing winds; (b) the "fining" of component particles to the northeast; and, (c) an east-northeast progressive overlap of loess sub-units (Rigby and Othberg, 1979). The Palouse Formation reaches thicknesses of up to 250 feet (75 meters), is tan to brown in color, and is very fine grained (silt size). This unit may cover more than half of central and southeastern Washington (Rigby and Othberg, 1979) (Plates II-11 through II-19).

The youngest recognized loess unit is informally termed the "post-Palouse" loess. This light-tan colored unit has been interpreted as Pinedale (late Wisconsinan, or older than 10,000 years before present [Pierce and Others, 1976]) to recent in age (Richmond and Others, 1965). In general, this younger loess is capped by a weakly developed petrocalcic horizon (although not everywhere present) and is separated from the Palouse Formation by an unconformity. Evidence suggests that the post-Palouse loess is essentially a post-catastrophic flood loess (younger than 13,000 years before present) (Rigby and Othberg, 1979). The post-Palouse loess occurs discontinuously throughout the entire Columbia Plateau (Plates II-11 through II-19).

Other Surficial Deposits

Alluvium, colluvium, sand dunes, and landslide deposits occur throughout the map area (Figure II-7; Plates II-11 through II-19). Alluvial deposits are primarily Holocene and include all stream deposits as well as local lacustrine, paludal, and eolian deposits in scabland depressions. Older, probably Pleistocene, alluvium is present as fan deposits usually capped with a petrocalcic horizon. Colluvium, primarily Holocene talus deposits, is common at the base of steep slopes, particularly in coulees.

The Pasco and Quincy Basins contain large Holocene dune fields, both active and stabilized. Mazama and Glacier Peak ash horizons are commonly found in alluvium and sand dunes.

Landslide deposits are of variable age and genesis. Large bedrock landslides along the flanks of the Yakima ridges may be associated with ridge deformation; other, younger appearing landslides may have been induced by catastrophic flooding. Many small, active landslides, particularly in the Ringold Formation, are induced by irrigation.

LATE CENOZOIC VOLCANIC ROCKS

Simcoe Lavas

The "Simcoe Lavas" (or Simcoe Mountains Volcanics, [Sheppard, 1967]) cover an area of approximately 300 square miles (1,500 square kilometers), mostly to the northwest of Goldendale, Washington. These lavas unconformably overlie the Yakima Basalt and Ellensburg Formation and predate the Pleistocene and Holocene lavas from Mount Adams and its subsidiary volcanoes. Potassium-argon dates of Simcoe Lavas indicate they were extruded between 0.9 and 4.5 million years before present (Shannon and Wilson, 1973a).

Simcoe lavas are predominantly olivine basalt, with minor amounts of pyroxene-olivine basalt, rhyolite, and dacite. Most of the olivine basalt occurs as thin flows, which were erupted from northwest-southeast-trending fissures or from the flanks of numerous small, shield volcanoes and spatter cones in the area. The rhyolite, dacite, and pyroxene-olivine basalts occur in a few small flows and in cinder and spatter cones (Shannon and Wilson, 1973a). Outcrops of Simcoe Lavas are noted on Plates II-6 and II-9.

Tieton Andesite

The Tieton Andesite consists of several flows of hypersthene-augite andesite that were erupted from vents in the Cascade Range (Swanson, 1967). Only one flow of the Tieton Andesite extends into the map area (Plates II-6 and II-15). This flow is an intracanyon deposit restricted to the valleys occupied by Cowiche Creek and the Tieton and Naches Rivers (Rigby and Othberg, 1979; Swanson and Others, 1979a). A potassium-argon date obtained for the Tieton Andesite by Dymond (in Shannon and Wilson, 1973a) indicates that this lava was extruded approximately 1 million years before present.

Tephra Deposits

Pliocene to Holocene tephra horizons are present within the Columbia Plateau. Of these horizons, ashes from Mount St. Helens, Glacier Peak, and Mount Mazama are important Pleistocene and Holocene time stratigraphic marker units. At least 8 major ash sets were erupted from Mount St. Helens between 150 and 35,000 years before present (Mullineaux and Others, 1975). Mount St. Helens Set S has been dated at about 13,000 years

before present (Mullineaux and Others, 1977) and is associated with deposits of the last major scablands flood. Glacier Peak erupted many times between about 11,000 and 13,000 years before present (Smith and Others, 1977; Westgate and Evans, 1978; Porter, 1978). Porter (1978) recognized 7 Glacier Peak ash layers, 2 of which cover large areas of the Columbia Plateau. Mazama ash deposits, dated at 6,600 years before present (Wilcox, 1965), are also common throughout the plateau. Work by Mullineaux and Wilcox (1979) suggests that more than 1 Mazama ash may be present.

REGIONAL STRUCTURE

CONTENTS

This section includes a general description of the pattern and timing of Columbia Plateau deformation. The emphasis of the section is on important folds, faults, and photolineaments identified within the Washington State portion of the plateau, or that area thus far studied under the regional reconnaissance geologic mapping (Plates II-1 through II-19) and remote sensing efforts (Plates II-21 through II-30) (see Appendix A for remote sensing procedures). The discussion is keyed to a generalized structure map included as Plate II-20. Information concerning the age of specific Columbia Plateau structures, provided either by previous work or by regional studies sponsored by Rockwell Hanford Operations, is also briefly addressed within this section. The discussion is organized around the three informal geologic subprovinces of the plateau which were defined within the introductory section of this chapter--the Yakima Fold Belt, the Palouse, and the Blue Mountains (Figure II-2). Structures trending into the Columbia Plateau from surrounding provinces are discussed primarily in Appendix G.

YAKIMA FOLD BELT SUBPROVINCE

The Yakima Fold Belt subprovince covers the central and western parts of the Columbia Plateau (Figure II-2). Reconnaissance mapping of the subprovince has been completed and the results are included as Plates II-4 through II-9, and II-13 through II-16. The western half of the Pasco Basin lies within this subprovince and this area of the Yakima Fold Belt will be discussed in more detail in Chapter III of this report.

The Yakima Fold Belt subprovince is characterized by long, narrow anticlines and broad synclines extending generally eastward from the Cascade Range province to the approximate center of the plateau, where they generally die out. Anticlinal ridges and synclinal valleys within the subprovince are located in Plate II-20. The east-west to northwest-oriented folds of this subprovince generally have an asymmetrical profile. Most known faults within the region are associated with anticlinal fold axes, are thrust or reverse (although normal faults are also present), and probably developed at the same time as the folding (WPPSS, 1977;

Grolier and Bingham, 1978; Swanson and Others, 1979a). Northwest- to north-south-trending shear zones and minor folds commonly transect these structures (Reidel, 1978a; Swanson and Others, 1979a). Most faults within the subprovince do not disrupt overlying late Cenozoic sediments or post-Columbia River basalt volcanic rocks (WPPSS, 1977; Rigby and Othberg, 1979).

Individual structures of the Yakima Fold Belt subprovince have been examined at various levels of detail (Shannon and Wilson, 1973a; WPPSS, 1977; Swanson and Others, 1979a; Rigby and Othberg, 1979). A discussion of those located within the Pasco Basin is included in Chapter III. An abbreviated description of major structures outside the basin follows.

Cle Elum-Wallula Deformed Belt

Deformation within the Yakima Fold Belt subprovince is most intense along a 25-mile (40-kilometer) wide zone between Cle Elum and Wallula, Washington, a distance of approximately 125 miles (200 kilometers) (Plate II-20). This zone is referred to as the Cle Elum-Wallula lineament (Kienle and Others, 1977a) or deformed belt. In the Yakima area, structures within the Cle Elum-Wallula deformed belt are oblique to the northwest-southeast trend of the belt; those near Cle Elum and Wallula are more parallel to it. Structures outside this zone (i.e., Ahtanum and Toppenish Ridges and Horse Heaven Hills) change trend from east-west and east-northwest to east-southeast where they merge with the Cle Elum-Wallula deformed belt (Kienle and Others, 1977a) (Plate II-20).

The Cle Elum-Wallula deformed belt coincides with the central one-third of a topographic lineament termed by Raisz (1945) the Olympic-Wallowa lineament. This lineament, as described by Raisz (1945), extends for 400 miles (640 kilometers) from the Straits of Juan de Fuca in northwestern Washington to the Wallowa Mountains in northeastern Oregon. Recent geologic mapping and geophysical studies conducted by the Washington Public Power Supply System, Inc. (WPPSS, 1977) suggest that the lineament is not continuous through the Cascade Range and may merely be a coincidental topographic alignment beyond the extent of the Cle Elum-Wallula deformed belt. However, the structural significance of the Olympic-Wallowa lineament remains controversial and this lineament (and, therefore, the Cle Elum-Wallula deformed belt) has been postulated to have regional tectonic significance. Tectonic hypotheses concerning the Olympic-Wallowa lineament and the Cle Elum-Wallula deformed belt are discussed in Appendix G.

Manastash Ridge Structure

The 35-mile (55-kilometer) long Manastash Ridge structure extends northwest from Badger Gap (T14N, R20E) to just west of Shushuskan Canyon (T17N, R18E), where it assumes a more east-west trend along the south fork of Manastash Creek (Plates II-6 and II-20). The ridge separates the Kittitas Valley depression to the north from the Squaw Creek syncline to the south (Plate II-20). Specific information concerning the Manastash structure has been condensed primarily from work conducted by Bentley (1977b; in Swanson and Others, 1979a), Diery (1967), Glass (1977), and Hanson and Campbell (in Rigby and Othberg, 1979).

The geometry of Manastash Ridge is best exposed in the water gap cut by the Yakima River, 6 miles (10 kilometers) south of Ellensburg (Plate II-6). A generalized cross section through the structure at this locality as interpreted by Bentley (1977b) is included as Figure II-29. In the vicinity of the water gap, the Manastash structure is a broad, low, asymmetrical anticline with steeper dips on the north limb. Two second-order folds, the Thrall syncline and the Thrall anticline, are superposed on the north flank of the Manastash structure. Axes of the Manastash anticline and the Thrall anticline are parallel and are separated by a distance of less than 1 mile (1.6 kilometers) (Figure II-29). On the south side of the Thrall syncline, a continuous section, from Thorp gravel down through R_2 Grande Ronde Basalt flows, is exposed. The southern flank of Manastash Ridge is composed of R_2 and N_2 Grande Ronde Basalt flows. At the crest of the anticline, the structural surface is composed of the Vantage Member.

Most faults associated with the Manastash structure are near vertical and are located along the steep north limb. The most continuous of these faults may be part of a much longer fault system, termed the Manastash-Hanson Creek fault system, which can be traced to the east for 30 to 40 miles (50 to 60 kilometers) (Bentley, 1977b) (Plate II-6). Along this structure, R_2 Grande Ronde Basalt on the upthrown, north side of the fault abuts against Frenchman Springs units on the downthrown, south side of the structure. At least one north-south cross fault displaces the structure at Badger Gap (Kienle and Others, 1977a; Swanson and Others, 1979a) (Plate II-6).

Bentley (1977a) concluded that most deformation along Manastash Ridge occurred after sediments interpreted to be Thorp Gravel (Table II-7) were deposited and before development of the 1-million-year old Thrall pediment surface (Figure II-29). Therefore, much of the deformation on Manastash Ridge may be late Pliocene or early Pleistocene in age (1 to 3.7 million years before present). Regional reconnaissance mapping of late Cenozoic sediments in the area by Campbell (in Rigby and Othberg, 1979) has produced no data which are contrary to this age interpretation.

Umtanum Ridge Structure

The Umtanum Ridge structure forms a nearly continuous ridge from Gable Butte-Gable Mountain (within the Pasco Basin) northwestward to the margin of the Columbia Plateau, a distance of nearly 70 miles (112 kilometers) (Plate II-20). The ridge is flanked on the north by the Squaw Creek syncline and on the south by the Roza-Burbank-Cold Creek syncline. The general structure and stratigraphy of the ridge west of the Pasco Basin are shown on Plate II-6.

The most recent detailed studies of the Umtanum structure (beyond the Pasco Basin) have been conducted by Bentley (1977b; in Swanson and Others, 1979a) and by Shannon and Wilson (1977a, 1977b; Kienle and Others, 1977a). The ridge was considered by Kienle and Others (1977a) to form the "backbone" of the Cle Elum-Wallula deformed belt and was

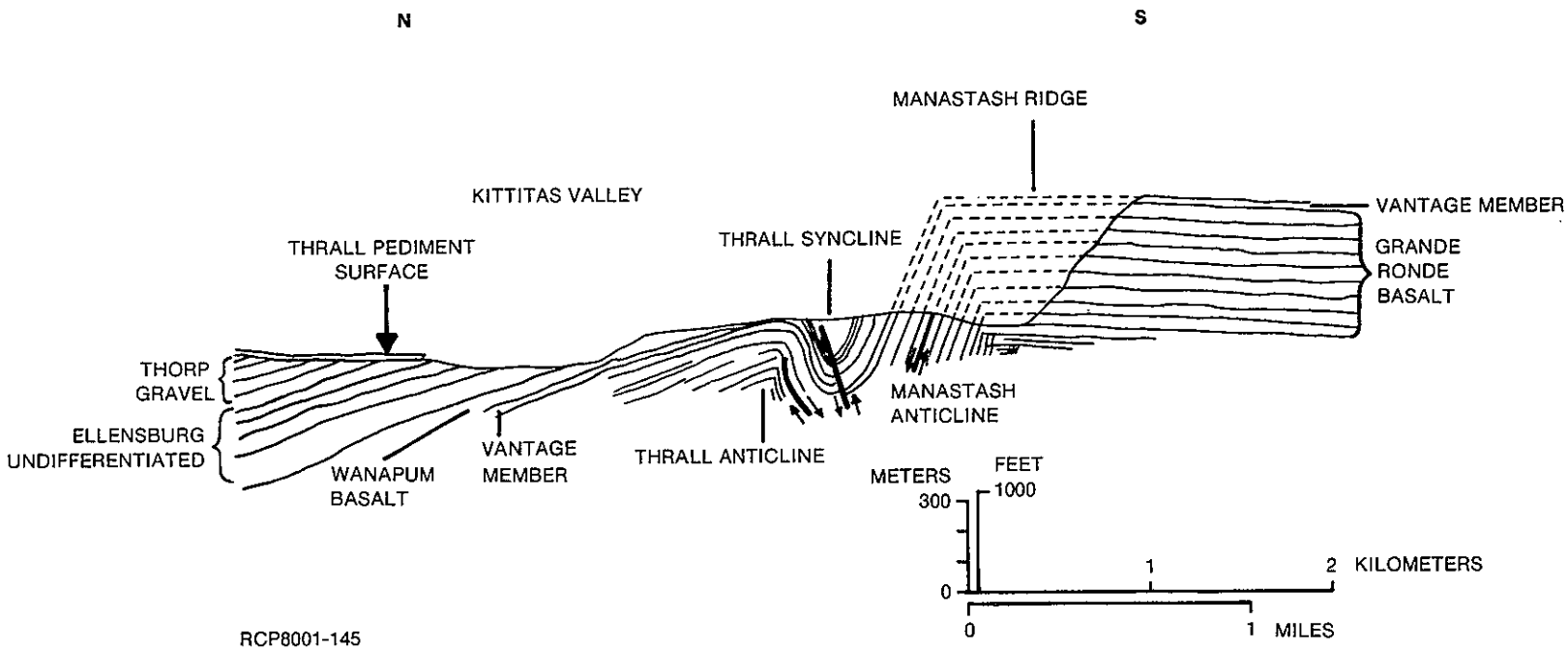

FIGURE II-29. Generalized Cross Section through Manastash Ridge (after Bentley, 1977b).

examined by them as part of their overall study of this zone. A description of the general character of the Umtanum structure, as interpreted by these workers (Kienle and Others, 1977a) is included below.

> "To the east of Ellensburg Pass (T17N, R17E), the Umtanum Ridge (western segment) continues east-southeast as the Umtanum anticline with the Wymer fault on its northeast side (Bentley, 1977b). The Umtanum anticline has about 300 feet (90 meters) of structural relief across the structure. Near the Yakima River, a cross fault (the Baldy fault) shifts the asymmetry of the anticline to the south. From this cross fault, the middle segment of Umtanum anticline extends east-southeast to Hog Range Buttes (T14N, R22E) (Plate II-6), where the asymmetry of the structure shifts back to steep on the north. This portion of the Umtanum anticline appears to be bounded on the south by the reverse Burbank fault. East of Hog Range Buttes, the Umtanum anticline increases in structural relief to about 5,000 feet (1,515 meters) as it approaches the northeast boundary of the Cle Elum-Wallula lineament near Priest Rapids Dam. Just west of Priest Rapids Dam, an imbricated thrust-fault zone is present in the area of maximum structural relief. West of Ellensburg Pass, Umtanum Ridge changes trend to N80°W and passes into several smaller folds and faults."

Exposed along Umtanum Ridge are Columbia River basalt flows ranging in age from R_2 Grande Ronde Basalt to Pomona basalt and sediments predominantly of the upper Ellensburg Formation (Plate II-6). Studies by Shannon and Wilson (1977a, 1977b) have indicated that the age of deformation of Umtanum Ridge is post-Pomona Member and pre-upper Ellensburg (suprabasalt Ellensburg) fanglomerate. Reconnaissance mapping of late Cenozoic sediments within the vicinity of this structure by Campbell and Hanson (in Rigby and Othberg, 1979) has produced no data contrary to this age interpretation.

Yakima Ridge Structure

Yakima Ridge extends from the vicinity of the city of Yakima, Washington to the western border of the Hanford Site (Plate II-20). Information concerning this 50-mile (75-kilometer) long structure has been provided by Waters (1955), Diery (1967), and Newcomb (1970), and most recently by Kienle and Others (1977a) and Bentley (1977a, 1977b; in Swanson and Others, 1979a). The general stratigraphy and structure of the ridge are shown on Plate II-6.

The Yakima Ridge structure can be divided into three segments on the basis of topography. The segments are informally termed the eastern, middle, and western segments (Shannon and Wilson, 1977b). The character of the eastern segment, located nearest to the Pasco Basin, is discussed in Chapter III; only the general geometry of the remaining two segments is discussed here.

The middle segment of Yakima Ridge extends east-west for a distance of 15 miles (25 kilometers) from Cairn Hope Peak (T13N, R23E) to Selah Gap (T13N, R18E) (Plate II-6). This segment is a box-fold anticline with sharp hinge lines (Waters, 1955; Bentley, 1977b). Local faults are present in the hinge area and core of the anticline. Principal stratigraphic units exposed within this segment include R_2 and N_2 Grande Ronde Basalt flows, and Frenchman Springs, Roza, Priest Rapids, and Umatilla flows (Swanson and Others, 1979a). Figure II-30 illustrates the general geometry and stratigraphy of the middle section of Yakima Ridge at Selah Gap as interpreted by Bentley (1977b).

The western segment of Yakima Ridge extends 10 miles (16 kilometers) from Selah Gap along Cowiche Mountain to Sedge Ridge (Plate II-6). Principal units within this segment are flows of R_2 and N_2 Grande Ronde Basalt. In gross character, the ridge is a box-fold anticline with sharp hinge lines along both flanks. Along the western segment, in the vicinity of Cowiche Mountain, the axis of the structure changes from an essentially east-west orientation to a southwest orientation (Plates II-6 and II-20). Along Cowiche Creek (T13N, R18E) (Plate II-6), a minimum age of deformation for Yakima Ridge is established where one-million-year-old Tieton Andesite laps on the truncated north side of the anticline (Shannon and Wilson, 1977b).

Based on his geologic mapping of Yakima Ridge, Bentley (1977b; in Swanson, 1978; in Swanson and Others, 1979a) suggested at least two periods of deformation. The first of these periods involved uplift along a north-south-trending axis during post-Priest Rapids and pre-Pomona time (12 to 14 million years before present). The second, and most important period of deformation, involved uplift along N50°-80°W axes in post-Elephant Mountain time (about 10.5 million years before present). Uplift, as indicated by undisturbed Tieton Andesite along Cowiche Creek, had ceased one million years before present (Shannon and Wilson, 1977b). Reconnaissance mapping of late Cenozoic sediments in the vicinity of this structure by Campbell and Hanson (in Rigby and Othberg, 1979) has produced no data contrary to this age interpretation.

Ahtanum Ridge Structure

Ahtanum Ridge is an east-west-trending structure which extends between Union Gap and the south fork of Ahtanum Creek, a distance of approximately 20 miles (32 kilometers) (Plates II-6 and II-20). The ridge is essentially the western extension of the Rattlesnake Hills, a structure discussed in Chapter III. In general, the Ahtanum structure is an asymmetrical anticline developed in N_2 Grande Ronde, Frenchman Springs, Roza, Priest Rapids, and Pomona flows. Steeply dipping and overturned basalt flows and thrust faults are exposed on both the north and south flanks of the structure (Bentley in Swanson and Others, 1979a).

Late Cenozoic sediments exposed on Ahtanum Ridge were mapped by Campbell (in Rigby and Othberg, 1979). He found no evidence of faulting in recent loess and stream alluvium locally overlying the surface of the ridge. However, a belt of folded and faulted suprabasalt Ellensburg sediments and cemented basalt gravels (possibly equivalent to "Gravels of

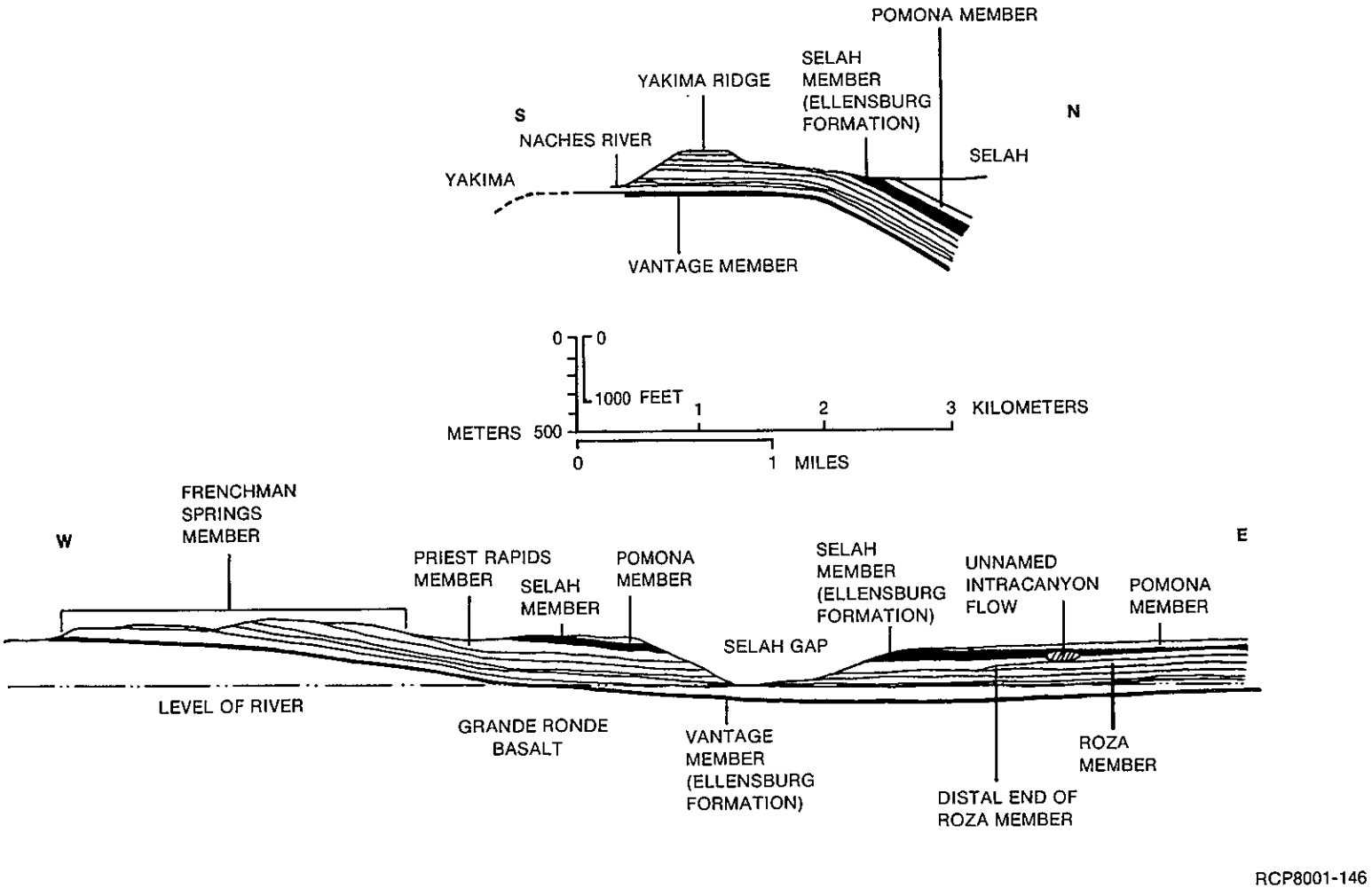

FIGURE II-30. Generalized Cross Section through the Middle Section of Yakima Ridge at Selah Gap (after Bentley, 1977b).

Terrace Remnants" [Table II-7]) were found on the lower slopes of the north flank of Ahtanum Ridge (T12N, R18E) (Plate II-15). Faulting of these deposits was interpreted predominantly by relationships between dips of the respective units and the topography; direct evidence of faulting was observed at only two localities. The absolute age of deformation of the older sediments is unknown, but post-dates the deposition of suprabasalt Ellensburg sediments and pre-dates the deposition of recent loess and alluvium.

Toppenish Ridge Structure

Toppenish Ridge is an 80-mile (125-kilometer) long east-west-trending anticlinal ridge located in the southwestern portion of the Yakima Fold Belt subprovince (Plate II-20). The Toppenish Basin, a broad synclinal valley, is situated between the ridge and Ahtanum-Rattlesnake Ridge to the north. Toppenish Ridge has recently been mapped for this study by Campbell (in Rigby and Othberg, 1979) (Plate II-15) and by Bentley (in Swanson and Others, 1979a) (Plate II-6). Information concerning the structure of the ridge is abstracted from field data collected by these two workers.

Columbia River basalt flows exposed along Toppenish Ridge range from R_2 Grande Ronde through Elephant Mountain. Generalized cross sections illustrating an interpretation of the pattern of basalt deformation along the ridge are shown in Figure II-31. The east end of the ridge (Figure II-31a) consists of an anticline in Wanapum and Saddle Mountains Basalts. A small syncline near the crest of the ridge produces a double fold in the basic anticlinal structure. Two thrust faults are also developed within this area of the ridge. Westward, a high-angle, reverse fault is encountered on the south side of the ridge and Wanapum Basalt is exposed in the deeper drainages dissecting this flank. In addition, an anticline-syncline fold system is developed on the north side of the ridge in Saddle Mountains Basalt (Figure II-31b). Farther westward, N_2 and R_2 Grande Ronde Basalt flows form much of Toppenish Ridge and are disrupted by a low-angle thrust fault (Figure II-31c). In this area, the lower anticline-syncline fold system dies out (Figure II-31c).

During geologic reconnaissance mapping conducted for this study, scarps that disrupt sediments mantling Toppenish Ridge were discerned in the vicinity of the Tecumseh-Pumphouse Road Junction (T9N, R19E) (Plates II-6 and II-15) (Campbell in Rigby and Othberg, 1979; Bentley in Swanson and Others, 1979a). The scarps were observed to cut late Cenozoic sediments consisting of upper Ellensburg units (defined as post-Elephant Mountain in age), Touchet-like beds (dated elsewhere as 13,000 years before present), landslides of several ages, loess, and alluvial fans of several ages. Surface mapping of these features suggests that they may be fault scarps. Other theories of origin, such as mass landsliding, down-slope creep, or withdrawal of ground water, are difficult to justify on the basis of current field data. The scarps appear to be Holocene in age (younger than Touchet-like sediments) and to have developed independently of the older thrust faulting along the ridge. Volcanic ash, organic material, and caliche samples from Toppenish Ridge have been submitted for dating; analytical results were not yet available for inclusion in this report.

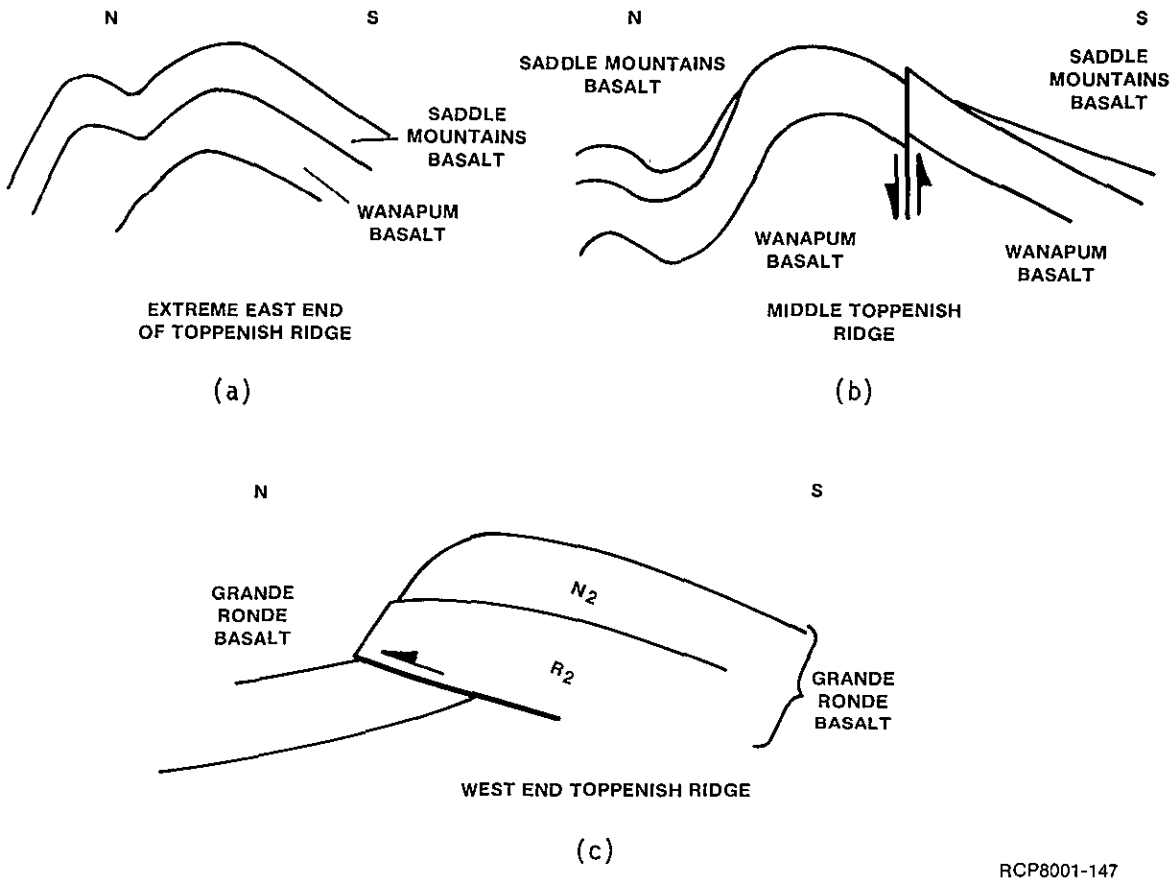

FIGURE II-31. Generalized Cross Sections through Toppenish Ridge (after Rigby and Othberg, 1979).

Figure II-32 is a generalized cross section illustrating the placement and character of the Toppenish Ridge scarps. These scarps appear to be clustered into two groups: (a) an upper group constituting a "graben" and located near the crest of the ridge; and, (b) a lower group constituting a "horst" associated with auxiliary folds low on the north side of the ridge. The upper scarp system was traced for 20 miles (32 kilometers) along Toppenish Ridge and the lower system for 12 miles (19 kilometers). The eastern extent of the scarp groups lies in the vicinity of U.S. Highway 97. To the west, both the upper and lower scarp systems appear to die out north of Satus Peak (T9N, R17E), although forest cover in this area may obscure their true extent.

Each group is comprised of as many as 12 individual scarps. Discrete scarps usually do not extend for more than 2 miles (3 kilometers) before splitting. Most scarps appear to dip vertically, or nearly so, and show surface displacements from 3 to 10 feet (1 to 3 meters). However, the total displacement along the ridge is difficult to determine, as there are nearly as many "up-to-the-north" as "down-to-the-north" scarp displacements.

Within the lower "horst series" (Figure II-32), the scarps exhibit slightly curved patterns which in general parallel the deformation of Elephant Mountain and upper Ellensburg (post-Elephant Mountain) units. Alluvial fan and landslide debris has washed or slid from the upper part of the ridge into the depression created behind the "horst" (Figure II-32). Caliche developed on some surfaces, in addition to stream dissection of this material, indicates several ages of fan building. Some of the older fan material may be caught up in the folding within the "horst." If the "horst" is caused by faulting, the nature and variable age of sediments trapped by the "horst" would indicate fault activity along this structure for an extended period of time.

Faults within the upper "graben" set (Figure II-32) can be seen to cut flows of N_2 Grande Ronde Basalt, the Vantage Member of the Ellensburg Formation, and Wanapum Basalt. At one locality, a fault developed in basalt was observed to pass upward into a young-appearing scarp, thus indicating continued or renewed movement along the fault plane over an extended period of time. In cases where upthrown blocks have displaced drainage channels, sag ponds have been created which are filled with sediment.

Toppenish Ridge is structurally and topographically similar to several other nearby ridges--Horse Heaven, Ahtanum, Rattlesnake, and Manastash. After the discovery of the scarps on Toppenish Ridge, these other ridges were examined in more detail to see if similar scarps might have been overlooked. Although high-angle faults were observed to be associated with the auxiliary folding on the north flanks of these ridges, no evidence of scarps similar to those on Toppenish Ridge was found (Campbell in Rigby and Othberg, 1979).

3 2 1 2 1 9 4 1 5 1 7

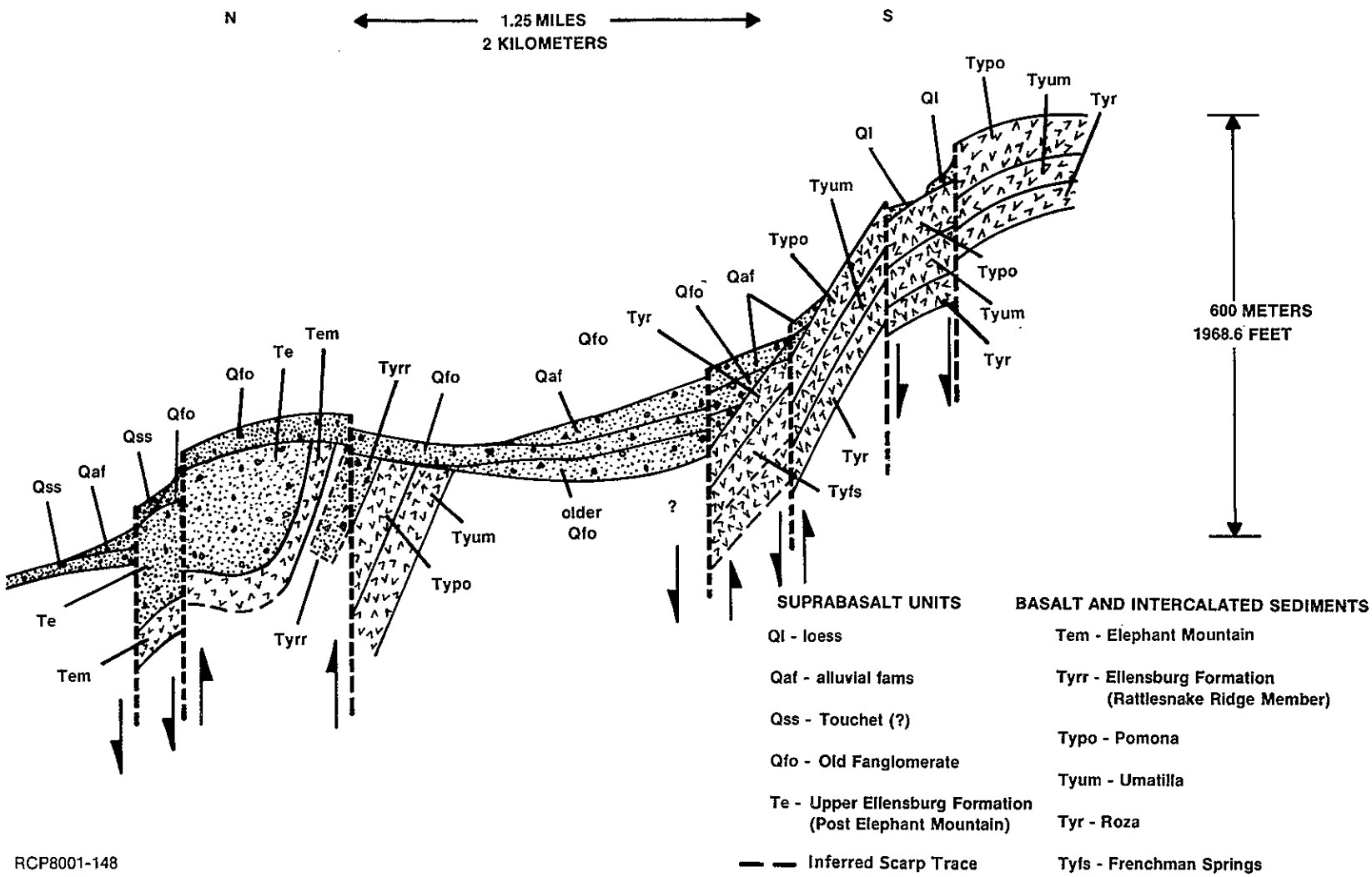

FIGURE II-32. Generalized Cross Section through Toppenish Ridge Scarps near the Tecumseh-Pumphouse Road Junction (after Rigby and Othberg, 1979).

Horse Heaven Hills Structure

The Horse Heaven Hills structure extends from the Cascade Range province eastward to the Blue Mountains subprovince (Plates II-6, II-7, II-9, II-20), a distance of nearly 150 miles (240 kilometers). For purposes of this discussion, the structure has been divided on an informal basis into 3 segments: (a) a western segment, extending from Dog Mountain T3N, R9E) to BZ Corner (T4N, R10E); (b) a middle segment, extending from the vicinity of BZ Corner north-northeastward to Chandler (T9N, R26E); and, (c) an eastern segment, extending from Chandler southwest to Walla Walla (T7N, R36E). The character of the western and middle segments of the Horse Heaven Hills structure is briefly discussed within this section; the character of the eastern segment of the structure is discussed in Chapter III.

The western segment of the Horse Heaven Hills structure is comprised of a northeast-trending fault with its downthrown side to the north. Southwest of Camas Prairie (T5N, R11E), N_2 Grande Ronde Basalt flows on the south side of the fault are juxtaposed against Frenchman Springs flows on the north side of the structure (Plate II-9) (Swanson and Others, 1979a).

The middle segment of the Horse Heaven Hills structure consists of a broad anticlinal arch. Between BZ Corner and Bickleton (T6N, R20E), the principal Columbia River basalt units exposed along the structure are Grande Ronde Basalt flows (N_2 and possibly R_2) and Frenchman Springs flows (Plates II-7 and II-9). Thrust faults occur along this segment of the ridge in association with numerous low- and high-angle faults. In the vicinity of Grayback Mountain (T6N, R13E) (Plates II-6 and II-9), thrust faults are present on both limbs of an anticline that is overturned to the north (Anderson in Swanson and Others, 1979a).

Between Bickleton and Chandler, the principal Columbia River basalt units exposed along the structure are N_2 Grande Ronde Basalt, Frenchman Springs, Roza, Priest Rapids, Umatilla, and Elephant Mountain flows (Plate II-6). Structurally, this portion of the Horse Heaven Hills is dominated by a series of northeast-trending anticlines along the north side of the Columbia River Valley and near the crest of the hills, and by dip slopes and gentle folds in the intervening flat terrain (Plates II-7 and II-8) (Gardner in Swanson, 1978; Gardner in Swanson and Others, 1979a). Faults are commonly associated with the folds and are generally thrust or high-angle reverse structures. The youngest basalt unit, the Elephant Mountain Member, is cut by faults (Gardner in Swanson, 1978).

Mapping of sediments mantling the Horse Heaven Hills structure was conducted by Campbell (in Rigby and Othberg, 1979). Between Prosser and Bickleton (T7N, R21E) (Plate II-15), Campbell noted a scarp developed in late Cenozoic material. The scarp trends approximately N70°E for a distance of 0.6 mile (1 kilometer). The southwest end of the scarp is terminated against a landslide, and its northeast end dies out in alluvium. Campbell suggested that the scarp possibly represents a dip slope of a resistant unit within ancestral Columbia River Gravels (Table II-7). Two

small patches of this gravel were found in float near the scarp. However, the possibility that the scarp may be attributable to faulting cannot be ruled out until more detailed studies of the feature are conducted.

Columbia Hills Structure

The southern part of the Yakima Fold Belt subprovince is characterized by both east-west- and northwest-trending structures (Plate II-20). The predominant east-west-trending structure in the area is the Columbia Hills anticline, which extends from the vicinity of The Dalles, Oregon to the Horse Heaven Hills, a distance of nearly 90 miles (150 kilometers) (Plate II-20). The western half of this anticline is intersected by a series of northwest-trending structures, the most prominent of which are the Arlington-Shutler Butte, Luna Butte, Laurel, Warwick, and Goldendale structures (Plate II-20). The following brief description of deformation in the Columbia Hills area is based on information collected during reconnaissance mapping conducted for this study (Plate II-6) (Swanson and Others, 1979a) and information included in a report by Shannon and Wilson (1973a).

The Columbia Hills structure is comprised of a series of asymmetrical, doubly plunging anticlines, which expose Columbia River basalt ranging in age from N_2 Grande Ronde to Elephant Mountain. The amplitude of the structure, greatest in the vicinity of The Dalles, Oregon progressively decreases eastward. Thrust faults and high-angle and low-angle faults are present, especially along the steep south limb of the structure (Plates II-6 and II-20) (Swanson and Others, 1979a).

The most prominent of the northwest-trending features appears to be wrench structures in which narrow, doubly plunging anticlines combine to form a continuous structure. Right lateral displacement along several northwest-trending structures and lineaments is suggested by the en echelon arrangement of small anticlines southeast of Camas Prairie (Plates II-20 and II-9) (T5N, R11-12E) (Swanson and Others, 1979a). Vertical displacements for some of the northwest-trending structures are estimated to be on the order of tens of feet (meters) (Shannon and Wilson, 1973a).

Examination of the age of the northwest-trending structures was conducted by Shannon and Wilson (1973a). On the basis of potassium-argon dating of Simcoe "lavas," they concluded that the age of last movement on the structures occurred between 3.5 and 4.5 million years before present. However, they also concluded that alignment of volcanic cones (some less than 100,000 years old) along the trend of these structures suggests that the system has been a zone of crustal weakness providing conduits for late Cenozoic magmas.

A determination of the age relationship between the northwest-trending structures and the Columbia Hills anticline is problematical. Following a study of fold-fault intersections, Shannon and Wilson (1973a) concluded that: (a) final movement along northwest-trending faults (interpreted to be 3.5 to 4.5 million years before present) was mostly an accumulation or response to the same forces that produced the folding;

and, (b) that the end of folding and final movement of the faults was contemporaneous. However, reconnaissance geologic mapping conducted for this study (Swanson and Others, 1979a) provided evidence which suggests that the northwest structures may postdate the northeast-trending anticlinal uplift. As such, the field studies conducted by Swanson and Others (1979a) indicate that further examination of the age relationship between the two sets of structures within the Columbia Hills area is warranted.

Kittitas Valley Depression

The Kittitas Valley depression (WPPSS, 1977) is a topographic and structural low located along the northwestern margin of the Columbia Plateau. The depression is bounded to the west by the Cascade Range, to the north by the Wenatchee Mountains uplift, to the east by the Naneum-Hog Range anticline, and to the south by the Manastash-Thrall structure (Plate II-20). The geology of the area has recently been the subject of investigations by Bentley (1977a, 1977b). Tabor and Others (1977), Martin (1977), Waitt (1979), and Hanson (in Rigby and Othberg, 1979). Mapping in the area by Tabor and Others (1977) and Hanson in Rigby and Othberg, 1979) is compiled on Plates II-5 and II-14.

Exposed along the flanks of the Kittitas Valley depression are R_2 and N_2 Grande Ronde Basalt flows and Ellensburg Formation units which dip from 10 to 50 degrees. The dip of these units flattens out to about 5 degrees near the axis of the downwarp (Waitt, 1979a). Additional rocks exposed within the confines of the depression include pre-Tertiary gneiss, early Tertiary volcanics, Thorp Gravel, and glacial drift (Kittitas) (Rigby and Othberg, 1979).

Most faults within the Kittitas Valley depression (Plate II-5) appear to be older than late Cenozoic sediments of the area. However, Martin (in WPPSS, 1977) and Waitt (1979a) cited three east-west-trending faults in the valley which they interpreted to be younger than Thorp Gravel (3.7 million years before present) and to be older than Kittitas drift (120,000 years before present). These faults, termed the Dry Creek, the Reecer Creek, and the Wilson Creek by Martin (in WPPSS, 1977), were further examined by Rigby (in Rigby and Othberg, 1979). Rigby (in Rigby and Othberg, 1979) concluded that the evidence for the presence of at least two of the faults, the Reecer Creek and the Wilson Creek, is tenuous.

Badger Mountain and Beezley Hills Structures

The Badger Mountain structure is an anticlinal flexure developed primarily in R_2 and N_2 Grande Ronde Basalt. The structure extends from the Columbia River near the town of Orondo, Washington (T25N, R21E) southeastward for a distance of approximately 30 miles (48 kilometers)

(Plates II-4, II-5, and II-20). A general description of the Badger Mountain structure, as interpreted by Clayton (in WPPSS, 1977), follows.

> "The anticline is a broad, asymmetrical structure that plunges southeastward from the Columbia River at about 100 feet per mile. Its northern limb dips relatively steeply into a broad downward known as the Waterville syncline; whereas the southern limb typically slopes less than about five degrees into a minor downwarp exposed in the basalt along the west edge of Badger Mountain. The fold axis more closely resembles a monocline and is located north of the crest of the fold."

The major development of the Badger Mountain structure was clearly a post-Grande Ronde Basalt event, as indicated by the deformation of Vantage Member sediments (Ellensburg Formation) (Clayton in WPPSS, 1977). Although a minimum age for the structure has not been determined with certainty, Clayton (in WPPSS, 1977) and Hanson (in Rigby and Othberg, 1979) found no evidence of faulting in late Cenozoic sediments which mantle much of the anticline. Swanson and Wright (in Swanson and Others, 1979a) also found no evidence for geologically "young" tectonism in the Badger Mountain area. In addition, they reinterpreted the Orondo "fault," a structure described to the north of the Badger Mountain uplift by Clayton (in WPPSS, 1977), as a monocline which forms the margin of the Waterville syncline (Plate II-20).

The Badger Mountain and Moses Stool anticlines (Plates II-4 and II-20) form an en echelon set which merges west of Moses Coulee in a complex manner. The structure then merges eastward into the Beezley Hills anticline (Plates II-4 and II-20) (Swanson and Others, 1979a). At the approximate location of this juncture, the Beezley Hills structure curves north and becomes the Coulee monocline, which extends a distance of approximately 30 miles (48 kilometers) to the northeast. The terminus of the monoclinal axis coincides with a thrust fault developed in Wanapum Basalt (Roza and Priest Rapids Members) just south of which is a second thrust fault exposing Grande Ronde Basalt above Wanapum Basalt (Priest Rapids Member) (Plate II-4) (Swanson and Others, 1979a). Mapping by Swanson and Others (1979a) has discounted the existence of a more northward-trending branch of the Coulee monocline, termed by Newcomb (1970) the Barker monocline. No evidence of structures offsetting late Cenozoic sediments within the Beezley Hills anticline-Coulee monocline area was found by Hanson (in Rigby and Othberg, 1979).

Photolineament Analysis of the Yakima Fold Belt Subprovince

A photolineament map covering the extreme eastern portion of the Cascade Range province and the Yakima Fold Belt subprovince have been compiled using the procedures and photolineament classification scheme outlined in Appendix A. Table II-8 is keyed to this map (Plates II-25 through II-30) and contains a brief description of specific photolineaments of known or suspected geologic significance. Information contained in Table II-8, as well as in the remainder of this section, was derived primarily from a report prepared by Sandness and Others (in press) to accompany the photolineament map (Plates II-24 through II-29).

TABLE II-8. Description of Specific Photolineaments of the Yakima Fold Belt Subprovince and Cascade Range Province.

(After Sandness and Others, in press.)

PLATE AND DESIGNATION	SYMBOL*	LENGTH MILES (Kilometers)	STRIKE	COMMENTS
II-24 A-A'	KU4 LU4 U34 LU2 U4 LU3 L1U3 U14	5-7 (8-11)	--	Photolineaments coinciding with a large circular drainage and topographic pattern northeast of Soap Lake, Washington (T23N, R28E). Defined most strikingly on its east side by arcuate shape of Billy Clapp Lake. Northern portion defined by combination of known faults (Newcomb, 1970) (Plate II-4) and stream drainages.
II-24 B-B'	U3 LU4	23 (37)	N60°E	Distinct topographic and textural lineament apparently related to Coulee monocline (Plate II-4).
II-24 C-C'	U4	9 (14)	N45°W	Coincides with synclinal trough (Plate II-4).
II-24 D-D'	LU34	7 (11)	N80°W	Coincides with monoclinal axis (Plate II-4).
II-24 E-E'	U4	9 (14)	N45°W	Coincides with complex zone of closely spaced anticlines, synclines, and thrust faults (Plate II-4).
II-24 F-F'	LU3 U3	9 (14)	N75°W	Coincides with synclinal trough (Plate II-4).
II-24 G-G'	U4	12 (19)	N45°E	Coincides, in part, with anticlinal crest line (Plate II-4).
II-24 H-H'	LU12 U12 L1	15 (24)	N80°W to N10°E	Coincides with approximate position of anticlinal axis (Plate II-4).
II-25 A-A'	KSLU4 SLU3	13 (21)	N50°W	Winesap lineament (Clayton, 1977). Easily seen on Landsat, Skylab, and U-2 imagery as a straight stream channel both northwest and southeast of the Columbia River at Winesap, Washington (T26N, R21E).

*See page II-96 for explanation of photolineament classification symbol.

Table II-8 (continued)

PLATE AND DESIGNATION	SYMBOL*	LENGTH MILES (Kilometers)	STRIKE	COMMENTS
II-25 B-B'	SLU34	21 (34)	N45°E	Pine Canyon section of Bumping Lake lineament. Bumping Lake lineament is a regional photolineament which enters Washington near Portland, Oregon and extends northeastward to the Columbia River near Chief Joseph Dam. Lineament also noted by Hodgson (1977). Lineament easily seen on Landsat, Skylab, and U-2 imagery as a straight canyon (SLU34) (T25N, R21E and T26N, R22E). Reconnaissance geologic mapping (Sandness and Others, in press) indicates that the lineament in Pine Canyon is located on or near lower hinge of a monocline.
II-25 C-C'	KU14 KU42 KU3 LSU43 KU1 LU34 KU31	60 (96)	N50°W to N5°E	Leavenworth fault zone (Plate II-5). Fault zone defined by a continuous lineament(s) from the northern map edge along the Chiwana River (T29N, R16E) to the mission peak area (T21N, R19E). Defined almost entirely by stream alignments and topographic lows; color and textural discontinuities define only a minor portion of the total length. Fault zone is visible in all 3 types of imagery (Landsat, Skylab, and U-2) in various areas.
II-25 D-D'	U13 KU4 KU42 KLU42 U34 KLU14 LU3 L3	50 (80)	N15°W to N30°W	Entiat fault zone (Plate II-5). Lineaments coinciding with fault zone traceable for a distance of at least 45 miles (72 kilometers).

*See page II-96 for explanation of photolineament classification symbol.

Table II-8 (continued)

PLATE AND DESIGNATION	SYMBOL*	LENGTH MILES (Kilometers)	STRIKE	COMMENTS
II-25 E-E'	U4 KU13	15 (24)	N50°W to N85°W	Lineament along Taneum Creek (T18N, R16E) coinciding with fault (Plate II-5). Strong lineament, especially near its southeast end.
II-25 F-F'	U14 KU3	8 (13)	N45°W to N70°E	Lineament south of Snow Lakes (T23N, R16E). Crosses Ingalls Creek, then arcs eastward where it is expressed as a stream lineament and a fault (Huntting and Others, 1961). Many strong faults occur in the area from Mount Stuart (T23N, R15E) to the Snow Lakes.
II-25 G-G'	U14	3 (5)	N40°E to N65°E	Lineament north of the Snow Lakes (T23N, R16E). It arcs eastward and is expressed by a sharp scarp with apparent uplift of its south side.
II-25 H-H'	U3	5 (8)	N65°E	Lineament just north of Cholchuck Lake (T23N, R16E). Western end of lineament is formed by a straight stream section. At the point where the stream turns northward, the lineament continues to the northeast along the slope of Cannon Mountain (T23N, R16E) as a sharp scarp showing an apparent downdrop on its south side.
II-25 I-I'	U17 U1	9 (14)	--	An apparent joint set in the Lake Chelan area (T29N, R20-21E); expressed by several small groups of lineaments along the lake. The directional trends are west-northwest-east-southeast and northeast-southwest.

*See page II-96 for explanation of photolineament classification symbol.

Table II-8 (continued)

PLATE AND DESIGNATION	SYMBOL*	LENGTH MILES (Kilometers)	STRIKE	COMMENTS
II-25 J-J'	U34	11 (18)	N10°E to N50°E	Strong photolineament crossing Table Mountain (T20-21N, R18E). Expressed mainly as an alignment of valleys. Distinctive because its orientation is perpendicular to the dominant northwest-southeast trend in that area.
II-25 K-K'	U1	2 (3)	N35°W	Lineament in northeast corner of T18N, R19E. Feature is a thin line of green vegetation along the limb of a southwest dipping monocline on the north side of the Kittitas Valley (Plate II-5).
II-25 L-L'	U4	3 (5)	N76°W	Distinct scarp on a south facing valley wall at T29N, R19E.
II-26 A-A'	U1 KLU4 LU13	10 (16)	N25°W	Coincides with east branch of Moxee fault zone (Glass, 1977). Well expressed geomorphically and can easily be seen on both Landsat and U-2 imagery. Western branch not seen on Landsat imagery, but a discontinuous lineament on the U-2 photographs was seen which was coded U4 and U1.
II-26 B-B'	U3 U4 LU3 U17	10 (16)	N20°W to N45°W	Group of lineaments in Toppenish Ridge area; expressed by a greater concentration of vegetation along fractures in terrain otherwise having only sparse vegetation. Visible on U-2 photography due to differential growth of vegetation.
II-26 C-C'	LU3 LU34 U35 LU23	50 (80)	N45°E	Coincides with portion of Bumping Lake lineament (also see description of photolineament B-B', Plate II-25). Follows Carlton Creek and the Bumping River. Continues northeast, eventually following the Columbia River near Chief Joseph Dam.

*See page II-96 for explanation of photolineament classification symbol.

Table II-8 (continued)

PLATE AND DESIGNATION	SYMBOL*	LENGTH MILES (Kilometers)	STRIKE	COMMENTS
II-26 D-D'	U3 U4 U24 LU3	2-14 (3-22)	N80°E to N78°W	Several small topographic breaks on the north side of Toppenish Ridge (T9-10N, R18-21E).
II-26 E-E'	U4 LU1	7 (11)	N45°E	Coincides with fault along Clemans Mountain (Plate II-6).
II-27 A-A'	U1 LU4 LU34	30 (48)	N30°W	Coincides with trace of Anderson Ranch anticline, Snipes Creek anticline, and Badger Canyon fault (Plates II-7, III-1).
II-27 B-B'	U4	3 (5)	N45°W	Group of lineaments corresponding with extension of Rattlesnake structure (Plates II-7, III-1).
II-27 C-C'	U4	9 (14)	N80°W	Lineament coinciding with part of Silver Dollar fault (Plates II-7, III-1).
II-27 D-D'	U4	9 (14)	N45°W	Lineament coinciding with Hanson Creek fault (Plates II-7, III-1).
II-27 E-E'	KLU4	15 (24)	N80°W	Lineament coinciding with part of Umtanum structure (Plates II-7, III-1).
II-27 F-F'	LU4 U4	6 (10)	N80°W	Lineament coinciding with Gable Mountain structure (Plates II-7, III-1).
II-27 G-G'	KLU4	11 (18)	E-W	Lineament coinciding with Saddle Mountains fault (Plates II-7, III-1).
II-27 H-H'	U4	3 (5)	N10°W	Lineament coinciding with north-south trending fault in the Saddle Mountains (Plates II-7, III-1).
II-27 I-I'	U4	10 (16)	N50°W to N80°W	Topographic lineament crossing the Saddle Mountains directly north of the horn of the Columbia River (T15N, R26E) (Plates II-7, III-1).

*See page II-96 for explanation of photolineament classification symbol.

Table II-8 (continued)

PLATE AND DESIGNATION	SYMBOL*	LENGTH MILES (Kilometers)	STRIKE	COMMENTS
II-27 J-J'	U4 U34	12 (19)	N65°W to N60°E	Group of lineaments on the south slope of the Horse Heaven Hills south of Prosser, Washington (T6-7N, R24-25E). Three longest lineaments in the group consist of drainage alignments and a scarp-like topographic feature that cuts across the basic drainage pattern. A few miles to the southeast there is a set of east-west trending, arcuate, semi-parallel lineaments. In the U-2 photos, these have the appearance of thin, rather sharply defined, topographic lines. Can be seen in both cultivated and uncultivated fields. Ground examination revealed no detectable offset along lineaments (Sandness and Others, in press).
II-27 K-K'	U4	4 (6)	N65°E	Lineament northwest of Benton City, Washington. Located at southeast "end" of Rattlesnake Ridge. Coincides with approximate position of Corral Creek anticlinal axis (Plates II-7, III-1).
II-28 A-A'	K14	9 (14)	N5°W	Coincides with known fault west of McNary Dam (Plate II-8). Apparent in imagery as distinct eroded ridge.
II-28 B-B'	K4	9 (14)	N60°E	Coincides with known fault along north flank of Patterson Ridge (Plate II-8) (T6N, R26E). Visible in imagery as sharp topographic break roughly on line with 2 shorter lineaments along its northeast projection. The 3 segments were all seen as one lineament on the Landsat imagery, but no connection was seen on the U-2 photos.

*See page II-96 for explanation of photolineament classification symbol.

Table II-8 (continued)

PLATE AND DESIGNATION	SYMBOL*	LENGTH MILES (Kilometers)	STRIKE	COMMENTS
II-28 C-C'	U4	3 (5)	N65°E	Coincides with approximate location of anticlinal crest line (Plate II-8). Area of several landslide zones (Golgotha Butte [T4N, R23E]).
II-29 A-A'	U6	8 (13)	N35°W	Alignment of 4, and possibly 6, volcanic cones west and northwest of Goldendale, Washington (T4N, R16E). Four cones have strong northwest-southeast alignment, the southernmost being just north of Rockhouse (T4N, R15E). Two others southwest of Goldendale are slightly east of the line extended from the first 4 cones, and could be placed on the same lineament. Lineament between, and nearly parallel to, the Goldendale and Warwick structures (Plate II-9), suggesting fault control for this volcanism. Lineament also nearly colinear with a known fault at its north end (Plate II-9).
II-29 B-B'	KLSU KLU34	30 (48)	N40°W	Warwick structure (Plates II-9, II-20). One of most easily seen lineaments on imagery. Traceable for about 2 miles (3.2 kilometers) into Oregon and northwest to Camas Prairie (T5N, R21E) by distinct color and topographic alignments.
II-29 C-C'	U3 U4 LU14 KLU3	30 (48)	N40°W	Laurel structure (Plates II-9, II-20). Can be seen as a color or tonal lineament on Landsat and Skylab images from Fifteen Mile Creek in Oregon (T2N, R15E) to Camas Prairie (T5N, R21E). Its northern half is expressed in U-2 photos as stream and topographic alignments, but its southern half is not readily discernible in those photos.

*See page II-96 for explanation of photolineament classification symbol.

Table II-8 (continued)

PLATE AND DESIGNATION	SYMBOL*	LENGTH MILES (Kilometers)	STRIKE	COMMENTS
II-29 D-D'	L3U3	22 (35)	N25°W	Goldendale structure (Plates II-9, II-20). Extends from point north of Rufus, Oregon (T3N, R17E), through Goldendale, Washington, and out of the map area west of Indian Rock (T6N, R15E). On its central portion, it is clearly expressed on U-2, Landsat, and Skylab images as stream and topographic alignments, but it is weakly expressed as its northern and southern ends. Volcanic cones are scattered along its northern portion. Trends slightly more northerly than that of the Warwick or Laurel structures.
II-29 E-E'	KLU34 KLU4	36 (58)	N20°W to N45°W	Coincides with Arlington-Shutler Butte lineament (Shannon and Wilson, 1973). Extends in a gentle arc from south of Arlington, Oregon (T3N, R21E), to near Lone Pine, Washington (T6N, R18E). Expressed topographically in its southern half and mainly by stream alignments in its northern half. In area from Quartz Creek to Dairy Canyon (T5N, R18E), it seems to show a right lateral move by offset of stream channels.
II-29 F-F'	LU4 KU4	20 (32)	N55°E	Coincides with known fault (Plate II-9). Lies along southeast side of Camas Prairie (T5N, R12E). Its projection to the southwest runs into a straight portion of the Columbia River below Stevenson, Washington (T3N, R7E). Drawn in segments for most of total distance because it cannot be seen continuously on the U-2 imagery. Appears to be offset right laterally about 3.5 miles (5.6 kilometers) by the Klickitat River valley west of Grayback Mountain (T6N, R14E), east of Camas Prairie.

*See page II-96 for explanation of photolineament classification symbol.

9 2 1 2 4 9 4 1 5 3 0

Table II-8 (continued)

PLATE AND DESIGNATION	SYMBOL*	LENGTH MILES (Kilometers)	STRIKE	COMMENTS
II-29 G-G'	LU3 LU14 L1UØ LU1	36 (58)	N55°W	Lineament extending from the mouth of the White Salmon River (T3N, R10E) to Dry Creek (T6N, R7E). Lineament was seen as a tonal and topographic lineament on the Landsat and Skylab coverage, but only about two-thirds of its length could be seen on U-2 photos. Its northern end is expressed by stream alignments, its center as topography or ridge alignments, and its southern end as a tonal lineament.
II-29 H-H'	L1U0 LU1	18 (29)	N75°E	Lineament extending from Pitt (T4N, R13E) on the Klickitat River, to White Salmon, Washington (T3N, R10E). If extended to the southwest, it runs down a straight section of the Columbia River for about 8 more miles (12.8 kilometers).
II-29 I-I'	U3 KU2 KLU1 SU14 LSU14	15 (24)	N65°E to N75°E	Lineament may be an extension of known faulting that occurs along ridge paralleling Columbia River in area from Maryhill (T3N, R16E) to Rock Creek (T4N, R19E). Visible on Landsat, U-2, and Skylab imagery.
II-29 J-J'	LU4	11 (18)	N70°E	Topographic lineament extending from south of Pothole Lake (T5N, R16E) to just east of the Little Klickitat River (T5N, R17E). Lineament is northernmost member of a set of sub-parallel lineaments located between the Goldendale and Arlington-Shutler Butte structures (Plate II-9).
II-29 K-K'	LU14	9 (14)	N30°W	Luna Butte lineament (Plate II-9). Northernmost portion coincides with fault (Plate II-9).

*See page II-96 for explanation of photolineament classification symbol.

PHOTOLINEAMENT CLASSIFICATION SYSTEM

LETTER CODE	IMAGE OF DATA TYPE
N	NOAA (National Oceanic and Atmospheric Administration)
L	Landsat
U	U-2
S	Skylab
R	SLAR (Side-Looking Airborne Radar)
A	Aerial Photographs other than U-2
M	Magnetic Anomaly or Lineament
K	Known Fault
F	Data from Current Field Work

NUMBER CODE	DESCRIPTION OF LINEAMENT
Ø	Cultural Feature
	Erosional Feature without Apparent Tectonic Significance
	Lighting Artifact
	Random Alignment of Features
1	Linear Color or Tonal Pattern or Discontinuity
2	Linear Textural Discontinuity
3	Straight Stream or River Section or Alignment
4	Linear Topographic Features or Alignment of Topographic Features
5	Stratigraphic Discontinuity
6	Linear Patterns of Volcanic Features
7	Probable Joint

The stratigraphy and structure of the Cascade Range province is relatively complex in comparison to that of the adjoining Yakima Fold Belt subprovince. The contrast between the two areas is reflected by an increase in the density of photolineaments west of the plateau margin (Plates II-25, II-26, and II-28). Within the Cascade Range province, the dominant lineament trend is northwest-southeast, which conforms to most Cascade Range structures (Table II-8; Plates II-5, II-6, and II-9; Appendix G).

Photolineaments of the Yakima Fold Belt subprovince are classified primarily as stream alignments or topographic alignments seen on Landsat, U-2, or Skylab imagery. Within the central portion of the subprovince, the predominant trend of these photolineaments is northwest-southeast (Slemmons and Glass, 1977; Slemmons, 1979; Sandness and Others, in press). The singlemost conspicuous zone with this orientation is a broad belt of northwest-southeast-trending lineaments that coincides with the Cle Elum-Wallula deformed belt (Plates II-26 and II-27).

Within the Kittitas Valley region, located to the north of the Cle Elum-Wallula deformed belt, a northwest-southeast structural trend also prevails (Plate II-5). This trend is expressed by photolineaments classified as stream and topographic alignments (Table II-8; Plate II-25). The strike of the Badger Mountain anticline and Coulee monocline, located in the northernmost area of the subprovince (Plate II-20), is also paralleled by photolineaments classified predominantly as stream alignments (Table II-8; Plate II-25).

Within the Goldendale, Washington area (located to the south of the Cle Elum-Wallula deformed belt), the predominant photolineament trend (northwest-southeast) is consistent with structures such as the Arlington Shutler Butte, Luna Butte, Laurel, and Warwick (Plates II-20 and II-29). The next most predominant photolineament trend in the area, northeast-southwest, parallels the trend of a group of known folds (such as the Horse Heaven Hills and Columbia Hills structures) and faults (such as the fault south of Camas Prairie [Plate II-19]). Fewer photolineaments in the Goldendale area (Plate II-29) have a north-south trend; rarely do any (as for example the Alder Creek lineament [Table II-8]) approach an east-west trend. Photolineaments within the Goldendale area are predominantly classified as stream alignments seen on Landsat, Skylab, or U-2 images or a combination of these. To the west of Goldendale, in the vicinity of the Cascades Range province, photolineaments associated with alignments or volcanic cones are common (Plate II-29). As previously discussed, such alignments may be structurally controlled (Shannon and Wilson, 1973a; Swanson and Others, 1979a).

A general comparison between geologic and photolineament maps indicated that Yakima Fold Belt structures with distinct topographic reflections are best identified using the remote sensing techniques described in Appendix A. Furthermore, such a comparison showed that an evaluation of the geologic significance of Landsat lineaments was greatly enhanced through the use of U-2 and Skylab photography. However, it was found that faults parallel to ridges are usually more difficult to identify than features that have an oblique or perpendicular orientation.

In addition, low-angle faults, such as thrusts, are also not readily identifiable because of the small amount of vertical displacement visible at the surface. Although well suited for a regional overview, U-2 and Skylab imagery does not have the resolution of large-scale imagery and subtle geologic features may have gone undetected. Additional work is planned to evaluate selected areas of the subprovince using larger scale photography.

Although photolineament maps serve to indicate the general structural trend of the Yakima Fold Belt subprovince, there are many more lineaments than mapped structures. Possible causes for such photolineaments are varied, but may include: (a) cultural features; (b) structures missed during mapping; (c) regional joints; and, (d) landforms attributable to geomorphic rather than to structural processes. The structural significance (if any) of these photolineaments can only be evaluated after a more thorough integration of field and remote sensing data is conducted.

PALOUSE SUBPROVINCE

The Palouse subprovince is located in the northeastern portion of the Columbia Plateau province (Figure II-2). The subprovince is underlain by basalt flows with a regional dip of less than 5 degrees to the southwest. In general, the area is structurally simple, with the most prominent structures consisting of broad folds with tens of feet (meters) of amplitude (Swanson and Wright, 1978). Reconnaissance geologic maps covering this subprovince are included as Plates II-1 through II-4, II-7, and II-10. A generalized structural map of the subprovince, compiled from these plates, is shown in Plate II-20. Structural features to be discussed in more detail include the Cheney fracture zone and the Palouse Hills alignment.

Cheney Fracture Zone

An area of prominent regional joints near Cheney, Washington was first described by Griggs (1976) and is informally termed the Cheney fracture zone (Plates II-1 and II-20). The fracture zone consists of three sets of parallel lineaments located in an area where waters of the Spokane flood stripped loess from the basalt over large areas (Plates II-1 and II-20). As described by Griggs (1976), the lineaments strike about N60°W, can be traced for about 25 miles (40 kilometers), and are spaced 6 to 8 miles (10 to 13 kilometers) apart. The lineaments are marked by shallow gullies, indentations, or simply by lines of trees in otherwise grass-covered areas. Griggs (1976) suggested that these lineaments are surface expressions of narrow fracture zones along which broken rock was more easily eroded or which produced a more favorable environment for trees to grow.

The Cheney fracture zone was examined during reconnaissance mapping of the northeast portion of the plateau (Swanson and Others, 1979a; Kiver and Stradling in Rigby and Othberg, 1979) (Plates II-1 and II-11). Although the existence of the fracture zone was known previously, mapping for this project has extended its limits. The zone is now known to

extend from near Bonnie Lake (T21N, R42E) to Tyler, Washington (T22N, R40E), where it appears to be transposed easterly to Cheney (T23N, R41E). From Cheney, the fractures pass through Medical Lake, Washington (T24N, R41E) to just west of Reardan, Washington (T25N, R39E) (Kiver and Stradling in Rigby and Othberg, 1979) (Plate II-11). Current mapping by Kiver and Stradling (in Rigby and Othberg, 1979) is in agreement with Griggs (1976), who found no observable offset in late Cenozoic sediments overlying the fractures. Griggs (1976) noted that the fractures in the Spokane area are along projections of major structures in older rocks in northern Idaho. Therefore, he (Griggs, 1976) and Swanson and Others (1979a) have suggested that the fractures might reflect slight post-Priest Rapids adjustment of the basalt pile to structurally controlled topography in underlying rocks.

Palouse Hills Alignment

Within the eastern portion of the subprovince (Figure II-2), the Palouse Hills are aligned in a northeast-southwest direction. This preferred orientation can be attributed to prevailing southwesterly winds which transported loess from the western and central parts of the plateau. However, Ringe (1970) has speculated that it may be due to bedrock orientation. Ringe (1970) noted gentle undulations in the basalt surface underlying the loess in exposed areas of the basalt-loess contact. No data were gathered during reconnaissance geologic mapping of late Cenozoic sediments to clarify the origin of this apparent alignment of the Palouse Hills (Rigby and Othberg, 1979).

Photolineament Analysis of the Palouse Subprovince

Photolineament map coverage of the Palouse subprovince and the southern extent of the Okanogan province is included as Plates II-21 through II-24, II-27, and II-30. The number of photolineaments mapped in the Columbia Plateau is considerably less than that mapped in the Okanogan province. Sandness and Others (in press) concluded that the dense network of lineaments in the Okanogan Province is probably due to one or both of two causes: (a) the pre-Tertiary bedrock of most of the province is extensively folded, fractured, and faulted; and, (b) the province, except for high elevations, was covered by Pleistocene continental ice sheets; many of the shorter lineaments are oriented in the same direction as glacier movement (i.e., north-south). Specific photolineaments of known or suspected geologic significance within the Okanogan province are listed in Table II-9.

In general, photolineaments within the Palouse subprovince show two principal trends--northeast-southwest and northwest-southeast. Flood erosion caused by Pleistocene catastrophic flooding probably was a major factor in establishing the northeast-southwest trend (Sandness and Others, in press). Major photolineaments in the scablands area correspond with stream alignments or straight drainage channels oriented in this general direction. Numerous other lineaments (such as those within the southeast corner of Plate II-24) correspond with joints in the exposed basalt surface. The most prominent directional trend of the joints

TABLE II-9. Description of Specific Photolineaments of the Palouse Subprovince and Okanogan Province.

(After Sandness and Others, in press.)

PLATE AND DESIGNATION	SYMBOL*	LENGTH MILES (Kilometers)	STRIKE	COMMENTS
II-21 A-A'	FZ KU1 U1	11 (18)	N55°W	Group of lineaments coinciding with northernmost fracture zone cited by Griggs (1973, 1976). Zone can be seen in two distinct segments. One segment is near Medical Lake, Washington (T24N, R41E) and is separated from the second segment which extends to the southeast from Cheney, Washington (T23N, R42E) by a large loess "island" to the northwest of Cheney.
II-21 B-B'	FZ U1 U3	18 (28)	N55°W	Fracture zone approximately 3 miles (5 kilometers) to the southwest of lineament A-A'. Most visible area of zone is near South Cheney (T24N, R41E). Several more short segments visible over a distance of about 15 miles (24 kilometers) to the northwest.
II-21 C-C'	FZ U13 U14 LU14 KU41 KU1	30 (48)	N55°W	Most distinct of 3 fracture zones cited by Griggs (1973, 1976). Extends from near Tyler, Washington (T23N, R40E) at the edge of the loess cover, across the Cheney-Palouse scablands tract to the north end of Bonnie Lake (T21N, R42E). Zone may extend further as a pair of lineaments, coded U34 and LU3, through the loess-covered terrain, to the area south of Rosalia,

*See page II-96 for explanation of photolineament classification symbol.

Table II-9 (continued)

PLATE AND DESIGNATION	SYMBOL*	LENGTH MILES (Kilometers)	STRIKE	COMMENTS
II-21 D-D'	FZ KLU4 U1	12 (19)	N50°W	Most southerly of fracture zones cited by Griggs (1973, 1976). Can be traced from the north end of Rock Lake (T20N, R41E) to the northwest where it becomes indistinguishable among the more randomly oriented lineaments or joints seen in the scabland channels (T20N, R41E to T21N, R40E).
II-21 E-E'	U4 SLU3 LU3 LU34	58 (93)	N30°W	One of three major lineaments intersecting at the confluence of Hangman and California Creeks (T23N, R43E). It follows Hangman Creek northwestward from near Tekoa, Washington (T20N, R46E) to the Spokane area where it continues down the Spokane River Valley to Tumtum, Washington (T28N, R40E). Lineament has no visible offset over its 55-mile (88-kilometer) length according to Griggs (1973, 1976).
II-21 F-F'	LU24 LU3	36 (58)	N70°W	A second major lineament intersecting at the confluence of Hangman and California Creeks. It follows Rock Creek northwestward through Rockford, Washington (T23N, R45E), crosses Hangman Creek and extends to the vicinity of Fairchild Air Force Base (T25N, R41E). An extension of this lineament into Idaho would join a known fault (Swanson and Others, 1979a) between the southern end of Coeur d'Alene Lake and St. Maries, Idaho.

*See page II-96 for explanation of photolineament classification symbol.

Tabl^ II-9 (continued)

PLATE AND DESIGNATION	SYMBOL*	LENGTH MILES (Kilometers)	STRIKE	COMMENTS
II-21 G-G'	LU3 K LU34	20 (32)	N60°E	A third lineament to cross at the confluence of Hangman and California Creeks. It follows California Creek from Hangman Creek to near the Washington-Idaho border (T9N, R5W). A 1-mile (1.6-kilometer) long section of this lineament southwest of Saltese Creek (T24N, R45E) is a known fault (Plate II-1).
II-21 H-H'	LU4 LU34 U3	36 (58)	N35°E to N55°E	Lineament passing through Rock (T19N, R41E) and Bonnie Lakes (T21N, R42E). It extends into the southeast corner of T22N, R42E where it curves slightly eastward and intersects Hangman Creek northwest of Fairfield (T22N, R44E). Lineament easily seen on Landsat imagery except for 5-mile (8-kilometer) long segment immediately west of Hangman Creek.
II-21 I-I'	L1 U4 LU34	33 (53)	N65°W	A lineament crossing lineament H-H' at almost right angles. Entire length of lineament is seen on Landsat imagery, but only sections in the U-2 photos. At its western end, it may join lineament C-C'.
II-22 A-A'	KLU4 LU34	23 (37)	N25°E	Lineament extending south-southwest from Usk, Washington (T33N, R44E). Visible in U-2 photos as a topographic or stream lineament over its entire length. Coincides with known fault (Plate II-2) in area north of Horseshoe Lake (T30N, R43E), where it is a steep-walled valley.

*See page II-96 for explanation of photolineament classification symbol.

Table II-9 (continued)

PLATE AND DESIGNATION	SYMBOL*	LENGTH MILES (Kilometers)	STRIKE	COMMENTS
II-22 B-B'	U4 KU34	10 (16)	N60°E to N80°W	Lineament coinciding with upper Cottonwood Creek Valley (T32N, R41E), a sharp-walled valley with a northeast-southwest trend. Valley aligned with a fault (Plate II-2) with the down-thrown block on its south side. Lineament continues across the drainage divide almost to the North Fork of Calispell Creek (T32N, R42E) as an alignment of smaller stream valleys.
II-22 C-C'	U34	5 (8)	N85°W	Lineament crossing the northern part of Bead Lake (T32N, R45E). Defined by straight stream valleys both east and west of the lake and by a strong, light colored, U1 lineament across the peninsula extending into the lake from the north.
II-22 D-D'	U14	10 (16)	N50°W	Lineament extending southeast from Marshall Lake (T32N, R45E) into Idaho north of Freeman Lake to just south of Priest River (T56N, R5W). Strong topographic lineament expressed as an alignment of small valleys in the area south of Marshall Lake.
II-22 E-E'	U4 LU3 U3	8 (13)	N70°E	Lineament in T33N, R45E. Distinctive in imagery due to its steepness, straightness, and alignments with other stream valleys.
II-22 F-F'	KU4 U4	7 (11)	N30°E	Coincides with fault (Plate II-2) extending northeast-southwest through Chewelah, Washington magnesite quarry (T31N, R38-39E). Can be seen clearly on U-2 photos as one of several lineaments in that area and to the southwest. Most of these other strong lineaments are also known faults (Huntting and Others, 1961).

*See page II-96 for explanation of photolineament classification symbol.

Table II-9 (continued)

PLATE AND DESIGNATION	SYMBOL*	LENGTH MILES (Kilometers)	STRIKE	COMMENTS
II-23 A-A'	LU3 LU34 SLU134 LU34 SU3	40 (64)	N40°E to N55°E	Most prominent lineament in map area. Northeast extension of Bumping Lake lineament (see lineament B-B' of Plate II-25, C-C' of Plate II-26). Follows Columbia River northeastward from Chief Joseph Dam and continues northeastward out of valley of Columbia River past west side of Goose Lake (T31N, R28E) to headwaters of Karter Creek (T32N, R29E). Field studies in area (Sandness and Others, in press) failed to show any faulting along lineament between Chief Joseph Dam and Karter Creek.
II-23 B-B'	KSU4 KLU4 SU3 KSU34 LSU2 U2 KSU4	18 (29)	N5°E to N35°E	Numerous north-northeast-south-southwest trending lineaments coinciding with known faults and fractures (Huntting and Others, 1961) defining the western and eastern boundaries of the Republic graben (T34N, R33E to T32N, R32E).
II-23 C-C'	LU14	19 (30)	N10°E	Several strong topographic lineaments in T29-32N, R32E. Coincide with probable faults which may be a southern extension of known faulting on the east side of the Republic graben (Huntting and Others, 1961). Lineament zone possibly associated with Republic graben extends southward to the Ritzville quadrangle (Plate II-24).
II-23 D-D'	U1 U4	2 (3)	N65°W	Coincides with set of topographic lineaments in basalt south of Omak Lake (T31N, R27E). Cross-cut the trend of glacial grooves. May be preferentially eroded joint or fracture set.

*See page II-96 for explanation of photolineament classification symbol.

Table II-9 (continued)

PLATE AND DESIGNATION	SYMBOL*	LENGTH MILES (Kilometers)	STRIKE	COMMENTS
II-23 E-E'	SU3 SU34 SLU4 LSU34	30 (48)	N25°E	Lineament extending from point near Columbia River west of Brewster (T30N, R24E) to northwest of Omak (T34N, R26E). At its north end, lineament is expressed as a distinct fracture in a ridge. South of Salmon Creek (T34N, R25E) lineament follows a narrow valley and the west side of the Okanogan River Valley.
II-23 F-F'	U34	6 (10)	N5°E	Lineament with a strong topographic expression located on the east side of the ridge containing Ruby Hill (T34N, R25E). A parallel, known, north-south fault (Shannon and Wilson, 1977b) follows the Loup Creek Valley on the west side of the ridge.
II-24 I-I'	C	--	--	Coincides with ring structures present in the Sylvan Lake area east of Odessa, Washington (T21N, R33E) (McKee and Stradling, 1970; Hodges, 1978).
II-24 J-J'	LU3 LU4 L23	35 (56)	N50°E	Lineament extending in a northeasterly direction from a point east of Coulee City, Washington (T25N, R28E) to Red Wine Canyon (T27N, R35E). Well defined on its southwest portion by a long linear creek (LU3 portion) and a scabland channel (LU4 portion). Farther to the northeast, it was observed only in Landsat imagery.

*See page II-96 for explanation of photolineament classification symbol.

Table II-9 (continued)

PLATE AND DESIGNATION	SYMBOL*	LENGTH MILES (Kilometers)	STRIKE	COMMENTS
II-24 K-K'	U47 U1 U4 U7 U2 U14	5 (8)	--	Lineament group coinciding with area of dense jointing. Common where scabland flood erosion dominant. Most of the apparent joints are expressed as color or tonal lineaments, but many are topographic or drainage lineaments that have been enlarged by erosion. Prominent directional trend appears to be northeast-southwest.
II-24 L-L'	L13 L12 L1U3 U14	36 (58)	N60°W	Segmented lineament extending from Chalk Hills (T28N, R26E) in a southeasterly direction to Govan (T26N, R32E). Except for straight course of East Foster Creek, it is not well expressed in U-2 photos; prominent in U-2 imagery.
II-24 M-M'	U3 U43	10 (16)	N5°W	Lineament coinciding with a U-shaped valley about 2 miles (3.2 kilometers) wide. West side of valley corresponds to a lithologic contact between Tertiary volcanic and Mesozoic granitic rocks (Huntting and Others, 1961). An apparent north-south fault is evident along the east valley wall (Huntting and Others, 1961). A short, north-south reach of the Columbia River (Franklin D. Roosevelt Lake [T28N, R34E]) constitutes a possible southward extension of the valley as shown by the corresponding lineament.
II-24 N-N'	LU4	10 (16)	N80°W	Lineament extending eastward from the Sanpoil River. Several east-west lineaments cross Whitestone Ridge (T29N, R33E). Also a strong north-south lineament trend in this area. None of the lineaments appear to continue into the Columbia Plateau basalts.

*See page II-96 for explanation of photolineament classification symbol.

Table II-9 (continued)

PLATE AND DESIGNATION	SYMBOL*	LENGTH MILES (Kilometers)	STRIKE	COMMENTS
II-24 O-O'	U3	10 (16)	N75°W	A small spur extends eastward from the bend in the Columbia River where its course turns from north-south to east-west. A U3 lineament is shown along the alignment of that spur, the south shore of the river, and Indian Creek. That lineament is crossed by a second lineament (LU34) trending approximately north-northwest.
II-24 P-P'	U345	18 (29)	N30°W	Two lineaments along a straight section of the Spokane River. River flows through a channel in granitic rocks near the boundary between the granites and the plateau basalts (Plate II-4). At its north end, the lineament suggests a possible truncation of a northeasterly trending belt of Cambrian and pre-Cambrian rocks exposed to the northeast of the Spokane River.
II-24 Q-Q'	LU34	5 (8)	N10°W	Lineament just west of Lincoln, Washington (T27N, R35E). Located where Welch Creek flows into the Columbia River through a straight canyon. Strong parallel fractures along the south shore of the river suggest either fault or joint control of the stream.
II-24 R-R'	LU3	10 (16)	N-S	Lineament along a straight reach of the Columbia River (R27-29N, R35E). Possible indication of fault control of the river in that area.
II-24 S-S'	GM	--	--	Coincides with irregular arc formed by terminal moraine. Extends from McNeil Canyon (T27N, R24E) in the northwest to the west shore of Banks Lake (T25N, R28E). Clearly visible over this distance as a textural change from the smooth, loess-covered basalt on the south side to the hummocky gravel terrain north of the moraine.

*See page II-96 for explanation of photolineament classification symbol.

Table II-9 (continued)

PLATE AND DESIGNATION	SYMBOL*	LENGTH MILES (Kilometers)	STRIKE	COMMENTS
II-24 T-T'	W	--	--	Large area of active sand dunes present in Potholes Reservoir area (T18N, R27-28E).
II-24 U-U'	LU3 U2	29 (46)	N25°E	Lineament drawn down the length of Grand Coulee. Aligned with the west side of the Republic graben (Plate II-23).
II-27 L-L' M-M'	LU3 LU34	48 (76) 34 (54)	N50°E N55°E	Two long, parallel lineaments, one located just north of the Snake River, the second north of Walla Walla, Washington (T7N, R36E). Best expressed in Landsat imagery, but can be seen as discontinuous segments in U-2 photos.
II-27 N-N' O-O' P-P' Q-Q'	L1 L1 L1 KLU12 L1	24 (38) to 6 (10)	N45°W to N60°W	Set of 4 sub-parallel lineaments in the Eureka Flat-Snake River area. Visible only as color discontinuities in Landsat imagery and are labeled L1. Northwestern end of northernmost lineament in group well defined in U-2 photos. Also plotted as fault near Scott Station (Plate II-4; T12N, R34E) on Snake River.
II-27 R-R'	LU3	17 (27)	N80°E	Alignment of stream segments. Lineament is plotted as an LU3 lineament near Connell, Washington (T14N, R31E).
II-27 S-S'	LU3	4 (6)	N45°W	Lineament located east of Wooded Island on the Columbia River (T11N, R28E).

*See page II-96 for explanation of photolineament classification symbol.

Table II-9 (continued)

PLATE AND DESIGNATION	SYMBOL*	LENGTH MILES (Kilometers)	STRIKE	COMMENTS
II-27 T-T'	LU3	10 (16)	E-W	Lineament coinciding with Touchet River between Lamar and Prescott (T9N, R34-35E). Touchet River flows westward along a linear course for at least 10 miles (16 kilometers) before turning abruptly southward near Lamar. Lineament crosses general northeast-southwest trend in this area.
II-27 U-U'	U4	3 (5)	N30°W	A distinctive topographic lineament crossing a basaltic ridge between the Tucannon and Snake Rivers near Starbuck, Washington (T12N, R37E).
II-30 A-A'	KU4 KU34 KU3	22 (35)	N15°W	Coincides in part with fault (Plate II-10). Long south-southeast trending lineament from near Central Ferry (T13N, R40E), on the Snake River to the junction of Cummings Creek and the Tucannon River. North of Pataha Creek, lineament is visible on imagery as discontinuous stream segments and linear topographic alignments. Better expressed south of Pataha Creek, where a portion of the lineament follows the Tucannon River.
II-30 B-B'	L1U3	15 (24)	N60°E	Lineament extending northeastward from Clear Creek (T16N, R44E). Lineament well expressed as a line of color contrast on Landsat imagery, and as aligned segments of stream drainage on U-2 photos. However, in southwest corner of T17N, R45E it is not readily apparent, and from the central portion of T17N, R45E to the northwest, lineament is only slightly visible on imagery.

*See page II-96 for explanation of photolineament classification symbol.

appears to be northeast-southwest. Specific photolineaments of known or suspected geologic significance within the Palouse subprovince are listed in Table II-9.

BLUE MOUNTAINS SUBPROVINCE

The Blue Mountains subprovince is located in the southeastern part of the Columbia Plateau (Figure II-2). Most of this subprovince is within Oregon, an area where regional geologic mapping and remote sensing studies have yet to be completed for Rockwell Hanford Operations. Only the extreme northeastern part of the subprovince extends into Washington and is covered by geologic and photolineament maps included in this report.

The Blue Mountains subprovince is a broad anticlinal arch uplifted in Miocene-Pliocene time. This broad arch extends from central Oregon and continues northeast and east to the Snake River Canyon (Figure II-2). The general northeast trend of the Blue Mountains Uplift is cut by a series of north to northwest-trending, near-vertical faults, similar in nature to those developed in the High Lava Plains province to the south (Figure II-2).

The "core" of the Blue Mountains Uplift is composed of folded, faulted, and metamorphosed rocks of upper Paleozoic and Mesozoic age. Within the southwestern portion of the subprovince, this core is overlain primarily by lavas and volcaniclastic sediments (Eocene to Miocene in age) and by flows of the Picture Gorge Basalt. In the vicinity of the map area, this core is mantled by flows of Imnaha and Grande Ronde Basalts, except for small outcrops of pre-Tertiary rocks along the Tucannon River (T9N, R40E), Cummings Creek (T9N, R41E), and Menatchee Creek (T15N, R43E) (Plate II-10) (Swanson and Others, 1977). Named structures within the map area include the Hite fault, the Saddle Butte anticline-Grouse Flat syncline, the Limekiln fault, the Lewiston structure, and the Buroker fault(s). These five structures and selected photolineaments in the map area are discussed in the remainder of this subsection.

Hite Fault

The Hite fault is a 100-mile (160-kilometer) long normal fault which extends from the vicinity of Tollgate, Oregon northeast to the canyon of the Tucannon River in Washington (Plate II-20). The structure continues as a monocline beyond the Tucannon River (Plate II-20). Rocks on the east side of the fault have been upthrown in relation to those on the west. Within Oregon, the trend of the fault runs parallel to the axis of the Blue Mountains Uplift and essentially defines the western extent of the structure. However, the trends of the Hite fault and the Blue Mountains Uplift diverge east of Walla Walla, Washington at the approximate location where the fault crosses the Oregon-Washington border and extends into the reconnaissance map area (Plates II-7 and II-10). Within the map area, the greatest offset along the fault is in the vicinity of Eckler Mountain (Plate II-10) (T9N, R40E), where R_2 and N_2 Grande Ronde Basalt flows on the east side of the structure abut against Frenchman Springs and Roza flows (Wanapum Basalt) on its west side.

9 2 1 2 1 9 4 1 5 1 6

The youngest Columbia River basalt flows along the trend of the Hite fault belong to the 14-15-million-year-old Roza Member (Wanapum Basalt). Basalt of this member is offset near the northern terminus of the structure (Plate II-10) (T10N, R41E), just to the southwest of the main canyon of the Tucannon River. Surficial mapping has detected no offsets in the thin mantle of late Cenozoic sediments overlying the structure within the reconnaissance map area (Webster in Rigby and Othberg, 1979). Shannon and Wilson (1973a) estimated movement along the fault to have ceased by late Miocene time.

Saddle Butte Anticline-Grouse Flat Syncline

The northeasternmost extent of the Blue Mountains Uplift in the map area was examined in detail by Ross (1978). In this area (Plate II-20), the axis of the uplift coincides with a structure termed by Ross (1978) the Saddle Butte anticline (Figure II-33). This asymmetrical anticline is developed primarily in Grande Ronde Basalt; however, isolated outcrops of basalt of Dodge (Eckler Mountain Member of Wanapum Basalt) occur near the crest of the structure. In general, the anticline has gently dipping limbs and a broad, flat hinge zone. The flows dip most steeply (as much as 70 degrees) on the south face of the structure, where they comprise what has been termed by Ross (1978) the Slide Creek monocline. Maximum structural relief between the crest of the anticline and the base of the monocline is estimated at 2,818 feet (854 meters) (Ross, 1978). Figure II-33 is a generalized cross section through the Saddle Butte anticline as interpreted by Ross (1978).

The Grouse Flat syncline of Ross (1978) lies to the south of the Saddle Butte anticline in an area referred to as the Troy Basin (Figure II-33). Here, the course of the Grande Ronde River parallels the axis of the structure. As described by Ross (1978), the east-west-trending syncline is a very broad fold with gently dipping limbs (less than 3 degrees). Beyond the west end of the syncline, dips of the flows increase slightly due to the gradual southward bending of the entire Blue Mountains Uplift (Newcomb, 1970; Swanson and Others, 1977) (Plate II-20).

The youngest known Columbia River basalt flows within the area, the Wenaha (Elephant Mountain Member equivalent) and the Buford, crop out within the trough of the Grouse Flat syncline (Figure II-33). Ross (1978) presented evidence indicating that this structure began to subside about the time of the R_2-N_2 polarity change, as most younger flows are confined to the Troy Basin. To the east, both the Saddle Butte anticline and the Grouse Flat syncline decrease in amplitude and are terminated by the Limekiln fault.

Limekiln Fault

The trace of the Limekiln fault transects the far southeastern corner of the map area (Plates II-10 and II-20). The structure extends a length of approximately 20 miles (32 kilometers) from the Washington-Oregon border northeast into westernmost Idaho. The fault is normal,

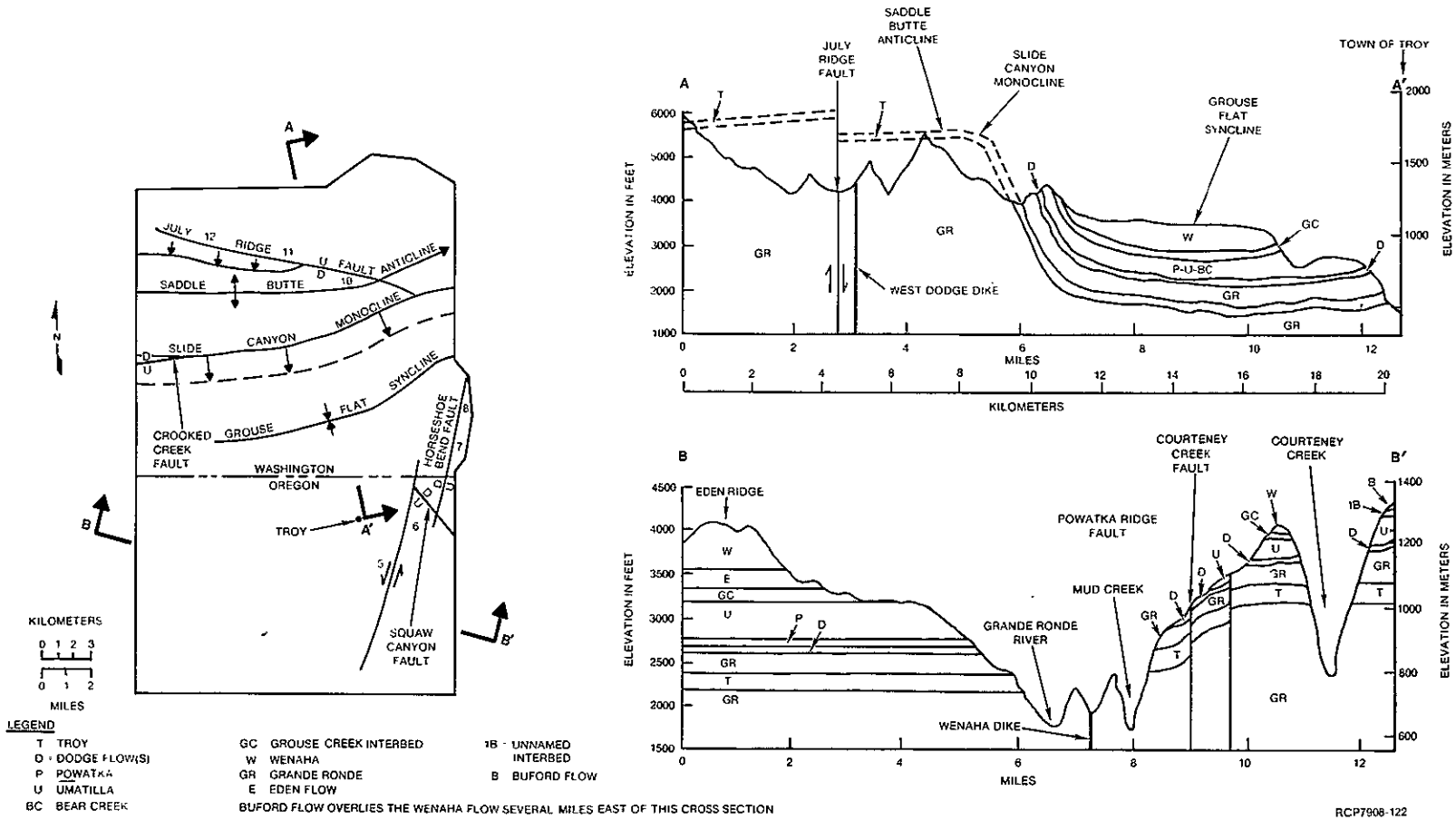

FIGURE II-33. Generalized Structural Map and Cross Sections through the Saddle Butte Structure (after Ross, 1978).

with the west block downthrown. Maximum displacement on the fault, an estimated 1,650 feet (500 meters) (Camp, 1976; Reidel, 1978b), occurs near the mouth of Joseph Creek (Plate II-10). Here, pre-Tertiary metamorphic rocks on the east side of the fault abut against Imnaha and Grande Ronde Basalt flows on the west side of the structure (Plate II-10). Less than 6 miles (10 kilometers) to the southwest, displacement along the fault decreases to less than 900 feet (273 meters) (Reidel, 1978b). To the northeast, the fault becomes a monoclinal flexure termed the Craigmont uplift (Bond, 1962).

Camp (1976) and Reidel (1978b) have proposed that formation of the Limekiln fault and the Craigmont uplift may have been syngenetic with Columbia River basalt volcanism. Reidel (1978b) found that two of the younger widespread R_2 Grande Ronde Basalt flows do not extend south of the Limekiln fault, suggesting it probably became active as early as R_2 time. These data agree with Ross (1978), who also suggested that deformation in the area began as early as R_2-N_2 Grande Ronde time. The absence of post-Grande Ronde Basalt flows in the vicinity of the Craigmont uplift suggests that it was definitely a "topographic" high by Wanapum time (Camp, 1976; Reidel, 1978b). Movement along the Limekiln fault (and development of the Craigmont uplift) is suspected to have terminated by the end of Miocene time; however, the minimum age of the structure has yet to be determined with certainty.

Lewiston Structure

The east-west-trending zone of complexly folded and faulted basalt flows north of Lewiston, Idaho and Clarkston, Washington is referred to as the Lewiston structure (Plate II-20). This structure separates the Uniontown Plateau to the north from the Lewiston Basin to the south, and partially extends into the map area (Plate II-10). The structure has been studied in most detail by Camp (1976) and information included in this section has been condensed from his work. Figure II-34 is a cross section through the structure showing the general stratigraphy and geometry of the deformed zone.

The Lewiston structure is a sharply asymmetrical, plunging anticline termed the Gaging Station anticline, which has been faulted on its south limb by the Wilma fault and on its north limb by the Vista fault (Figure II-34). The maximum vertical displacement along the Wilma fault is 2,000 feet (600 meters), with the north side upthrown. Displacement on the Vista fault is 900 feet (275 meters), with the south side upthrown (Figure II-34). The basic structure as envisioned by Camp (1976) is an upthrown block or horst (Figure II-34).

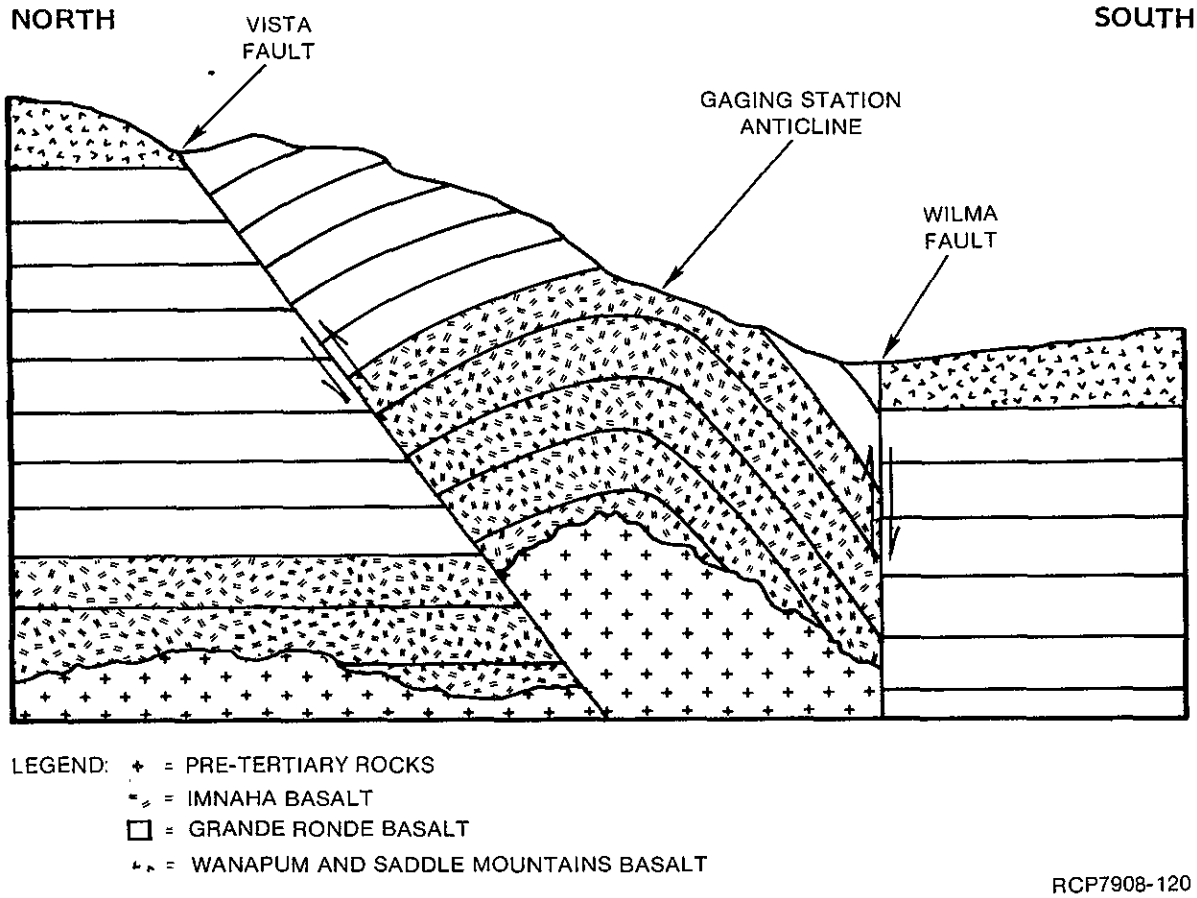

FIGURE II-34. Generalized Cross Section through Lewiston Structure (after Camp, 1976).

The portion of the Lewiston structure extending into the map area is the most severely deformed area of the uplift and has been described by Camp (1976) as follows.

> "The most severe deformation occurs northeast of Silcott, Washington, where the Snake [River] makes an abrupt bend to the north. In this area, the east-west-trending Gaging Station anticline swings to the southwest and plunges in that direction by approximately 10 degrees. The north limb of the anticline dips gently down to the northwest and then swings back up in the same direction creating an adjoining syncline which is truncated by the Vista fault. The structure in this area can thus be envisaged as a horst containing a plunging anticline-syncline pair."

To the east of Lewiston, Idaho, structural deformation gradually decreases, the Vista and Wilma faults show less displacement, and the Gaging Station anticline becomes monoclinal.

Available evidence indicates that the Lewiston structure began to form in late Grande Ronde time (Camp, 1976). During reconnaissance geologic mapping in the area, no offset of late Cenozoic sediments was observed. However, sediment cover along the structure is sparse (Webster in Rigby and Othberg, 1979).

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Buroker Fault(s)

Reconnaissance mapping of sediments within the Blue Mountains subprovince (Plate II-16) showed the presence of two minor faults which cross-cut late Cenozoic sediments. One of these faults is a small reverse fault in basalt exposed in a roadcut southeast of Walla Walla in the Buroker quadrangle (T7N, R37E). This fault appears to cut overlying fluvial gravels and an older loess, but does not deform overlying, younger loess. The age of these sedimentary units currently is not known; hence, age limits for the structure are not yet established. A second nearby fault, cutting the basalt (Frenchman Springs Member), is probably related to the previously described structure.

Photolineament Analysis of the Blue Mountains Subprovince

The photolineament map covering that portion of the Blue Mountains subprovince located in Washington State is included as Plates II-27 and II-30. Most photolineaments greater than 5 miles (10 kilometers) long correspond with the trends of mapped structures; i.e., the Hite fault, the Saddle Butte anticline-Grouse Flat syncline, and the Limekiln fault. Of the remaining photolineaments, most are classified as straight stream or river section alignments (Sandness and Others, in press). Significant numbers of such streams are consequent, with sources coinciding with slopes produced by deformation; as such, they generally reflect structural dip. Just north of the Washington-Oregon border (Plate II-30), several photolineaments are aligned in a north-south direction, similar to the trend shown by structures within the High Lava

Plains province (Figure II-2). Specific photolineaments of known or suspected geologic significance within the Blue Mountains subprovince are listed in Table II-10.

REGIONAL GEOMORPHOLOGY

CONTENTS

This section contains a general discussion of landforms and currently active geomorphic processes within the Washington State portion of the Columbia Plateau province. Physiographically, this area lies within the Columbia Basin and Central Highlands subprovinces of the Columbia Intermontane province as defined by Freeman and Others (1945) and Thornbury (1965). These two physiographic subprovinces have been further subdivided into 12 sections, 6 of which are located within the study area (Figure II-35). These sections include the: (a) Yakima Folds section; (b) Channeled Scablands section; (c) Central Plains section; (d) Waterville Plateau section; (e) Palouse Hills section; and, (f) Blue Mountains section (Figure II-35). The geomorphic discussion which follows is organized around these 6 physiographic subdivisions.

YAKIMA FOLDS SECTION

The dominant topographic features of the Yakima Folds section (Figure II-35) are the series of anticlinal ridges which rise as much as 1,700 feet (515 meters) above adjacent synclinal troughs or valleys. Major through-going drainages of the subprovince include the Columbia and Yakima Rivers. These drainages have cut prominent water gaps through several of the anticlinal structures. Lesser drainages of the section generally have courses which coincide with synclinal valleys.

The Yakima Folds section lies within the rain shadow of the Cascade Range and has a semi-arid, but moderate, climate. As a result, present-day aggradational and degradational processes are limited. Along ridge summits and upper ridge slopes, aggradational processes are predominantly eolian, consisting of loess deposition. Mass-wasting is the most prominant degradational process. Mass-wasting landforms include earth flows, slump blocks, and landslides, the most extensive of which are noted on regional geologic and photolineament maps contained in this report (Plates II-1 through II-19 and II-21 through II-30). However, many of these mass-wasting landforms originated when climatic conditions in the section were pluvial and frost action processes greater. Present-day erosion of the ridge summits and upper ridge slopes is principally by fluvial processes which have formed an extensive network of "V"-shaped rills and gullies arranged in parallel or dendritic patterns.

TABLE II-10. Description of Specific Photolineaments of the Blue Mountains Subprovince.

(After Sandness and Others, in press.)

PLATE AND DESIGNATION	SYMBOL*	LENGTH MILES (Kilometers)	STRIKE	COMMENTS
II-27 V-V'	KLU4	9 (14)	N5°W	Kooskooski lineament. Known fault (Plate II-7) located about 10 miles (16 kilometers) east of Walla Walla, Washington (T7N, R36E). Distinct topographic expression visible in Landsat and U-2 imagery.
II-30 C-C'	KLU34 KLU3 KU4 KU31	51 (82)	N20°E to N40°E	Coincides with Hite fault (Plate II-10). Fault is clearly visible on both Landsat and U-2 imagery from southwest corner of map area to near Pomeroy, Washington (T37N, R42E), fault only apparent in a few localities along its trace. Northwest of Eckler Mountain (T9N, R40E), lineament appears to be offset (right laterally) about 1 mile (1.6 kilometers) along a small stream.
II-30 D-D'	KU4	12 (19)	N20°E	Lineament coinciding with Limekiln fault.
II-30 E-E'	U4	3 (5)	N60°E	Coincides with distinct, arcuate topographic lineament (U4) north of Snake River west of Clarkston, Washington (T35N, R45E). Lineament crosses at least 5 spurs and seems to offset several of the gullies between spurs. A marked difference in stratigraphic attitudes on the opposing sides of the river also suggests a fault along the river near Silcott. Coincides with trend of Lewiston structure (Plate II-10).

*See page II-96 for explanation of photolineament classification symbol.

9 2 1 2 1 9 1 5 5 3

Table II-10 (continued)

PLATE AND DESIGNATION	SYMBOL*	LENGTH MILES (Kilometers)	STRIKE	COMMENTS
II-30 F-F'	LU4 U4 LU34 U34	3-12 (5-19)	N50°E to N85°W	In southeast corner of map area, particularly prominent lineaments appear to form two groups. Lineaments of first group (e.g., F-F') have a generally east-west trend and typically have the form of scarps, aligned ridge notches, or slope changes. Examples of lineaments in this group are found along the north wall of the canyon of the Grande Ronde River. Lineaments in the second group (e.g., G-G') have directional trends in the range north-northwest to north-northeast.
II-30 G-G'			N10°E to N15°W	

*See page II-96 for explanation of photolineament classification symbol.

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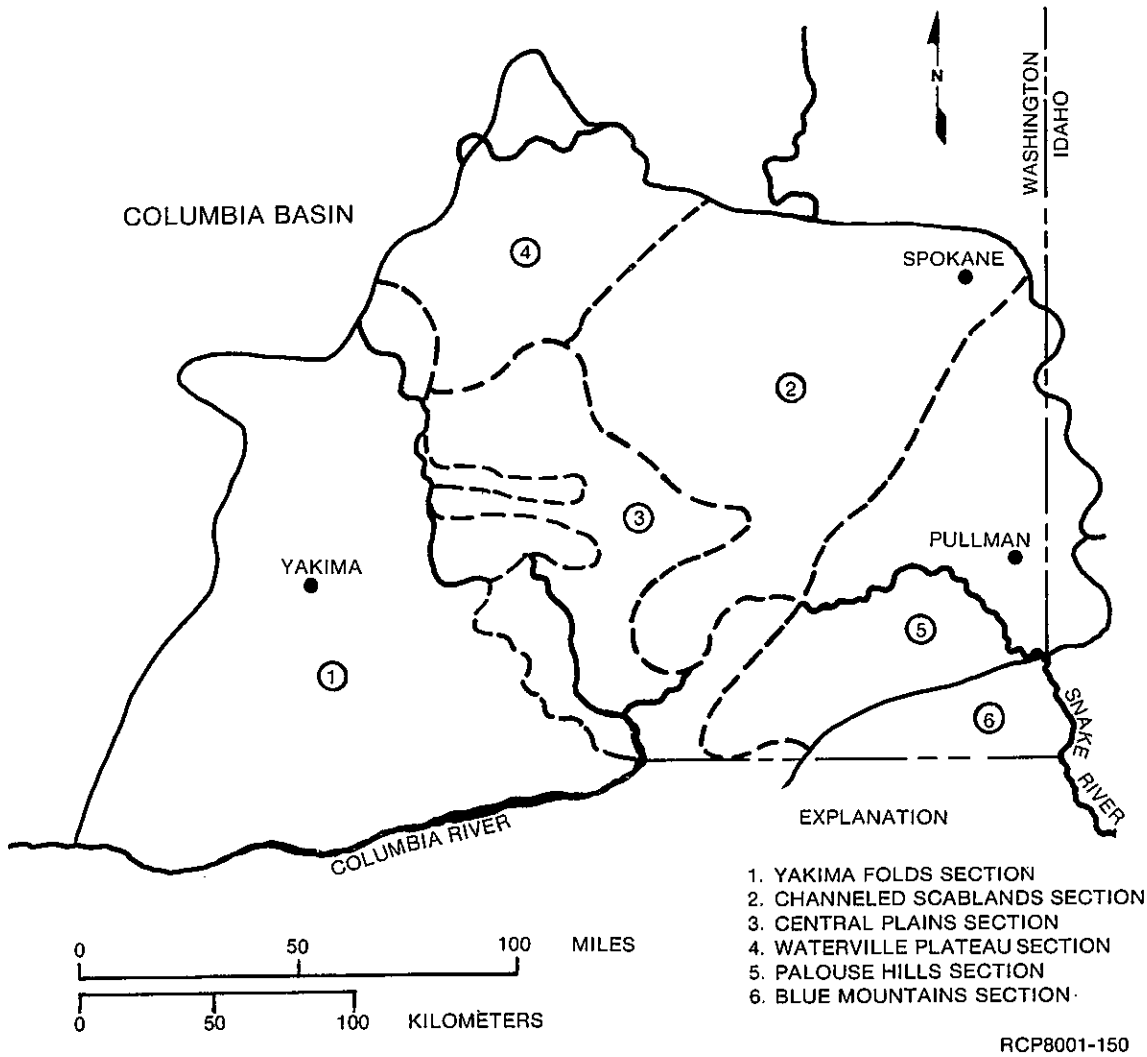

FIGURE II-35. Physiographic Subdivisions of the Columbia Basin and Central Highlands Provinces (after Thornbury, 1965).

Aggradation within the lower ridge slopes results primarily from the deposition of material derived from denudation at higher elevations. Aggradational landforms include alluvial fans, talus "aprons," and hummocky mounds comprised of basaltic and interbed debris. Degradation of lower ridge slopes is mainly by fluvial processes responsible for the production of a network of ephemeral stream gullies.

The synclinal valleys of the Yakima Folds section are filled with sediments which have been derived primarily from fluvial and glaciofluvial processes most active during the Pleistocene. Common aggradational landforms include flood plain deposits, alluvial terraces, channel fill, alluvial fans, and glacial outwash deposits. Common degradational landforms include meander scars, cut terraces, and flood channels. Present-day aggradational and degradational processes are most active within channels of the Columbia and Yakima Rivers and other perennial streams of the section.

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CHANNELED SCABLANDS SECTION

The topography of the Channeled Scablands section (Figure II-35) was created by catastrophic flood erosion of loess and basalt. The colossal volumes of water which sculptured this section were released by the failure of ice dams impounding extensive glacial lakes located to the northeast of the plateau. The most prominent features of the Channeled Scablands section are the elongated, steep-sided, anastomosing bedrock channels, termed coulees (Figure II-36). Common coulee landforms include remnant sediment islands, giant gravel bars, giant ripple marks, cataracts, plunge pools, and rock basin lakes. Intercoulee areas are comprised of buttes, mesas, and plateau tracts generally covered by rolling hills of loess.

The climate of the Channeled Scablands section is semi-arid, and present-day fluvial processes are insignificant compared to those which were active during the Pleistocene catastrophic floods. Drainage within the section is intermittent, and fluvial aggradation and degradation are generally active only during times of spring runoff. Currently active eolian processes are responsible for the accumulation and redistribution of loess and for the maintenance of dune fields.

CENTRAL PLAINS SECTION

The Central Plains section is located in the approximate center of the study area (Figure II-35). This section contains the Quincy Basin and the Pasco Basin, two major structural downwarps bounded by eastward-projecting anticlinal ridges of the Yakima Folds section (Figure II-35). Both the Quincy and Pasco Basins are filled with thick accumulations of sediments which were derived primarily from fluvial and glaciofluvial processes active during the Pliocene and Pleistocene. The basins served as major depocenters for catastrophic flood sedimentation and contain both aggradational and degradational landforms attributable to the action of floodwaters.

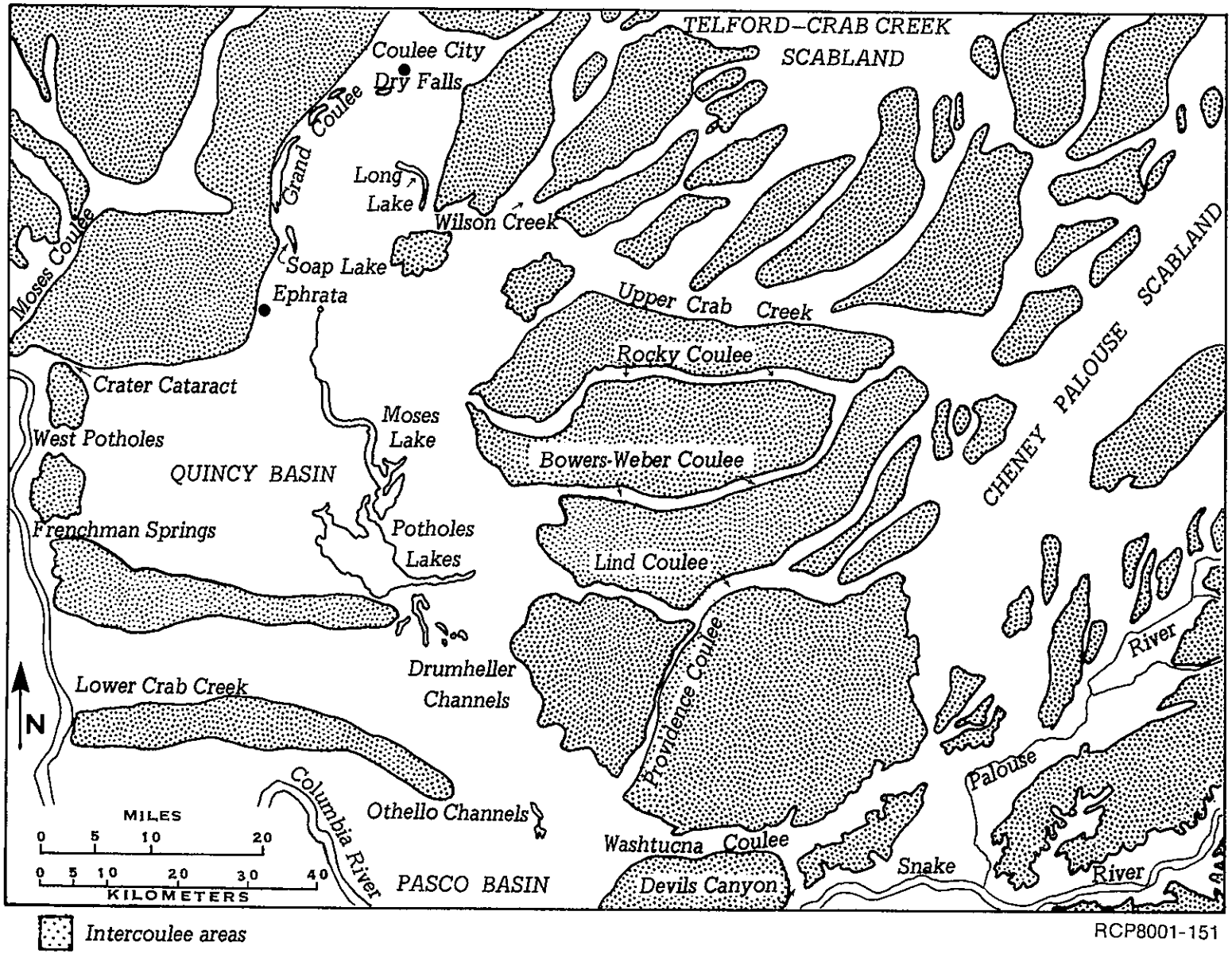

FIGURE II-36. Major Coulees of the Channeled Scablands.

The climate of the Central Plains section is semi-arid, a controlling factor of present-day geomorphic processes. Major drainages of the section, the Columbia, Snake, and Walla Walla Rivers, derive most of their waters from outside the Columbia Basin subprovince. Hence, fluvial aggradational and degradational processes are most active within the channels and flood plains of these rivers. Eolian aggradational and degradational processes are also currently active within the section. Such processes are responsible for the maintenance of large barchan dune fields, comprised primarily of Pleistocene glaciofluvial flood deposits. The larger of these fields are located on geologic maps (Plates II-4, II-7, II-13, and II-16) and photolineament maps (Plates II-24 and II-27). Eolian processes are also responsible for loess deposits which mantle much of the terrain of this section.

WATERVILLE PLATEAU SECTION

The Waterville Plateau section, located at the northwest corner of the Columbia Basin subprovince (Figure II-35), is underlain by an accumulation of nearly horizontal Columbia River basalt flows. Landforms of this section are attributable primarily to direct and indirect effects of Pleistocene glaciation. The Waterville Plateau is the only known area of the Columbia Basin subprovince to be overriden by glacial ice, and much of the section is mantled by deposits of the Withrow moraine (see Plates II-12, II-13, II-23, and II-24 for geologic and photolineament maps which defined the approximate extent of this moraine). The most prominent of these deposits includes ground moraine, eskers, and large basalt erratics locally termed "haystack rocks." The Waterville Plateau section is also dissected by a number of coulees (i.e., Grand Coulee and Moses Coulee), which were cut by Pleistocene catastrophic flood waters.

The dominant drainage of the Waterville Plateau is the Columbia River which skirts the northern and western boundaries of the section. Here, the river flows through an 1,800-foot (545-meter) deep canyon which was partially cut by Pleistocene catastrophic flooding. Extending down the Columbia River Valley (from the mouth of the Okanogan River to below the mouth of the Chelan River [Plates II-12 through II-14]) is the "Great Terrace," first described by Russell (1893). The origin of this "terrace" is still not known with certainty. However there is little doubt that deposits from glacial outwash contributed to its formation (Rigby and Othberg, 1979).

In the Waterville Plateau section, modern aggradational and degradational processes are minor. These processes are most active along the current course of the Columbia River and within steep-walled coulees (i.e., Grand Coulee and Moses Coulee). During Holocene time, much of the surface of the section has been virtually undissected. Eolian processes are responsible for the maintenance of a thin layer of loess which mantles much of the Waterville Plateau area.

PALOUSE HILLS SECTION

The Palouse Hills section (Figure II-35) of the Columbia Basin subprovince is mantled by an accumulation of eolian loess up to 225 feet (75 meters) thick. The loess has been dissected to form a topography of rolling hills with relief generally less than 350 feet (106 meters). The average elevation of the Palouse Hills declines from northeast to southwest, reflecting the gentle southwest slope of the underlying basalt surface. Along the eastern margin of the section, remnants of pre-basalt topographic highs, termed "steptoes," protrude through the loess cover.

The formation of the Palouse Hills is attributable to eolian processes active since the Pleistocene. In general, the hills are asymmetrical and many show a distinct northeast-southwest alignment, possibly reflective of the prevailing wind direction. Loess accumulation is still ongoing within the section and is most active on the northeast-facing slopes of the hills.

The Palouse Hills section has a moister climate than more western sections of the Columbia Basin subprovince. Precipitation retained by the loess cover enhances earth flow, earth creep, and frost heaving within the area. Landforms attributable to these mass-wasting processes are particularly evident on the steeper hill slopes. Fluvial processes are active along the mature, superposed drainage system of the section, especially during times of spring runoff.

BLUE MOUNTAINS SECTION

Within the study area, the Blue Mountains section (Figure II-35) is an area of high relief that has been deeply dissected. Major drainages of the area, the Snake, Grande Ronde, and Tucannon Rivers, have cut deep, narrow canyons exposing thick sections of Columbia River basalt. Along canyon walls, mass-wasting and erosional processes are most active and are responsible for landsliding, slumping, and talus formation--especially along interbed horizons. Fluvial processes are also most active along the canyon-cutting drainages. Secondary streams of the section commonly exhibit "annular" courses reflective of structural dip-slopes.

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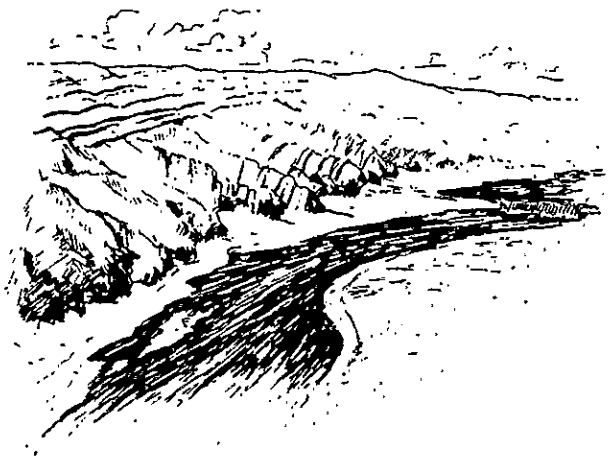
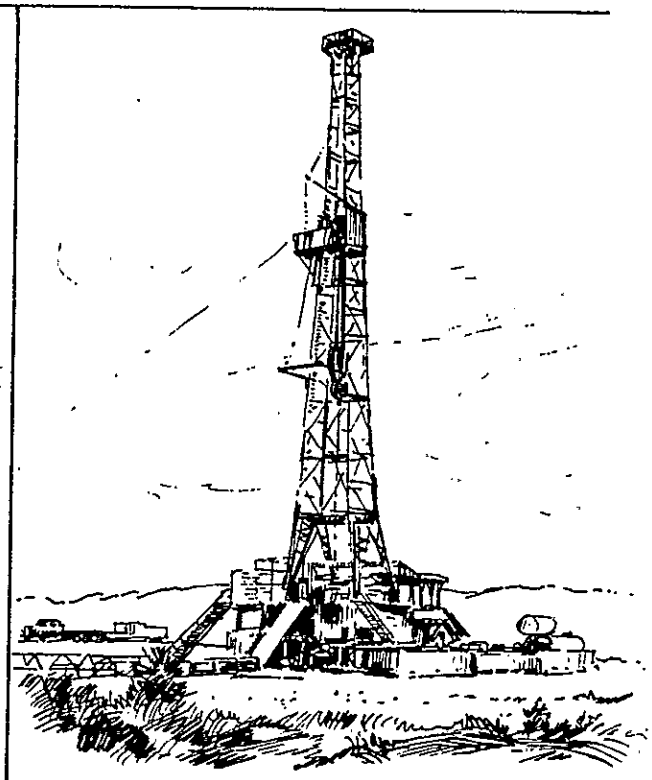
PASCO BASIN GEOLOGY





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CHAPTER III

PASCO BASIN GEOLOGY

INTRODUCTION

The results of geological and geophysical studies in the Pasco Basin, primarily as they relate to the stratigraphy and structure of the Columbia River Basalt Group, are presented in this chapter. Most of these studies were conducted during fiscal years 1977 to 1979 by Rockwell Hanford Operations and subcontractor geologists and geophysicists.

PASCO BASIN STUDY AREA

The Pasco Basin (Figure III-1) is one of several structural and topographic basins within the western Columbia Plateau. The Pasco Basin is partly surrounded by large anticlinal ridges, the Yakima Folds, that developed during Miocene and Pliocene time. The Saddle Mountains form the northern boundary of the Pasco Basin, Umtanum Ridge and Yakima Ridge form the western boundary, Rattlesnake Hills and Horse Heaven Hills form the southern boundary, and a broad zone of gradually increasing westward dip forms the eastern boundary. Umtanum Ridge and Yakima Ridge plunge eastward, decrease in relief, and die out within the basin interior.

The Pasco Basin occupies about 2,000 square miles (5,180 square kilometers) between 46°00' and 46°50' north latitude, and 119°00' and 120°20' west longitude. It is a semiarid steppe with a sparse covering of vegetation. Descriptions of the climate, soil, vegetation, terrain, and other aspects of the geography of the basin are in reports that describe the Hanford Site environment (Stone and Others, 1972; Fecht, 1978; ERDA, 1975; Brown and Isaacson, 1977).

The Pasco Basin is underlain by a bedrock section of the Columbia River Basalt Group at least 4,800 feet (1,460 meters) thick. This bedrock section is overlain by 0 to 700+ feet (220 meters) of fluvial, lacustrine, and glaciofluvial sediments of Pliocene and Pleistocene age, with the greater sediment thicknesses in the synclinal positions in the basin interior. Volcaniclastic sedimentary layers are interbedded between the basalt flows in the upper part of the bedrock section. Many of the basalt flows throughout the bedrock section are apparently blanket-like and extend laterally as single rock-stratigraphic units (and time-stratigraphic units) across the Pasco Basin and beyond; whereas other flows are less extensive, although still blanket-like, and pinch out within the basin. A few flows in the upper part of the section were emplaced as valley fills and are restricted in their lateral extent.

Yakima Folds bound the Pasco Basin on the north and south and plunge eastward into the basin from the west. Structural deformation that formed the Yakima Folds was occurring during deposition of the younger basalt flows and sedimentary interbeds. Consequently, these

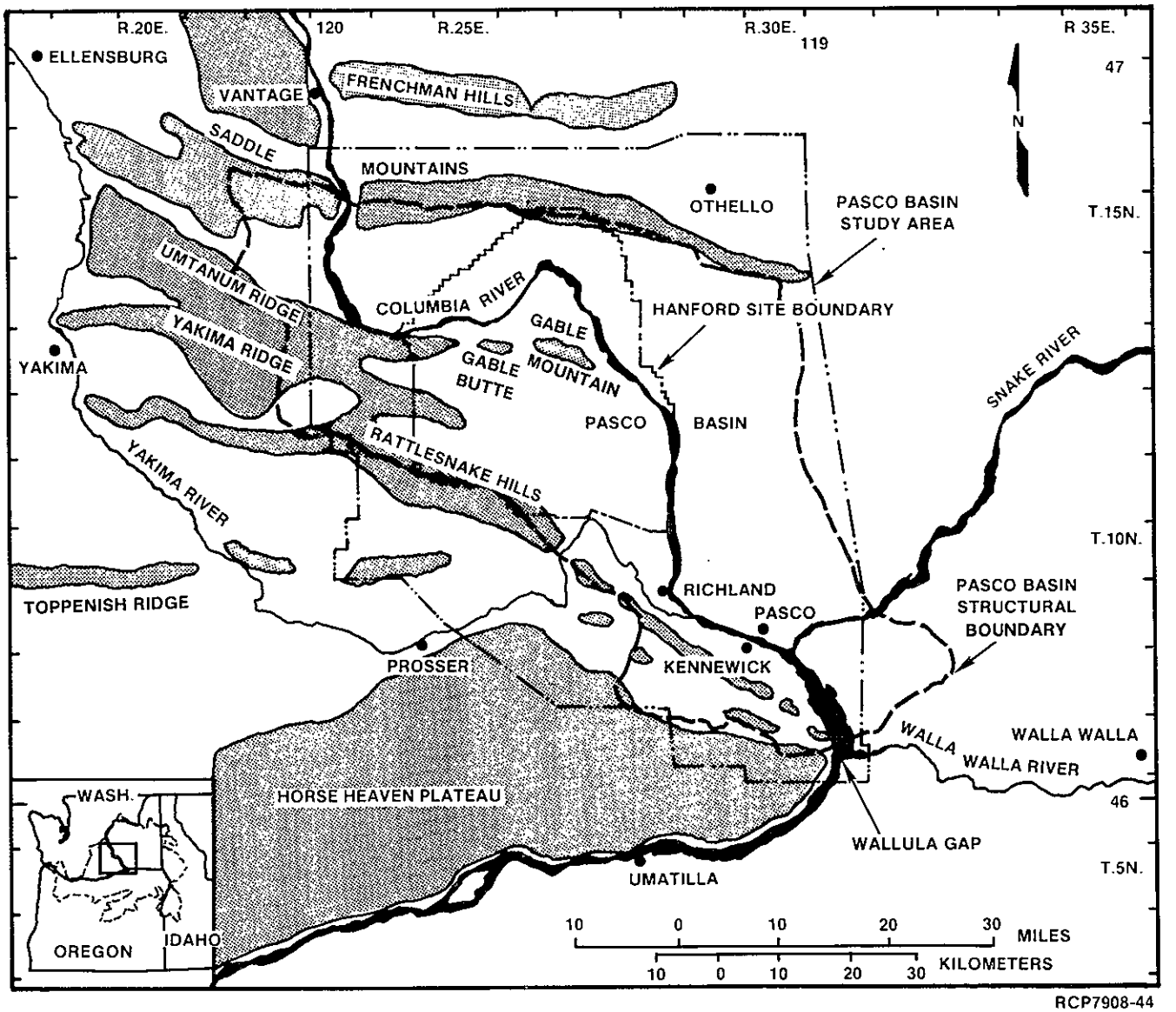

FIGURE III-1. Pasco Basin Study Area.

younger units are thick in synclines and thin or pinch out toward anticlines. Most anticlines are asymmetric and have second-order folds in their hinge zones. Their style of deformation changes along strike and their steep flanks are commonly faulted where structural relief is high. Synclines between the anticlines are generally broad, open folds. Drill holes and geophysical surveys reveal that most subsurface structures in the central Pasco Basin appear to be extensions of the Yakima Folds and their associated second-order structures, but a few subsurface structures might be related to northwest-trending structures that appear to cross-cut the east-west-trending Yakima Folds.

The boundary of the Pasco Basin study area (Figure III-1) was selected primarily on the basis of where detailed geological and geophysical information was needed. This boundary does not coincide exactly with the topographic or structural boundary of the Pasco Basin, but the studies encompassed nearly the entire Pasco Basin and, in places, included ridges and exposures beyond the basin boundary. Many investigations were concentrated in the central part of the Pasco Basin, across the southern part of the Hanford Site.

PREVIOUS WORK

Basalt

See the section on Previous Work in Chapter II for a discussion of early work on the Columbia Plateau by the U.S. Geological Survey. Also described in Chapter II is the evolution of Columbia River basalt stratigraphic nomenclature and the history of efforts to identify and correlate individual basalt flows. The discussion of previous work in this chapter is limited to that directly related to Pasco Basin geology.

Between 1920 and 1960, several theses and published papers expanded the general geologic understanding of the Pasco Basin. Shedd (1925) published a geologic map of the Prosser and Pasco 30-minute quadrangles; Twiss (1933) investigated the general structure and stratigraphy of the eastern Saddle Mountains; and, Hammer (1934) discussed the relationship of the Rattlesnake Hills structure to the Rattlesnake Hills gas field. In 1945, Raisz identified the Olympic-Wallowa lineament; a segment of the lineament forms the southern and western margins of the Pasco Basin. Mason (1953) investigated Ellensburg Formation sediments interbedded with basalt along the western margin of the Pasco Basin. Waters (1955), Laval (1956), and Mackin (1961) traced and named flows throughout portions of the Pasco Basin. Waters' paper detailed areas west of the basin, but described portions of the Pasco Basin. Laval's dissertation includes the southern part of the Pasco Basin. Mackin's (1955) detailed stratigraphic and structural investigation between Vantage and Priest Rapids Dam was part of the Priest Rapids and Wanapum hydroelectric development study.

In 1961, Waters published a basic stratigraphic study of the Columbia River Basalt Group which illustrated the chemical nature, diversity, and stratigraphic variation in the basalts. Schmincke (1964a, 1964b) studied the Ellensburg Formation and Columbia River Basalt Group in

parts of the Pasco Basin and elsewhere in south-central Washington using detailed petrographic studies and chemical analyses. Grolier (1965) and Bingham and Walters (1965) demonstrated the lateral continuity of flows along the northern margin of the Pasco Basin. Grolier and Bingham (1971) published a geologic map of the Columbia Basin Project which includes the northern and western parts of the Pasco Basin. Farkas (1971) studied the stratigraphy and structure of a portion of Umtanum Ridge. Newcomb and Others (1972) reported the geology and ground-water characteristics of the Hanford Site in the Pasco Basin. WPPSS (1974, 1977) contains maps of basalt outcrops in parts of the Pasco Basin; Brooks (1974) mapped Gable Mountain; Taylor (1976) mapped a portion of the Saddle Mountains; and Helz (1978) and Swanson and Helz (1979) published a map of the vent system for the Ice Harbor Member in the eastern Pasco Basin.

Late Cenozoic Sediments

The Cenozoic sediments of south-central Washington in and near the Pasco Basin were first described by Russell (1893). In those days, geologic reconnaissance was part of regional exploration. Russell assumed that the White Bluffs beds were "typical" of the John Day Formation he had seen in Oregon. He also suggested that the White Bluffs sediments are related to the Ellensburg Formation as found near Thorp, Washington. Belief in the stratigraphic equivalency to the Ellensburg Formation was supported by other early workers (Smith, 1903a; Calkins, 1905). Calkins (1905) suggested that the White Bluffs rocks are essentially fluvial in origin. The White Bluffs were investigated further by Merriam and Buwalda (1917). They formally named sediments that crop out along the White Bluffs as the Ringold Formation. From paleontologic evidence and the fluvial sorting of these sediments, they proposed a flood plain origin with the Columbia River being the agent of deposition and, from paleontologic evidence, suggested a Pleistocene age for the upper part of the Ringold Formation.

The mapped areal extent of the Ringold Formation was expanded by Culver (1937) to include most depositional basins of the western half of the Columbia Plateau. Culver (1937) further suggested that more than one major drainage basin was responsible for Ringold deposition, and that deposition occurred prior to uplift of the major east-west-trending ridges on the western half of the Columbia Plateau. A re-examination of the Ringold Formation fauna compared to the Big Bone Lick, Kentucky locality (Strand and Hough, 1952) resulted in an age assignment of late Pleistocene, but a more thorough study (Gustafson, 1973, 1978) of the mammalian assemblage of the White Bluffs showed that the middle Ringold Formation conglomerate facies is late Hemphillian (Pliocene) in age. Gustafson agrees that the Ringold Formation is of flood plain origin.

Of the many studies of the Ringold Formation in this area, only three (McConiga, 1955; Brown and McConiga, 1960; Brown, 1970) deal with deformation. These authors concluded that the Ringold Formation was deformed with the underlying basalt and generally dips radially inward toward the center of the Pasco Basin.

Soils of the Pasco Basin were mapped by Kocher and Strahorn (1919) who noted the differences between the "wheat soils" (loess) and the "glacial" (actually glaciofluvial) deposits of the scablands; however, it wasn't until 1923 (Bretz, 1923) that the significance of the channeled scabland of eastern Washington was realized. From 1923 until 1969, Bretz faced a mostly unbelieving scientific audience as he defended his "outrageous hypothesis" that the scablands were the result of catastrophic flooding across eastern Washington. Recent work on qualitative and quantitative hydrodynamics of these floods (Baker, 1973; Baker and Nummendal, 1978) not only confirmed Bretz's stand, but also presented evidence that the largest of these floods was even larger than first suggested.

The geologic maps by Newcomb and Others (1972), Grolier and Bingham (1971), and in WPPSS (1974, 1977) also included some work on the late Cenozoic sediments overlying the Columbia River basalt.

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Borehole Studies

This review of borehole studies is confined to boreholes that penetrate into the Columbia River Basalt Group.

Early boreholes on the Hanford Site were used to assist mapping the structure of the top of the basalt sequence (Brown and Brown, 1958; Brown, 1959). Only limited success was achieved at that time in the identification of individual basalt flows. Rattlesnake Hills Well Number 1 (RSH-1) (10,655 feet [3,247 meters]), which was drilled on top of the Rattlesnake Hills, was reentered in 1968 to determine the geological and hydrological characteristics of the basalt sequence at that location (Raymond and Tillson, 1968). Borehole studies during the early 1970's utilized petrography, geochemistry, and borehole geophysics to identify and correlate a limited number of basalt flows between boreholes and surface outcrops (Crosby and Others, 1972; Brown and Ledgerwood, 1973; Myers and Brown, 1973; Myers, 1973; Siems, 1973; Siems and Others, 1974). Further refinement of the basalt stratigraphy using lithologic characteristics, stratigraphic sequence, and geochemical, petrographic, and geophysical analyses with additional deep core holes enabled identification and correlation of many individual flows and groups of flows between boreholes and surface outcrops throughout the Pasco Basin (Ledgerwood and Deju, 1976; ARHCO, 1976; Ledgerwood in BWIP, 1978).

Geophysical Surveys

High-altitude aeromagnetic surveys (Zietz and Others, 1971) revealed broad, low-amplitude anomalies with the highest magnetic intensity in the west-central Columbia Plateau near Pasco, Washington. Swanson and Others (1979c) geologically interpreted a low-altitude, draped, aeromagnetic survey flown in 1957. Ground magnetic surveys and a low-altitude, draped, aeromagnetic survey were made by Weston Geophysical Survey for the Washington Public Power Supply System, Inc. (WPPSS, 1977). This study identified several magnetic linears and anomalies associated with mapped structures. Regional Bouguer gravity maps (Bonini and Others, 1974; Konicek, 1975; WPPSS, 1977) show the Columbia Plateau as a broad gravity low with an axis trending northeast and centered near the Pasco Basin. Using gravity data, Danes (1969) inferred that the Columbia Plateau is in isostatic equilibrium.

Hill (1972) made long-range seismic refraction measurements across the Columbia Plateau and concluded that P-wave arrival times indicated crustal thinning or extensive magma intrusion beneath the Pasco Basin. Cantwell and Others (1965) and Cantwell and Orange (1965) interpreted deep resistivity measurements in eastern Oregon and Washington as indicating lateral resistivity changes within the upper 25 miles (40 kilometers) of the earth's crust near the Oregon-Washington border, perhaps--they stated--related to the Olympic-Wallowa Lineament.

Tectonic Studies

Tectonic investigations of the Pasco Basin were emphasized in the 1960's. Brown (1969) suggested rates of deformation of the basalt sequence in the Pasco Basin. Newcomb (1970) prepared a tectonic map that includes the Pasco Basin. Bingham and Others (1970) conducted detailed mapping related to fault investigations in the Pasco Basin following recommendations made by Waldron and Bonilla (1968). Studies by the Washington Public Power Supply System,Inc. (WPPSS, 1974, 1977) were concerned with the question of the tectonic stability of the Pasco Basin as applied to nuclear power plant siting in the basin. (Additional previous work relating to tectonics and seismicity of the Pasco Basin is presented in Chapter IV.)

STRATIGRAPHY

GENERAL

Stratigraphic relationships presented in this section are based on interpretations of the succession of lavas and sediments penetrated by Pasco Basin boreholes and on the results of geologic mapping across the basin. Emphasis is on Grande Ronde Basalt stratigraphy.

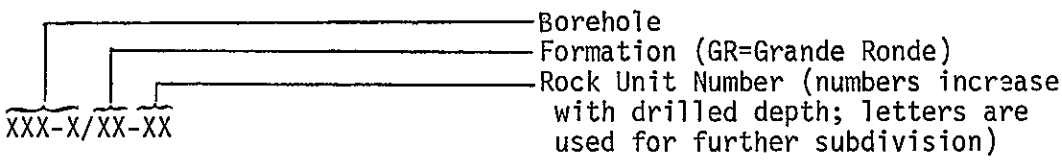
The stratigraphic relationships are presented by formations from oldest to youngest (Grande Ronde Basalt, Wanapum Basalt, and Saddle Mountains Basalt). A formational basis of presentation is used because the data coverage varies depending not only on borehole type and depth, but also on the formation penetrated. Overall, more data are available from the Grande Ronde Basalt than the Wanapum Basalt or Saddle Mountains Basalt in those boreholes penetrating all three formations. There are two reasons for this: first, the Grande Ronde Basalt flows are very similar physically and chemically and more information is needed to subdivide them stratigraphically; and, second, more information and stratigraphic detail are required in the Grande Ronde Basalt because it contains those flows currently being considered as potential repository host rock. Also, statistically, a more valid stratigraphic correlation can be obtained with increased numbers of variables. Reidel (1978b) has shown a 66 percent probability of correctly correlating Grande Ronde Basalt flows exposed in the lower Salmon River Canyon and adjacent Snake River Canyon based on chemical analyses alone. The probability of correct correlations increases with identification of additional variables such as paleomagnetics, borehole geophysical log data, and known stratigraphic sequence.

Lateral distribution and thickness variations of basalt and sediment units are also described and shown on maps in this section and on the plates. Distribution and thickness variations are best known for the younger, better exposed Saddle Mountains Basalt units than for the older, more poorly exposed Grande Ronde Basalt units. Preparation of the distribution maps was recently begun and they should be considered preliminary.

Nomenclature

Formal rock stratigraphic nomenclature used in the Pasco Basin is shown on Table III-1. Informal names are used for rock units below the member level.

Grande Ronde rock units penetrated by boreholes have been labeled according to the following format:



For example, DC-6/GR-9 refers to Grande Ronde Basalt unit number 9 in DC-6. Plate III-2 indicates that DC-6/GR-9 has an upper contact at 3,036 feet (1,012 meters) and a lower contact at 3,258 feet (1,089 meters). (Note: This format has been used for labeling intraflow structures, for flow units, and for individual flows.) Wanapum Basalt and Saddle Mountains Basalt units penetrated by boreholes have been labeled according to field mapping symbols (Plate III-1), except where noted otherwise.

Basalt units along the Emerson Nipple and Sentinel Gap measured sections (Plates III-3a, 3b, and 3c) are labeled analogous to boreholes. For example, unit EN/GR-7 is a 128-foot (43-meter) thick Grande Ronde Basalt flow located along the Emerson Nipple measured section traverse (Plate III-3a).

Description of Rock Units

The Pasco Basin is underlain by three major rock units: (a) Pre-Columbia River Basalt Group rocks; (b) Columbia River Basalt Group (includes the Ellensburg Formation); and, (c) late Cenozoic sediments (includes the Ringold Formation, Palouse Soil, and Hanford formation [informal name]). Outcrops of Columbia River Basalt Group rocks and late Cenozoic sediments occur throughout the Pasco Basin and were studied as part of surface geologic mapping. However, rocks that are pre-Columbia River Basalt Group in age (probably middle Tertiary) do not crop out within the basin, although they were penetrated in borehole RSH-1 at depths below about 4,000 feet (1,280 meters); these rocks are not discussed.

TABLE III-1. Pasco Basin Stratigraphic Nomenclature.

GEOLOGIC MAPPING SYMBOL	FLOW OR BED	LITHOLOGY	^{14}C AGE YEARS	SEDIMENT STRATIGRAPHY
9 UNITS SEE GEOLOGIC MAP	MAZAMA ASH	ASH FALL, CRATER LAKE, OREGON	6,600	ALLUVIUM, COLLUVIUM AND EOLIAN SEDIMENTS
	GLACIER PEAK ASH	ASH FALL, GLACIER PEAK, WASHINGTON	12,500	
	ST. HELENS ASH (SET S)	ASH FALL, MOUNT ST HELENS, WASHINGTON	13,000	HANFORD FORMATION (INFORMAL NAME)
(Qht)	TOUCHET BEDS	RYTHMICALLY BEDDED, FINE GRAINED FACIES OF GLACIOFLUVIAL DEPOSITS, BEDDED		
(Qhp)	PASCO GRAVELS	COARSE TO MEDIUM-GRAINED FACIES OF GLACIOFLUVIAL DEPOSITS CUT-AND-FILL STRUCTURE		
		CALCAREOUS SAND, SILT AND EOLIAN DEPOSITS		EARLY "PALOUSE" SOIL
Trs	UPPER RINGOLD	SILT AND SAND SOME GRAVEL, FLUVIAL, WELL BEDDED LOCALLY CAPPED BY CALICHE		RINGOLD FORMATION
Trl	MIDDLE RINGOLD	SAND AND GRAVEL, VARIABLY WELL SORTED COMPACT BUT VARIABLY CEMENTED		
Trl	LOWER RINGOLD	SAND, SILT, AND CLAY INTERBEDDED GRAVEL AND SAND		
	BASAL RINGOLD (RINGOLD FANGLOMERATE: TRANSGRESSES RINGOLD TIME, ANGULAR TO SUBANGULAR BASALT FRAGMENTS, INCLUDES SOME SAND AND SILT)	SAND AND GRAVEL WITH SILT POORLY SORTED POORLY CEMENTED		

BASALT STRATIGRAPHY

FORMATION	K - AR AGE YEARS X 10^6	MEMBER OR SEQUENCE		FLOW OR BED	LITHOLOGY	MAGNETIC POLARITY
COLUMBIA RIVER BASALT GROUP / YAKIMA BASALT SUBGROUP / SADDLE MOUNTAINS BASALT (FLOWS EXHIBIT DIVERSE PETROGRAPHY AND CHEMISTRY)	8.5	ICE HARBOR MEMBER (Ti)	(Tig)	GOOSE ISLAND FLOW	BASALT, PHYRIC	N (N NORMAL, T TRANSITION, R REVERSED)
			(Tim)	INDIAN MEMORIAL FLOW		N
			(Tim)	MARTINDALE FLOW		R (VARIABLE)
			(Tib)	BASIN CITY FLOW		N
				LEVEY	TUFF AND TUFFACEOUS SANDSTONE	
	10.5	ELEPHANT MOUNTAIN MEMBER (Tem)	(Tem2)	ELEPHANT MT., UPPER FLOW (WARD GAP)	BASALT APHYRIC	N-T
			(Tem1)	ELEPHANT MT., LOWER FLOW	BASALT APHYRIC	R-T
			(Ter)	RATTLESNAKE RIDGE	SANDSTONE, TUFFACEOUS	
	12.0	POMONA MEMBER (Tp)	(Tp2)	POMONA, UPPER FLOW	BASALT, PHYRIC	R
			(Tp1)	POMONA, LOWER FLOW	BASALT PHYRIC	R
			(Tes)	SELAH	SANDSTONE TUFFACEOUS	
		ESQUATZEL MEMBER		GABLE MOUNTAIN, UPPER FLOW	BASALT LOCALLY PHYRIC	N
			(Te)	GABLE MOUNTAIN BED	TUFF DISCONTINUOUS	
				GABLE MOUNTAIN, LOWER FLOW	BASALT LOCALLY PHYRIC	N
				COLD CREEK	SANDSTONE LOCALLY TUFFACEOUS AND CONGLOMERATIC	
		ASOTIN MEMBER	(Ta)	HUNTZINGER FLOW	BASALT APHYRIC, LOCALLY COARSELY PHANERITIC AND VERTICALLY DIFFERENTIATED	N
		WILBUR CREEK MEMBER	(Tw)	WAHLUKE FLOW	BASALT, APHYRIC	N
		UMATILLA MEMBER	(Tu)	SILLUSI FLOW	BASALT APHYRIC	N
				UMATILLA FLOW		N
			(Tems)	MABTON	SANDSTONE & TUFFACEOUS SANDSTONE	
WANAPUM BASALT (FLOWS HAVE SIMILAR CHEMISTRY, BUT VARIABLE PETROGRAPHY)	13.6	PRIEST RAPIDS MEMBER	(Tpr)	LOLO FLOW TYPE (1 FLOW)	BASALT, APHYRIC	R
				ROSALIA FLOW TYPE (1-4 FLOWS)	BASALT APHYRIC LOCALLY COARSE GRAINED	R
				INTERBED	LOCAL TUFFACEOUS SILT AND PETRIFIED WOOD OR DIATOMITE	
		ROZA MEMBER	(Tr)	ROZA, UPPER FLOW	BASALT, PHYRIC	T
				ROZA, LOWER FLOW	BASALT PHYRIC	T
				INTERBED	LOCAL DIATOMITE OR PETRIFIED WOOD	
		FRENCHMAN SPRINGS MEMBER	(Tf)	PHYRIC (Tfp) AND APHYRIC (Tfa) FLOWS, SOME USE OF LOCAL NAMES	ALTERNATING PHYRIC AND APHYRIC FLOWS WITH THIN FLOW UNITS COMMON	N N
	~ 14.5		(Tev)	VANTAGE MEMBER	SANDSTONE	TiO_2 HORIZON
GRANDE RONDE BASALT		SENTINEL BLUFFS FLOWS	(Tsb)	MUSEUM FLOW		ALL FLOWS NORMAL
				ROCKY COULEE FLOW		
				6 TO 10 FLOWS	BASALT APHYRIC	
	(Tgr)	SCHWANA FLOWS	(Tsu)	UMTANUM	BASALT, APHYRIC	MgO HORIZON; N N N N
			(Ts)	1 TO 3 FLOWS IN THE PASCO BASIN OF THE VERY HIGH Mg CHEMICAL TYPE		4 TO 7 FLOWS; PROBABLE POSITION OF THE REGIONAL N2 R2 MAGNETIC HORIZON
				AT LEAST 20 FLOWS (CURRENTLY KNOWN ONLY FROM DEEP BOREHOLES EXCEPT FOR THE UPPER LIMITS WHICH CROP OUT LOCALLY)		R
	>15.4					
PRE-COLUMBIA RIVER BASALT GROUP ROCKS						(INTERPRETED TO EXIST IN LOWER PART OF BOREHOLE RSH-1 BELOW 5000 FEET)

ELLENSBURG FORMATION (NOMENCLATURE NOT FORMALIZED)

UNDIFFERENTIATED (Tel) NAMES OF ELLENSBURG INTERBEDS USED ON THE NOMENCLATURE CHART ARE DEFINED IN RELATION TO OVERLYING AND UNDERLYING BASALT FLOWS. INTERBED ROCK UNITS MAY NOT BE LITHOSTRATIGRAPHICALLY EQUIVALENT TO THE TYPE LOCALITY ROCK UNITS

REPLACES RHO-BWI-LD-1, ROCKWELL HANFORD OPERATIONS, RICHLAND WASHINGTON (MAY 1978)

ARHCO, 1976 — COE AND OTHERS, 1978 — SWANSON AND HELZ, 1979 — SWANSON AND OTHERS, 1977 — TAYLOR, 1976 — WAITT, 1979a — WPPSS, 1977 — WATKINS AND BAKSI, 1974

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Table III-2 is a summary description of the Columbia River Basalt Group rocks and late Cenozoic sediments in the Pasco Basin. Other descriptive information is in Plate III-1, in Chapter II, and in the discussion of stratigraphic relationships in this chapter.

Some Comments on the Identification and Correlation of Basalt Units between Boreholes and Surface Sections. Basalt stratigraphic studies in the Pasco Basin depend on criteria that establish direct stratigraphic equivalencies (correlations) between boreholes and surface sections. Grande Ronde Basalt equivalencies have been established using known stratigraphic sequence in conjunction with three main criteria: (a) chemistry; (b) paleomagnetics; and, (c) borehole geophysical log character. Stratigraphic units identified by these three criteria are separated to avoid confusion. Chemical stratigraphic units, magnetostratigraphic units, and borehole geophysical log stratigraphic units are all used to develop and confirm correlations of rock-stratigraphic units.

Identification and correlation of chemical stratigraphic units and magnetostratigraphic units were made using three techniques: (a) visual comparison of data; (b) graphic plots of data followed by a visual comparison of the plots; and, (c) statistical analysis (magnetostratigraphic units only). Identifications and correlations of borehole geophysical log stratigraphic units were made by identifying similarities in log character.

Magnetostratigraphic correlations are based on between-flow difference in magnetic inclination values and on polarity changes. The magnetostratigraphic correlations in this report are taken from a study by Packer and Petty (1979), which involved demagnetization and directional measurement of 940 samples of Pasco Basin basalt cores, and an evaluation of the results of 2 previous studies of Grande Ronde Basalt magnetostratigraphy in the Pasco Basin (Coe and Others, 1978; Beck and Others, 1978). The analytical technique, data analysis procedure, and magnetostratigraphic correlation procedure used by Packer and Petty (1979) are described briefly in Appendix A.

Borehole geophysical logs are particularly useful for basalt correlations in boreholes spaced less than 10 miles (16 kilometers) apart. Good logs to use for this correlation are the gamma-ray log and a log that measures physical properties such as the density log, sonic log, or neutron log (Figure III-2). The gamma-ray log measures the natural gamma emissions of rocks in the borehole adjacent to the logging tool. Variations in tool response are associated with variations in the naturally occurring radioactive isotopes, primarily the ^{40}K content of the rocks. The gamma-ray log is particularly useful in identifying clay-rich interbeds interlayered with the basalts. Because the gamma-ray log responds to differences in the potassium content between basalt flows, it can be used to identify some basalt chemical types (the low-K_2O flows, the low-MgO flows, and the high-MgO flows). The density log, neutron log, and sonic log respond to variations in fracturing and vesicularity. Moreover, the sonic log has good vertical definition and

TABLE III-2. Summary Description of Pasco Basin Rock Units.

	FORMATION UNIT	GENERAL STRATIGRAPHY	OUTCROP OR BOREHOLE CHARACTERISTICS	HAND SPECIMEN AND PETROGRAPHIC CHARACTERISTICS	MAGNETIC PROPERTY
SURFICIAL UNITS	Loess	Limited lateral and vertical extent throughout Pasco Basin. Locally overlies all other units.	Generally massively bedded. Volcanic ash horizon (Mazama?) common.	Silty, very fine sand to sandy silt.	Not Determined
	Sand Dunes	Limited lateral and vertical extent throughout Pasco Basin. Occurs as longitudinal and barchan dune fields. Locally overlies all other units.	Massive to foreset bedding. Volcanic ash horizon (Mazama?) common.	Medium to fine sand, locally high silt content. Chiefly quartz with local, high concentrations of basaltic sand.	Not Determined
	Alluvium and Alluvial Fans	Limited lateral and vertical extent. Alluvium generally restricted to modern flood plains of perennial and ephemeral streams of Pasco Basin. Alluvial fans limited to ridge slopes and ridge fronts on margins of Pasco Basin. Includes both Pleistocene and Holocene deposits.	Massive to fine horizontal bedding. Caliche cementation of surface locally common on older (Pleistocene) fans. Volcanic ash horizon (Mazama?) locally common.	Silt to boulder size range, sorting variable. Composition very variable, loess, Hanford formation, Ringold Formation, and basalt.	Not Applicable
	Landslides	Limited extent, locally common. Displacement of basalt limited to anticlinal ridges. Displacement of Ringold common at White Bluffs. Most modern Ringold displacement induced by irrigation.	Includes slump blocks, block slides, and earth flows. Slump blocks and block slides of basalt often retain original structures.	Variable.	Not Applicable
	Talus	Limited lateral and vertical extent, locally common along basalt cliffs and steep rock faces.	Forms steep-faced cones and slopes with no bedding.	Chiefly composed of basalt clasts with minor amounts of loess and interbed material.	Not Applicable
	Colluvium	Limited lateral and vertical extent. Associated with ridge slopes and faces on margins of Pasco Basin.	Generally less than 3 feet (1 meter) thick. Composition and outcrop characteristics variable.	Sorting variable, composed of basalt, interbed material, Hanford formation, Ringold Formation, and loess.	Not Applicable

Table III-2 (continued)

	FORMATION UNIT	GENERAL STRATIGRAPHY	OUTCROP OR BOREHOLE CHARACTERISTICS	HAND SPECIMEN AND PETROGRAPHIC CHARACTERISTICS	MAGNETIC PROPERTY
	Touchet Beds	Thickness variable, ranges from 0 to greater than 40 feet (0 to greater than 12 meters), exposed on much of the Pasco Basin margins. In general, overlies Pasco Gravels.	Generally well sorted, rhythmically bedded. Ash bed common in upper part of unit. Contains clastic dikes. Tan to light brown in color.	Composed of silt and fine sand with coarse sand and pebble stringers. Primarily composed of quartz and feldspar with minor mica.	Not Applicable
HANFORD FORMATION	Pasco Gravels	Thickness variable, ranges from 0 to greater than 290 feet (0 to greater than 90 meters), exposed on surface throughout much of the Pasco Basin. Overlies the eroded surface of the Ringold Formation and, locally, the Yakima Basalt Subgroup.	Gravel facies commonly foreset bedded, but also occur with horizontal bedding. Bedding forms in sand facies include horizontal to massive bedding, foreset bedding, and various types of cross bedding. Contains clastic dikes. Color variable.	Texture ranges from medium-to-fine sand to boulders. Sorting is variable, gravel occurs as both open worked and as poorly sorted, silty, sandy, gravel. Pebbles to boulders composed of quartzite, granite, basalt, diorite, and porphyrys with minor gneiss, schist, pebble chert conglomerates and metasediments. Sand fraction predominantly quartz and feldspar.	Not Determined
	Early Palouse Soil	Generally 6 to 10 feet (2 to 3 meters) thick, present in subsurface of west-central Pasco Basin. Identified only in subsurface, probable equivalent units crop out on the eastern margins of Pasco Basin. Unconformable contact with the upper Ringold unit and the overlying Hanford formation.	Compact and massively bedded, no laminations or cross stratification observed. Tan to light brown in color.	Typically fine grained, fine sand to silt. Sand fraction is predominantly quartz and feldspar. Unit is generally calcareous and often contains calcic horizons.	Not Determined
RINGOLD FORMATION	Upper Ringold	More than 400 feet (121 meters) exposed along White Bluffs. Crops out in eastern and northern portions of the Pasco Basin. Also known to be present in subsurface of the western and central portions of the Pasco Basin. When not eroded, commonly capped by a thick calcic-to-petrocalcic horizon.	Consolidated units form vertical facies, unconsolidated units form slopes. Silt and sand units are both horizontal and cross bedded with ripple marks commonly present. Clay layers are typically horizontally bedded with fine laminations and lack current sedimentary structures. Contains diatomite beds, ash beds, clastic dikes and vertebrate fossils locally. Light brown to tan in color.	Composed of well-sorted sand, silt, and clay with minor lenses of pebbles. Sand and silt fractions predominantly quartz, feldspar, and mica. Clay fraction commonly contains smectite and mica.	At White Bluffs, generally reversed polarity, lower 65 feet (20 meters) generally normal polarity

Table III-2 (continued)

	FORMATION UNIT	GENERAL STRATIGRAPHY	OUTCROP OR BOREHOLE CHARACTERISTICS	HAND SPECIMEN AND PETROGRAPHIC CHARACTERISTICS	MAGNETIC PROPERTY
RINGOLD FORMATION	Middle Ringold	Thickness variable 0 to greater than 250 feet (0 to greater than 80 meters). Crops out only in the east-central portion of the Pasco Basin along southern half of the White Bluffs. Present throughout most of the Pasco Basin. Contact with the overlying Upper Ringold is gradational to sharp. NOTE: The Ringold stratigraphy is not well known north of Gable Mountain.	Commonly forms vertical to near-vertical faces. Matrix-supported gravel, massively bedded with minor imbrication of clasts. Sand stringers common throughout, cross bedded to massive. Variable induration.	Pebble-cobble gravel typically supported by a coarse-to-medium sand matrix. Gravel fraction composed of quartzite, basalt, metamorphic, granitic, and volcanic porphry rocks. Sand fraction predominantly quartz and feldspar.	Not Determined
	Lower Ringold	Thickest in synclinal troughs less than 350 feet (100 meters) thick and pinches out against basalt highs. Does not crop out in the Pasco Basin, known only from borehole and core hole samples. Present throughout much of the subsurface in the Pasco Basin, primarily in synclinal depressions. Contact with the overlying Middle Ringold unit is generally sharp.	Primarily composed of sand, silt, and clay. Unit is finely bedded to massive where observed in core. Stringers of gravel are commonly scattered throughout. Brown to tan in color.	Texture varies from silty, coarse-to-medium sand, to sandy silt. Sand fraction predominantly quartz and feldspar.	Not Determined
	Ringold Fanglomerate	Thickness at places on northern Saddle Mountains greater than 50 feet (15 meters). Very limited lateral and vertical extent. Crops out on north face of Saddle Mountain and at Smyrna Bench. Interfingers with Upper Ringold unit on Smyrna Bench. Stratigraphic relationship unknown in other areas.	Generally poorly bedded. Contains both fluvial (alluvium and alluvial fans) and mass wastage deposits.	Texture varies from silt to cobbles, angular. Composed chiefly of basalt and interbed material.	Not Determined

Table III-2 (continued)

	FORMATION UNIT	GENERAL STRATIGRAPHY	OUTCROP OR BOREHOLE CHARACTERISTICS	HAND SPECIMEN AND PETROGRAPHIC CHARACTERISTICS	MAGNETIC PROPERTY
RINGOLD FORMATION	Basal Ringold	Thickness in synclinal troughs approximately 50 to 60 feet (15 to 18 meters) and pinches out against basalt highs. Does not crop out in the Pasco Basin, known only from borehole and core hole samples. Present throughout most of the subsurface in the Pasco Basin. Basal Ringold is not distinguishable from Middle Ringold when in direct contact. Contact with overlying Lower Ringold is gradational to sharp.	Generally considered to be massively bedded. Stringers of coarse-to-fine sand common throughout.	Gravel supported by a coarse-to-fine sand matrix. Gravel fraction composed of basalt, quartzite, metamorphics, granitics, and other lithologies from outside the Pasco Basin. Sand fraction chiefly basalt, quartz, and feldspar.	Not Determined
SADDLE MOUNTAINS BASALT	Ice Harbor (Basalt)				
	Goose Island	Unit is greater than 68 feet (21 meters) thick at Goose Island, found only in the southeastern Pasco Basin. Source vents near Ice Harbor Dam and south of Basin City. Feeder dikes known near Reese (Swanson and Others, 1979b).	*Top*: Thickness unknown, poorly exposed. Entablature greater than 10 feet (3 meters) thick, consists of microvesicular, hackly pieces 4 to 8 inches (10 to 20 centimeters) in diameter. *Colonnade*: 60 feet (18 meters) thick, 1.5 to 5 foot (0.5 to 1.5 meter) diameter, well-formed, horizontal joints at 1- to 3-foot (0.3- to 1-meter) intervals. *Base*: Lower 1.5 feet (0.5 meter) is vesicular, lower 3 feet (1 meter) has platy joints.	*Color*: Dark gray fresh, weathers tan. *Phenocrysts*: 0.1- to 0.4-inch (2- to 10-millimeter) plagioclase and 0.1-inch (2-millimeter) green-black pyroxene phenocrysts, and 0.5- to 1-inch (1- to 3-centimeter) plagioclase pyroxene glomerophenocrysts. *Texture*: Phyric, 0.05- to 0.02-inch (1- to 5-millimeter) and 0.75- to 1-inch (2- to 3-centimeter) vesicles throughout flow.	Fluxgate: Normal Polarity
	Indian Memorial	Thickness of unit is not known, found only in the southeastern portion of the Pasco Basin. Source vents east of Ice Harbor Dam.	*Top*: Only the lower 7 feet (2 meters) of the flow have been observed. *Interior*: Entablature not observed. *Colonnade*: 3 to 5 feet (1 to 3 meters) wide, basal columns cut up platy joints. *Base*: Vesicular.	*Color*: Dull black. *Phenocrysts*: 0.5- to 0.15-inch (1- to 4-millimeter) plagioclase and pyroxene phenocrysts. *Texture*: Slightly phyric, felty texture, scattered aligned microvesicles and plagioclase microphenocrysts.	Fluxgate: Normal Polarity

Table III-2 (continued)

	FORMATION UNIT	GENERAL STRATIGRAPHY	OUTCROP OR BOREHOLE CHARACTERISTICS	HAND SPECIMEN AND PETROGRAPHIC CHARACTERISTICS	MAGNETIC PROPERTY
SADDLE MOUNTAINS BASALT	Martindale	Unit is up to 80 feet (25 meters) thick, occurs in southern portion of basin. Known source vents are near Ice Harbor Dam.	*Top*: Sheeted scoriaceous crust grading into as much as 25 feet (7 meters) of massive scoriaceous basalt. *Interior*: Entablature less than 7 feet (2 meters) thick. *Colonnade*: Poorly to well-developed, massive columns up to 5 feet (1.5 meters) across.	*Color*: Black to gray, weathers reddish. *Phenocrysts*: Phyric, plagioclase phenocrysts and glomeroporphyritic clots of plagioclase, clinopyroxene olivine up to 1 inch (2.5 centimeters). *Texture*: Glassy to grainy and coarsely porphyritic, vesicular to microvesicular.	Fluxgate: Reverse Polarity, but Variable
SADDLE MOUNTAINS BASALT	Basin City	Unit is 40 to 50 feet (13 to 15 meters) thick, occurs in the eastern Pasco Basin in the Mesa and Eltopia 15-minute quadrangles. Source vents are near Basin City, 11 miles (17 kilometers) west of Mesa. Feeder dikes exposed east of Ice Harbor Dam.	*Top*: Vesicular flow top 3 to 7 feet (1 to 3 meters) in thickness. *Interior*: Massive. *Colonnade*: Poorly developed, local spatter and vent material. Exposed dikes contain palagonite.	*Color*: Gray to black. *Phenocrysts*: Olivine and plagioclase phenocrysts and glomerophenocrysts up to 0.8 inch (2 centimeters). *Texture*: Phyric, fine grained.	Fluxgate: Normal Polarity
ELLENSBURG FORMATION	Levey Interbed	Unit is 0 to 20 feet (0 to 6 meters) thick, found in eastern Pasco Basin.	Light colored, tuffaceous, thinly laminated silt or siltstone locally overlain by bedded volcanic ash.	Silt size particles with ash beds.	Not Determined
SADDLE MOUNTAINS BASALT	Elephant Mountain II	Unit is 1 flow (Ward Gap), up to 65 feet (20 meters) thick, found throughout the Pasco Basin. Source area is east of Pasco Basin.	*Top*: Very vesicular with crude columnar joints. *Interior*: Hackly entablature. *Colonnade*: Constitutes half of flow thickness, columns 1.5 to 2 feet (0.5 to 2 meters) in diameter, platy jointing in upper part. *Base*: Irregular pipe vesicles where flow top is thickest.	*Color*: Fresh surfaces are black, weathers deep rust-red or brown. *Phenocrysts*: Plagioclase microphyric. *Texture*: Fine-to-coarse grained, glassy, occasionally diktytaxitic, generally coarser than Elephant Mountain I.	Fluxgate: Normal Polarity

Table III-2 (continued)

	FORMATION UNIT	GENERAL STRATIGRAPHY	OUTCROP OR BOREHOLE CHARACTERISTICS	HAND SPECIMEN AND PETROGRAPHIC CHARACTERISTICS	MAGNETIC PROPERTY
SADDLE MOUNTAINS BASALT	Elephant Mountain I	Unit is 1 flow (Elephant Mountain), up to 115 feet (35 meters) thick, occurs throughout the Pasco Basin. Source area is east of Pasco Basin.	*Top*: 6.5 to 16 feet (2 to 5 meters) thick, locally 1.5- to 13-foot (0.5- to 4-meter) thick flow-top breccia. *Interior*: Entablature hackly, 1.5- to 3-foot (0.5- to 1-meter) thick platy zone at contact with colonnade. *Colonnade*: 3- to 7-foot (1- to 2-meter) diameter columns. *Base*: Pipe vesicles, locally pillowed. NOTE: Abrupt intraflow facies change in Crab Creek.	*Color*: Black to dark gray, weathers to a reddish gray. *Phenocrysts*: Plagioclase microphyric. *Texture*: Fine-grained, glassy entablature; occasionally diktytaxitic in colonnade, felty texture.	Fluxgate: Reverse Polarity
ELLENSBURG FORMATION	Rattlesnake Ridge Interbed	Unit is 0 to 30 feet (0 to 9 meters) thick. Present throughout Pasco Basin.	Locally cross bedded, clastic dikes, pseudo-columnar jointing produced by dehydration of clay.	Tuffaceous silt, cream, buff-yellow, gray, well sorted.	Not Determined
SADDLE MOUNTAINS BASALT	Pomona	Unit has 2 or 3 flows, a thin upper flow and thick lower flow and a thin lowermost flow known only from core holes on Gable Mountain. Upper flow is 30 to 65 feet (10 to 20 meters) thick; lower flow is up to 200 feet (60 meters) thick. Units occur throughout the Pasco Basin, except when they pinch out against structures. Source area is east of Pasco Basin.	*Upper Flow*; Well-developed colonnade and entablature. Entablature has fanning columns, colonnade is locally absent. *Lower Flow*: Well-developed colonnade and entablature. *Top*: 6.5 to 32 feet (2 to 10 meters) thick, pods of pumice and glassy fragments. *Interior*: Entablature up to 30 feet (10 meters) thick. 1- to 1.5-foot (0.3- to 0.5-meter) columns, vertical to fanning, locally tiered with layers of 3- to 7-foot (1- to 2-meter) columns. *Colonnade*: Up to 30 feet (10 meters) thick. Base locally pillowed or peperite, invasive into underlying interbed.	*Color*: Upper flow gray-black, weathers brownish-gray. Lower flow blue-black, weathers brownish-gray. *Phenocrysts*: Upper flow has plagioclase and olivine phenocrysts up to 0.2 inch (5 millimeters). Lower flow has plagioclase phenocrysts up to 2.5 inches (1 centimeter), sparse olivine phenocrysts up to 0.02 inch (0.5 millimeter) and glomerocrysts of plagioclase and pytoxene up to 0.8 inch (2 centimeters). Distinctive sieve-textured plagioclase phenocrysts. *Texture*: Both upper and lower flows fine- to medium-grained, locally microvesicular to diktytaxitic.	Fluxgate: Reverse Polarity

Table III-2 (continued)

	FORMATION UNIT	GENERAL STRATIGRAPHY	OUTCROP OR BOREHOLE CHARACTERISTICS	HAND SPECIMEN AND PETROGRAPHIC CHARACTERISTICS	MAGNETIC PROPERTY
ELLENSBURG FORMATION	Selah Interbed	Unit variable in thickness and occurs locally in the Pasco Basin.	Vitric tuff, locally fused to perlitic, clean and well sorted, contains ripple marks.	Silty sand with some volcanic ash, chert and peperite. Gray to white.	Not Determined
SADDLE MOUNTAINS BASALT	Esquatzel	Unit is up to 100 feet (30 meters) thick and restricted to the central and eastern Pasco Basin, source area is east of Pasco Basin.	*Top*: 6.5 to 16 feet (2 to 5 meters) thick. *Interior*: Hackly entablature. *Colonnade*: Well developed, 3 feet (1 meter) across columns. *Base*: Almost aphanitic with glass chill zone.	*Color*: Blue-black fresh, weathers a distinctive brownish color. *Phenocrysts*: Scattered plagioclase phenocrysts 0.1 inch (3 millimeters) up to 0.6 inch (1.5 centimeters). *Texture*: Fine grained to diktytaxitic. NOTE: Microvesicular bands parallel to flow surface.	Fluxgate: Normal Polarity
ELLENSBURG FORMATION	Cold Creek Interbed	Unit is 0 to 115 feet (0 to 35 meters) thick. Few surface exposures, best developed in central Pasco Basin core holes.	See Hand Specimen and Petrographic Characteristics.	Tuffaceous to arkosic sandstone with a middle conglomerate of well-rounded and closely packed basalt cobbles in a black basaltic-sand matrix. In places, weakly cemented, andesitic gravels with alteration rims.	Not Determined
SADDLE MOUNTAINS BASALT	Asotin	Huntzinger flow. Unit is up to 200 feet (60 meters) thick and occurs as intracanyon flows, but locally sheet-like in the Pasco Basin. As many as 3 flows or units. Source area is east of Pasco Basin.	*Top*: Thin scoria. *Interior*: Well-developed, hackly entablature. *Colonnade*: Columns up to 3 feet (1 meter) in diameter. *Base*: Local minor pillowing.	*Color*: Black to gray, weathers gray. *Phenocrysts*: Plagioclase phenocrysts (approximately 1 percent) up to 0.5 inch (1 centimeter) and olivine up to 0.02 inch (0.5 centimeter). *Texture*: Ophitic to diktytaxitic. NOTE: Hand specimen easily confused with Pomona, but fluxgate polarity will discriminate.	Fluxgate: Normal Polarity
SADDLE MOUNTAINS BASALT	Wilbur Creek	Wahluke Flow. Unit is up to 100 feet (30 meters) thick and occurs as intracanyon flow in Pasco Basin. Sheet-like flow on east side of Saddle Mountains (Eagle Lake flow of Swanson and Others, 1977). Source area is east of Pasco Basin.	*Top*: Unknown from outcrop. *Interior*: Thin, hackly entablature. *Colonnade*: Massive columns up to 3 feet (1 meter) in diameter. *Base*: Local minor pillowing.	*Color*: Black to blue-black, weathers gray-black. *Phenocrysts*: Sparse plagioclase phenocrysts up to 0.5 inch (1 centimeter). *Texture*: Generally fine-grained and glassy, rare plagioclase phenocrysts. NOTE: Resembles Umatilla, also has concoidal fracture.	Fluxgate: Normal Polarity

Table III-2 (continued)

	FORMATION UNIT	GENERAL STRATIGRAPHY	OUTCROP OR BOREHOLE CHARACTERISTICS	HAND SPECIMEN AND PETROGRAPHIC CHARACTERISTICS	MAGNETIC PROPERTY
SADDLE MOUNTAINS BASALT	Umatilla	One to 2 flows or flow lobes. Unit is up to 300 feet (90 meters) thick, locally thinner across structures 50 feet (15 meters) to absent. Unit pinches out between Umtanum Ridge-Gable Mountain and Saddle Mountains. Source area east of Pasco Basin.	*Top*. Up to 32 feet (10 meters) thick, locally scoriaceous with cobbles, clinker, and flow-banded fragments. Almond-shaped vesicles 0.3 to 1.5 inches (1 to 4 centimeters). *Interior*: Distinctive hackly entablature, commonly makes up 80 percent of flow. *Colonnade*: Thin, but where found has a slabby to prismatic vertical jointing. *Base*: Locally pillowed, up to 100 feet (30 meters) in Cold Creek syncline.	*Color*: Black, weathers pseudo-palagonite yellow-orange, shades of red, blue, or varicolored. *Phenocrysts*: Aphyric, rare phenocrysts to 0.3 inch (0.7 centimeter). *Texture*: Fine-grained, glassy, dense, plagioclase laths to 0.3 inch (0.7 centimeter) coarse-grained and glassy in the entablature, "felted texture" and 0.5 inch (1 millimeter) equant plagioclase in entablature. NOTE: Conchoidal fracture.	Fluxgate: Normal Polarity
ELLENSBURG FORMATION	Mabton Interbed	Unit is up to 150 feet (45 meters) thick and crops out only on western margin of Pasco Basin; otherwise known only from boreholes.	Tuffaceous silt with red and purple opal near top.	See Outcrop or Borehole Characteristics.	Not Determined
WANAPUM BASALT	Priest Rapids	Unit is 160 to 260 feet (50 to 80 meters) thick, individual flows are up to 200 feet (60 meters) thick. Unit is composed of 1 to 2 flows throughout most of the Pasco Basin, but 4 flows or flow lobes in northwestern part. Not present in the Wallula Gap area. A sedimentary interbed occurs locally between upper and lower facies. Source area is east of Pasco Basin.	*Top*: Contains petrified wood locally, upper flow is deeply weathered. *Interior*: Well developed with hackly jointing in entablature in the northern part of the Pasco Basin. *Colonnade*: Well-developed, massive columns common 1.5 to 5 feet (0.5 to 1.5 meters) curvi-planar to prismatic jointing and horizontal partings locally present, some vesicle sheets.	*Color*: Black to gray-green, fresh weathers rusty brown. *Phenocrysts* Aphyric, but with rare 0.5 inch (1 centimeter) plagioclase phenocrysts (a separate area(s), coarse-grained phase in thicker flows). *Texture*: Fine-grained, glassy, dense with plagioclase laths to 0.3 inch (6.7 centimeters) in entablature. Distinctive conchoidal fracture. Coarse-grained, glassy, felted texture with equant plagioclase 0.5 inch (1 centimeter) in colonnade.	Fluxgate: Reverse Polarity (strong) Laboratory: Reverse Polarity (A few significant differences in inclination between flows)
ELLENSBURG FORMATION	Unnamed Interbed	Occurs locally throughout Pasco Basin up to 16 feet (5 meters) thick on Yakima Ridge and 26 feet (8 meters) thick in southeastern Pasco Basin.	Tuffaceous silt, local abundant petrified wood.	Tuffaceous.	Not Determined

Table III-2 (continued)

	FORMATION UNIT	GENERAL STRATIGRAPHY	OUTCROP OR BOREHOLE CHARACTERISTICS	HAND SPECIMEN AND PETROGRAPHIC CHARACTERISTICS	MAGNETIC PROPERTY
WANAPUM BASALT	Roza	Unit is 100 to 300 feet (30 to 60 meters) thick throughout most of the Pasco Basin, but thinner on some ridges and absent in the Wallula Gap area. Occurs as 1 to 2 flows throughout most of Pasco Basin, but 3 flows reported in the southwest Pasco Basin. Source area east of Pasco Basin.	*Top*: Rubbly, but some crude columnar jointing, local petrified wood. *Interior*: Poorly developed entablature. *Colonnade*: Well developed with pinch and swell structures common.	*Color*: Gray-black fresh, weathers rusty brown. *Phenocrysts*: Plagioclase phenocrysts, very porphyritic, evenly distributed, most 0.2 to 0.8 inch (0.5 to 2 centimeters). *Texture*: Fine- to medium-grained, moderately diktytaxitic.	Fluxgate: Normal Polarity Overprint Laboratory: Transitional Polarity
	Frenchman Springs	Three to 8 flows throughout the Pasco Basin, possibly more in the southeastern basin. The unit is 820 feet (250 meters) thick in the southeastern Pasco Basin at Wallula Gap, and 650 to 780 feet (200 to 240 meters) thick in the northern basin. Number of flows and total unit thickness decrease from south to north through the basin. The unit contains interbeds, some traceable for miles (kilometers). Alternating phyric and aphyric flows. Source east of Pasco Basin.	Aphyric Unit *Top*: Variable. *Interior*: Entablature generally well developed with hackly jointing. *Colonnade*: Poor to well developed with columns 5 to 6.5 feet (1.5 to 2 meters) in diameter. *Base*: Pillows locally found in Saddle Mountains. Phyric Unit *Interior*: Poor to well developed entablature, generally thin. *Colonnade*: Generally well developed with columns 1.5 to 5 feet (0.5 to 1.5 meters) in diameter. *Base*: Variable. NOTE: Flow-by-flow mapping is difficult, some areas are mapped as undivided Frenchman Springs because of similarity of features.	Aphyric unit *Color*: Black-gray fresh, weathers reddish brown. *Phenocrysts*: Plagioclase phenocrysts to 0.8 inch (2 centimeters) present, but not abundant. *Texture*: Fine-grained, dense, locally diktytaxitic. Phyric Unit *Color*: Greenish-gray fresh, weathers reddish black. *Phenocrysts*: Sparsely to abundantly phyric, large lateral and vertical variations, 1 to 7 percent, glomeroporphyritic clots 0.8 to 2 inches (2 to 5 centimeters). *Texture*: Medium to fine-grained, diktytaxitic commonly, some dense and glassy. NOTE: Local identifications have been proposed using alternating phyric and aphyric character.	Fluxgate: Normal Polarity (strong) Laboratory: Normal Polarity (A few significant differences in inclination between flows)
ELLENSBURG FORMATION	Vantage Sandstone	Unit is thickest in northwest Pasco Basin, locally absent but represented by Grande Ronde saprolite to the east.	Horizontal and cross bedded sandstone.	Fine-to medium-grained micaceous quartzose sand.	Not Determined

Table III-2 (continued)

FORMATION UNIT	GENERAL STRATIGRAPHY	OUTCROP OR BOREHOLE CHARACTERISTICS	HAND SPECIMEN AND PETROGRAPHIC CHARACTERISTICS	MAGNETIC PROPERTY
Sentinel Bluffs Sequence (High MgO)	Unit is 900 to 1,000 feet (275 to 300 meters) thick and consists of at least 13 flows; flow units are thinner in northeastern Pasco Basin. Unit occurs throughout Pasco Basin, contains local, thin, discontinuous interbeds. Source area is east of Pasco Basin.	*Top*: Flow-top breccia locally up to 50 feet (15 meters) thick. *Interior*: Entablature thickness variable, fanning columns common, tiered flows present. *Colonnade*: Variable thickness. *Base*: Vesicle cylinders and vesicle sheets in some flows, some pillow and palagonite zones. NOTE: Locally contains large vesicles throughout individual flows, "rafted" petrified wood occurs at various levels.	*Color*: Black-gray fresh, locally some flows weather to a distinctive orange-brown or gray. *Phenocrysts*: Aphyric, some slightly phyric flows, some with distinctive microphenocrysts. *Texture*: Fine-grained, locally medium-grained, dense, diktytaxitic texture locally distinctive in some flows, glassy. NOTE: Outcrop and hand specimen characteristics are locally distinctive between some flows and useful for mapping.	Fluxgate: Normal Polarity Laboratory: Normal polarity (Significant differences in inclination between flows)
Low K_2O Flows	Total thickness of unit is not known, contains at least 2 flows. Surface outcrops are unknown in Pasco Basin. Does not extend into the northern Pasco Basin. Source area east of Pasco Basin.	Surface outcrops are unknown in Pasco Basin.	*Color*: Black fresh, weathers gray. *Phenocrysts*: Aphyric. *Texture*: Fine grained.	Fluxgate: No surface exposure mapped Laboratory: Normal Polarity
Schwana Sequence (Low MgO)	Total thickness of unit is not known. Minimum of 25 flows occurs throughout Pasco Basin. Contains local, thin, discontinuous interbeds. Source area east of Pasco Basin.	*Top*: Locally up to 137 feet (42 meters) thick flow-top breccia. *Interior*: Entablature commonly constitutes high percent of flow. *Colonnade*: Variable thickness, very thin in some thicker flows with interior almost entirely entablature.	*Color*: Greenish-gray fresh. *Phenocrysts*: Plagioclase up to 0.5 inch (1 millimeter). *Texture*: Medium-grained, aphyric with rare plagioclase phenocrysts.	Fluxgate: Normal NOTE: Only 1 flow below N_2R_2horizon outcrops in Pasco Basin) Laboratory: Normal and Reverse

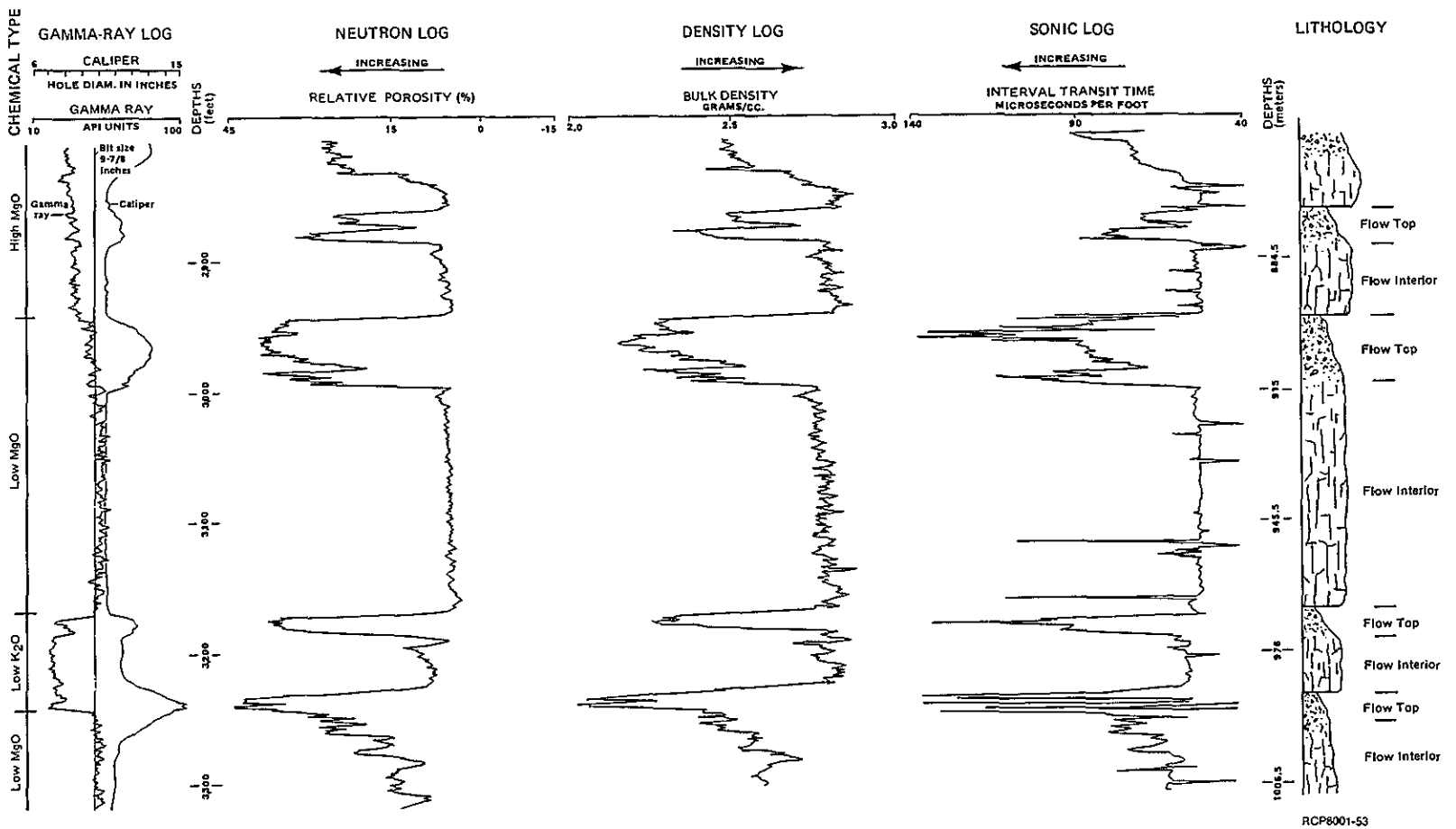

FIGURE III-2. Illustrative Borehole Geophysical Log Response in Columbia River Basalt. Flow tops have higher porosity, lower density, and higher interval transit time than flow interiors. Gamma-ray log is sensitive to chemical types with different potassium content.

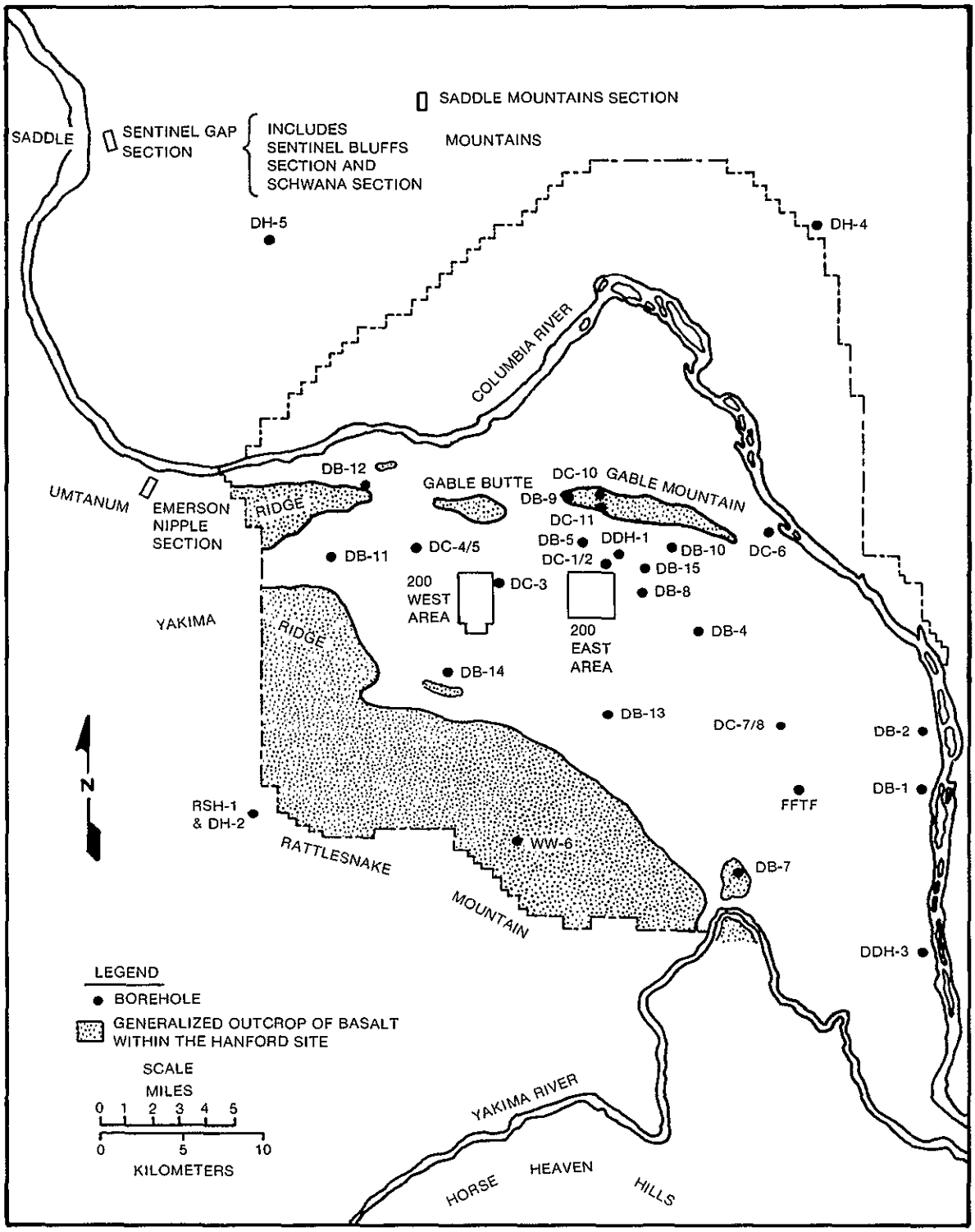

FIGURE III-3. Pasco Basin Boreholes and Surface Locations. Deep rotary boreholes are Walla Walla Number 6 (WW-6), RSH-1, DC-1, DC-3, DC-5, and DC-7. Core holes are all prefixed DC- (except DC-5 and DC-7), DB-, DH-, and DDH-. FFTF is a borehole drilled at the Fast Flux Test Facility. Cable tool holes and rotary-drilled water wells are not shown.

responds to thin but porous zones, such as vesicle sheets, and has a high degree of correlative character. Thus, not only can individual lava flows be correlated, but some intraflow structures can also be correlated because many lava flows have some internal patterns of vesicularity and fracturing that are laterally persistent, generally, over distances of about 5 miles (8 kilometers) or more. These flows can be correlated using borehole geophysical logs to identify similarity of fracture patterns.

Grande Ronde Basalt

Grande Ronde Basalt has been penetrated by 7 deep core holes and 5 deep rotary holes drilled in the Pasco Basin (a sixth rotary hole, Walla Walla Number 6, in the old Rattlesnake Hills gas field, also probably penetrated the Grande Ronde Basalt, but this hole has not been reentered and logged). The 7 core holes are: DH-4; DH-5; DC-2; DC-4; DC-6; DC-8; and, DDH-3. The 5 rotary holes are: DC-1; DC-3; DC-5; DC-7; and, RSH-1. (Note: DC-2/DC-1, DC-4/DC-5, and DC-8/DC-7 are core hole/rotary hole pairs, drilled at the same location.) Chemical analyses, paleomagnetic analyses, and lithologic logs have been made from continuous core sections. Borehole geophysical logs have been obtained from the rotary holes and from some core holes (Appendix A). In addition, chemical and paleomagnetic analyses of measured stratigraphic sections have been made from thick Grande Ronde Basalt exposures on Umtanum Ridge near Emerson Nipple and at Sentinel Gap. Borehole and surface section locations are shown on Figure III-3.

Grande Ronde Basalt correlations are shown on Plate III-2. Grande Ronde Basalt units in the Pasco Basin have been subdivided into two informal rock-stratigraphic units based on dominant chemical types: (a) the Sentinel Bluffs sequence, consisting entirely of flows with relatively abundant MgO (high-MgO chemical type); and, (b) the Schwana sequence, stratigraphically below, consisting mostly of flows with relatively less MgO (low-MgO chemical type) and a thin zone of low K_2O (very high-MgO chemical type). The contact between the Sentinel Bluffs sequence and the Schwana sequence is informally known as the "MgO horizon" (Plate III-2) and has been recognized for several years in the Pasco Basin (Myers, 1973; Brown and Ledgerwood, 1973). Basalts of the Sentinel Bluffs sequence average about 5.0 percent MgO; basalts of the Schwana sequence average about 3.5 percent MgO, except for the low K_2O flows which average about 5.5 to 6.0 percent MgO (additional information on the whole rock chemistry of these units is presented in a separate section of this chapter). The contact between the Sentinel Bluffs sequence and the Schwana sequence, the MgO horizon, is a fundamental stratigraphic horizon in the upper Grande Ronde Basalt of the Pasco Basin. Because of the sharp chemical contrast across the MgO horizon, it can be traced between boreholes and surface sections throughout the Pasco Basin.

Schwana Sequence. The Schwana sequence occurs throughout the Pasco Basin, but only in the subsurface in the southern part of the basin. Schwana sequence flows are exposed in the cliffs along Lower Crab Creek located southeast of Schwana near Sentinel Gap (Figure III-4). The MgO horizon, which has been previously identified at that location by the Atlantic Richfield Hanford Company (ARHCO, 1976), Taylor (1976), and Long (1978), defines the top of the sequence. The bottom of the Schwana sequence has not been defined, but is tentatively set at the top of the thick, weathered zone at about the 5,000-foot (1,280-meter) drilled depth in RSH-1 (Raymond and Tillson, 1968), which is also interpreted as the base of the Grande Ronde Basalt (Swanson and Others, 1979b). DH-4 and DH-5 are interpreted to have penetrated nearly 2,500 feet (750 meters) of Schwana sequence consisting of 15 to 25 separate flows. The only outcrops of the Schwana sequence in the Pasco Basin are at Sentinel Gap (Plates III-3b and 3c) and near Emerson Nipple on Umtanum Ridge (Plate III-3a; Figure III-5). Measured sections from these outcrops are included on the stratigraphic section, Plate III-2.

Correlations of chemical stratigraphic units and magnetostratigraphic units within the Schwana sequence are shown on Plate III-2. In DH-4 and DH-5, 5 chemical stratigraphic units are identified and correlated in the low-MgO chemical type and correlated between the 2 boreholes. These chemical stratigraphic units were identified by the pattern of vertically changing TiO_2 and MgO values plotted on the DH-4 and DH-5 strip logs. The 5 chemical stratigraphic units are shown on Table III-3 with the equivalent rock units in each borehole. These correlations are consistent with earlier correlations by Myers (1973) and in a report to Atlantic Richfield Hanford Company by Waters (1976). Both correlations were made on the basis of atomic absorption analyses, which are less precise and accurate than the X-ray fluorescence analyses used in this report. Statistically significant between-flow variations in P_2O_5, Zr, and Cr can probably be used to further subdivide the chemical stratigraphic units in the Schwana sequence; this is being evaluated.

Only SCH-1, the uppermost chemical stratigraphic unit in the Schwana sequence penetrated by DH-4 and DH-5, is correlated to other core holes in the Pasco Basin. None of the other core holes, except DC-6, was drilled deep enough to have penetrated chemical stratigraphic units below SCH-1. Chemical stratigraphic units below SCH-1 may have been penetrated in DC-6. Chemical data from DC-6 are still under study.

In the central and southern Pasco Basin boreholes (DC-1, DC-2, DC-3, DC-4, DC-5, DC-6, DC-7, DC-8, RSH-1, and DDH-3), a low-K_2O (very high-MgO) chemical type basalt sequence of 1 to 2 flows is interlayered within the upper Schwana sequence about 200 to 400 feet (64 to 120 meters) stratigraphically below the MgO horizon (Plate III-2). The low-K_2O flows are chemically similar to Flow Group C (Reidel, 1978a) in the type area of the Grande Ronde Basalt. The low-K_2O basalt sequence within the upper Schwana sequence is characterized by basalt compositions distinctively low in K_2O and high in MgO relative to other Grande Ronde Basalt compositions. Stratigraphically, the Umtanum flow (described in more detail

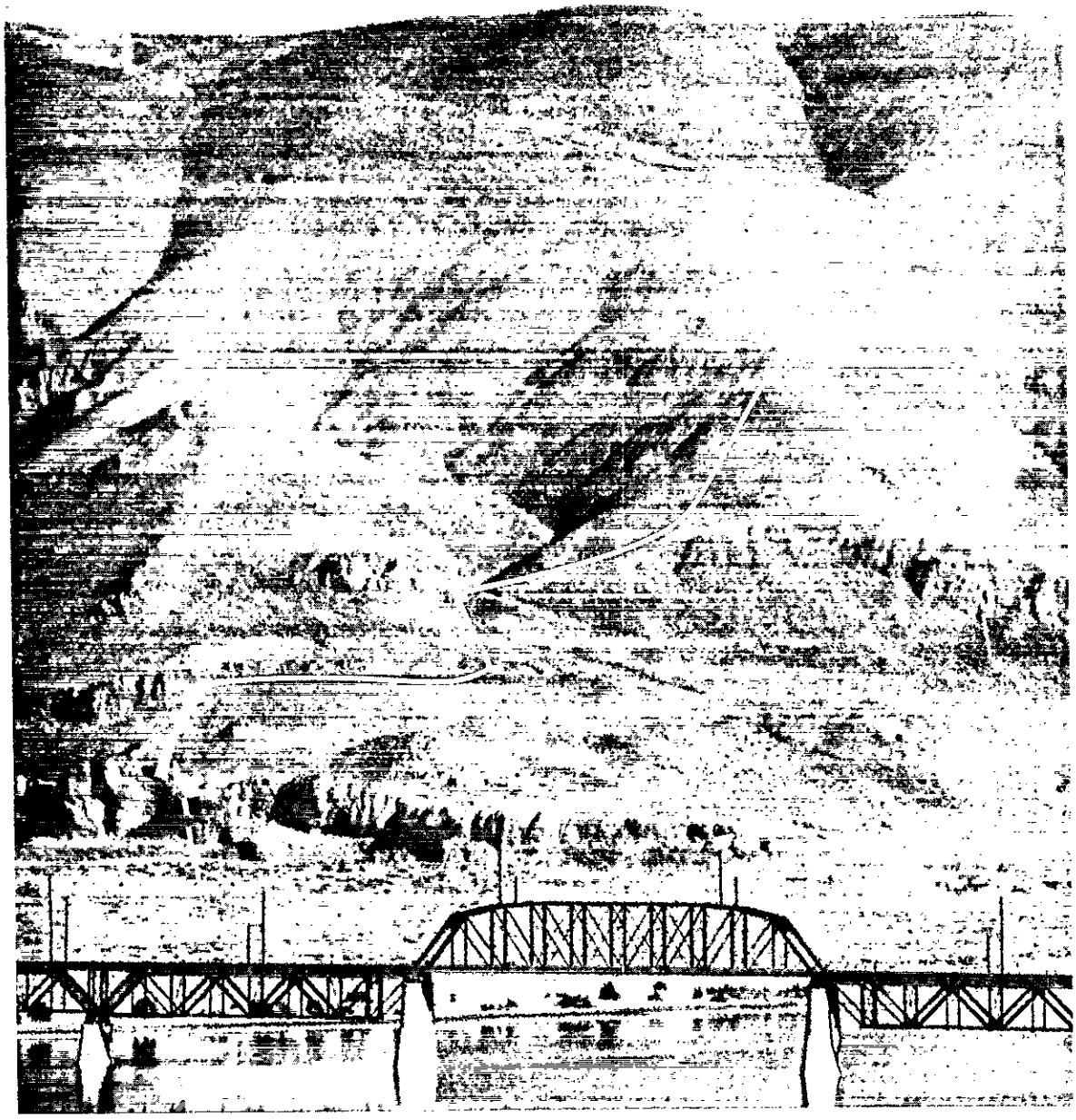

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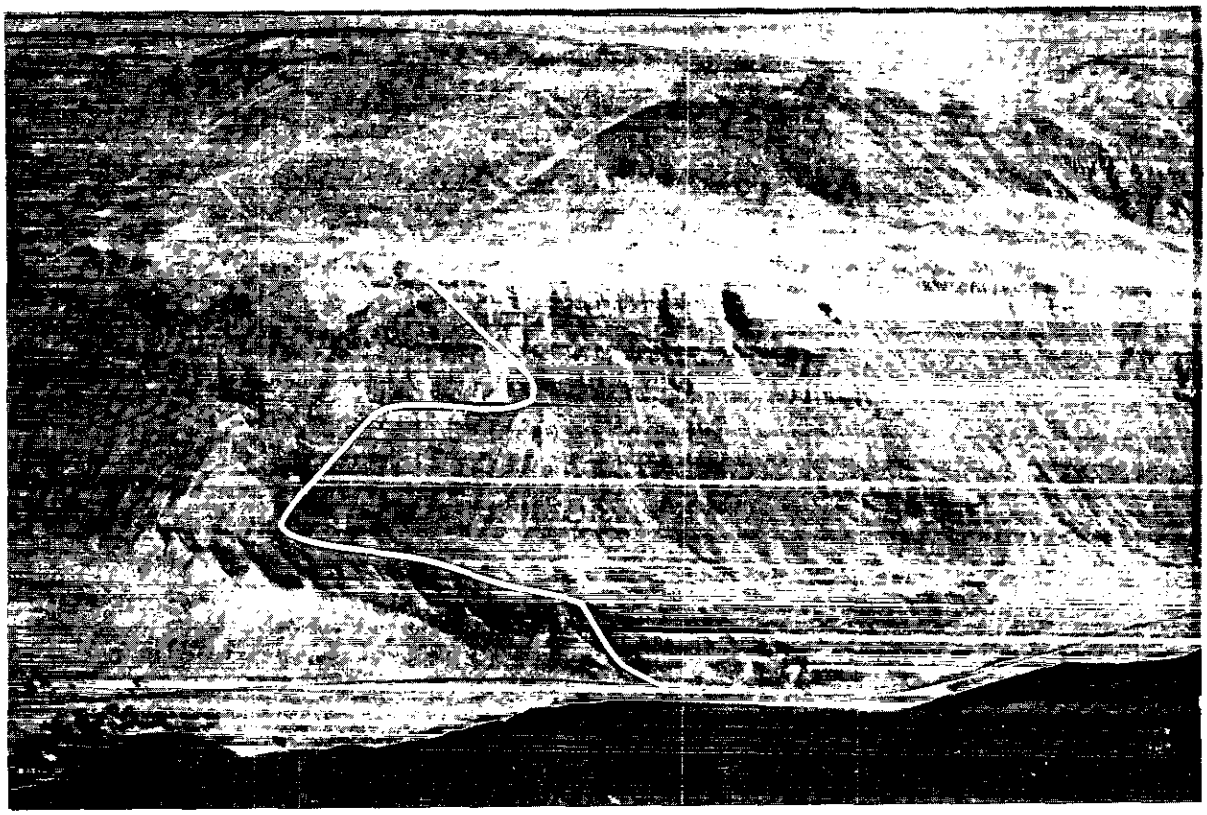
FIGURE III-4. Schwana Sequence Exposure along Lower Crab Creek. Line shows traverse of measured section (Plate III-3c).



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(a) Exposure at Sentinel Gap. Line shows traverse of measured section (Plate III-3b).

FIGURE III-5. Sentinel Bluffs Sequence.

52594-80

(b) Exposure at Emerson Nipple. Line shows traverse of measured section (Plate III-3a).

Figure 5 (continued)

TABLE III-3. Chemical Stratigraphic Units in the Schwana Sequence, DH-4 and DH-5.

CHEMICAL STRATIGRAPHIC UNIT		DH-5 ROCK UNITS	DH-4 ROCK UNITS
SCH-1	Umtanum Flow	DH-5/GR-9	DH-4/GR-10
		DH-5/GR-10	DH-4/GR-11
		DH-5/GR-11	DH-4/GR-12
		DH-5/GR-12	DH-4/GR-13
		DH-5/GR-13	DH-4/GR-14
			DH-4/GR-15
			DH-4/GR-16
			DH-4/GR-17a
			DH-4/GR-17b
SCH-2		DH-5/GR-14	DH-4/GR-18
		DH-5/GR-15	DH-4/GR-19
		DH-5/GR-16	DH-4/GR-20a
		DH-5/GR-17	DH-4/GR-20b
		DH-5/GR-18	DH-4/GR-20c
		DH-5/GR-19a	DH-4/GR-20d
			DH-4/GR-21
			DH-4/GR-22
			DH-4/GR-23
SCH-3		DH-5/GR-19b	DH-4/GR-24a
		DH-5/GR-20	DH-4/GR-24b
		DH-5/GR-21	DH-4/GR-24c
			DH-4/GR-25
			DH-4/GR-26
			DH-4/GR-27a
			DH-4/GR-27b
SCH-4		DH-5/GR-22	DH-4/GR-27c
		DH-5/GR-23	DH-4/GR-28a
		DH-5/GR-24	DH-4/GR-28b
			DH-4/GR-29
SCH-5		DH-5/GR-25	DH-4/GR-30
		DH-5/GR-26	DH-4/GR-31
			DH-4/GR-32a
			DH-4/GR-32b

Units DH-4/GR-27a, -27b, -32a, and -32 b appear to have no chemical-stratigraphic equivalents in DH-5.

SCH-1 refers to chemical stratigraphic unit Number 1 in the Schwana sequence.

below) directly overlies the low K_2O flows, except in DC-8 and DDH-3 where flows DC-8/GR-12, DC-8/GR-13, and DDH-3/GR-13, respectively, occur between the Umtanum flow and the low K_2O flows. The northernmost extent of the low K_2O flow is in the central Pasco Basin north of Gable Mountain and Gable Butte, south of DH-4 and DH-5, and between DC-4 and the Emerson Nipple section. The low-K_2O flows are interpreted to occur throughout the southern Pasco Basin subsurface, but to be absent in the northern Pasco Basin (Figure III-6).

Four magnetostratigraphic units within the Schwana sequence are shown on Plate III-2. Four magnetostratigraphic horizons were identified by Packer and Petty (1979). The lowermost magnetostratigraphic horizon, horizon X, was identified by Packer and Petty (1979) in core hole DH-4, but was not correlated by them to any other core holes. Horizon X represents a stratigraphically upward polarity change from normal to reversed. A polarity change in the same sense occurs in DH-5 between 4,095 and 4,339 feet (1,248 and 1,322 meters), and borehole units DH-5/GR-21 and DH-4/GR-26 have the same polarity and fall within the same chemical stratigraphic unit. Magnetostratigraphic horizon X is thus correlated into DH-5 at 4,339 feet (1,322 meters); it is probably the R_2/N_1 horizon recognized elsewhere in the Columbia Plateau (see Chapter II).

The next magnetostratigraphic horizon, horizon W, was identified and correlated by Packer and Petty (1979) between boreholes DH-4, DH-5, and the Sentinel Gap section. It represents a stratigraphically upward polarity change from reversed to normal, and is probably the N_2/R_2 horizon recognized in Grande Ronde Basalt elsewhere in the Columbia Plateau (see Chapter II). DC-6 appears not to have penetrated horizon W, but the paleomagnetic data from DC-6 in this interval are enigmatic (Packer and Petty, 1979). Interestingly, DC-4, DC-8, and DDH-3 would have crossed horizon W if they had been drilled slightly deeper, and horizon W probably lies about 300 feet (90 meters) beneath the lowermost exposed flows at the Emerson Nipple section.

The third and fourth magnetostratigraphic horizons in the Schwana sequence are horizons U and V, respectively. These two horizons bound a basalt unit which has an anomalously low average inclination and is, in effect, a magnetostratigraphic marker horizon. This basalt unit has been correlated throughout the Pasco Basin and is interpreted as a single flow, the Umtanum flow. The Umtanum flow is recognized by its distinctive chemical composition compared to surrounding flows. Indeed, the chemical composition of the Umtanum flow apparently distinguishes it as a single flow; whereas the magnetostratigraphic interval between horizons U and V in some places includes more flows than the Umtanum flow; these other flows have compositions slightly different from the Umtanum. Specifically, this interval consists of two flows in DDH-3, two or more flows in DH-4, and at Sentinel Gap. In all other core holes and at Emerson Nipple, the U and V stratigraphic interval bounds a single, thick flow identified chemically as the Umtanum flow. Magnetostratigraphic horizon U coincides with the MgO horizon.

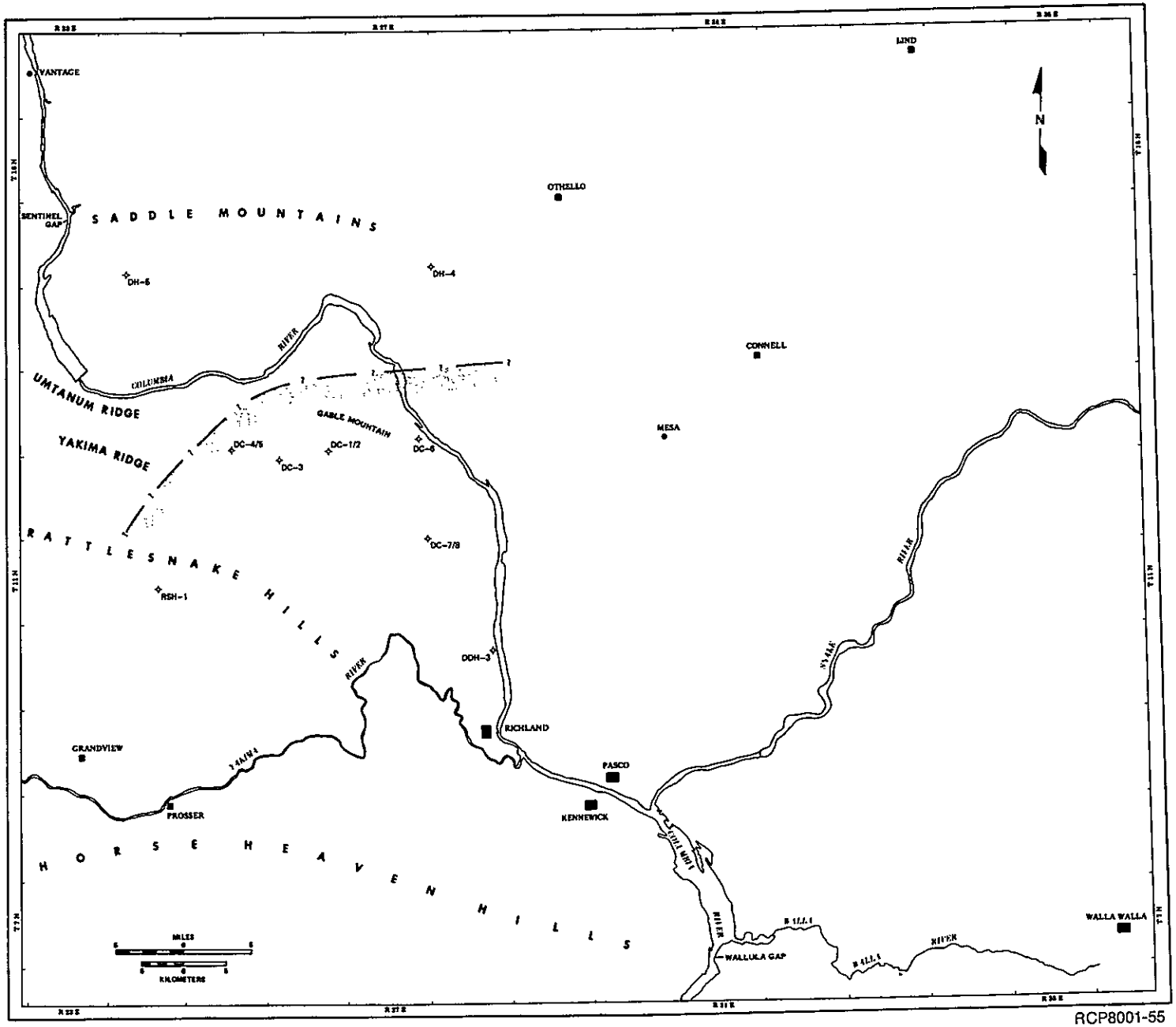

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FIGURE III-6. Extent of Low K_2O (Very High-Mg) Chemical Type Flows in the Pasco Basin.

In DC-2, DC-4, and DC-6, magnetostratigraphic horizon V coincides with the contact between the Umtanum flow and the low K_2O flows. In core hole DC-8, 2 flows, DC-8/GR-12 and DC-8/GR-13, are between the Umtanum flow and the low-K_2O flows, and placement of magnetostratigraphic horizon V is correlated between the Umtanum flow and DC-8/GR-12. Likewise in DDH-3, a 114-foot (35-meter) thick flow, DDH-3/GR-13, is between the Umtanum flow and the low-K_2O flow, and placement of magnetostratigraphic horizon V is between the Umtanum flow and DDH-3/GR-13. In DH-5 and in the Sentinel Gap and Emerson Nipple field sections, magnetostratigraphic horizon V coincides with the contact between the Umtanum flow and the underlying flows of chemical stratigraphic unit SCH-1. The correlation of magnetostratigraphic horizons U and V into DH-4 is tentatively made as shown on Plate III-2.

Sentinel Bluffs Sequence. The Sentinel Bluffs sequence occurs throughout the Pasco Basin. The informal type locality of the Sentinel Bluffs sequence is along the cliffs named Sentinel Bluffs on the east side of the Columbia River at Sentinel Gap (Figure III-5a). The top of the Sentinel Bluffs sequence is also the top of the Grande Ronde Basalt at this locality, stratigraphically above is the Vantage Member. The base of the Sentinel Bluffs sequence is the MgO horizon, which is the top of the Schwana sequence at this locality. The Sentinel Bluffs sequence was completely penetrated by 12 boreholes at 9 separate locations in the Pasco Basin (Figure III-3). The top and base of this sequence are exposed at Sentinel Gap and at Emerson Nipple on eastern Umtanum Ridge (Figure III-5b). The top of the Sentinel Bluffs sequence is exposed along the north face of the Saddle Mountains, along the north side of Umtanum Ridge, at scattered locations in the Rattlesnake Hills, and in the Wallula Gap area. The thickness of the unit appears to be remarkably constant across the Pasco Basin averaging 895 feet (272 meters) (range = 726 to 975 feet [221 to 297 meters]) using the thicknesses on Figure III-7. The map showing drilled thickness variation suggests that the Sentinel Bluffs sequence is thin in the northeastern Pasco Basin (724 feet [241 meters]) in DH-4 relative to the southwest (940 feet [313 meters]) in DC-3. The number of flows or flow units also appears to change from 8 to 12 in the central basin to 5 in DH-4. Farther to the southwest at RSH-1, the drilled thickness of the Sentinel Bluffs is 914 feet (304 meters). The contact between the Sentinel Bluffs sequence and Schwana sequence in RSH-1 was identified using the spectrochemical analyses of chip samples reported in Raymond and Tillson (1968) and using the gamma-ray log.

Correlations within the Sentinel Bluffs sequence are shown on Plate III-2. No chemical stratigraphic units have been identified to date in the Sentinel Bluffs sequence because of the chemical similarity of the flows; therefore, the Sentinel Bluffs sequence is shown on Plate III-2 as one chemical stratigraphic unit--the high MgO chemical type. Magnetostratigraphic units and borehole geophysical log stratigraphic units, however, have been identified and correlated in the Sentinel Bluffs sequence.

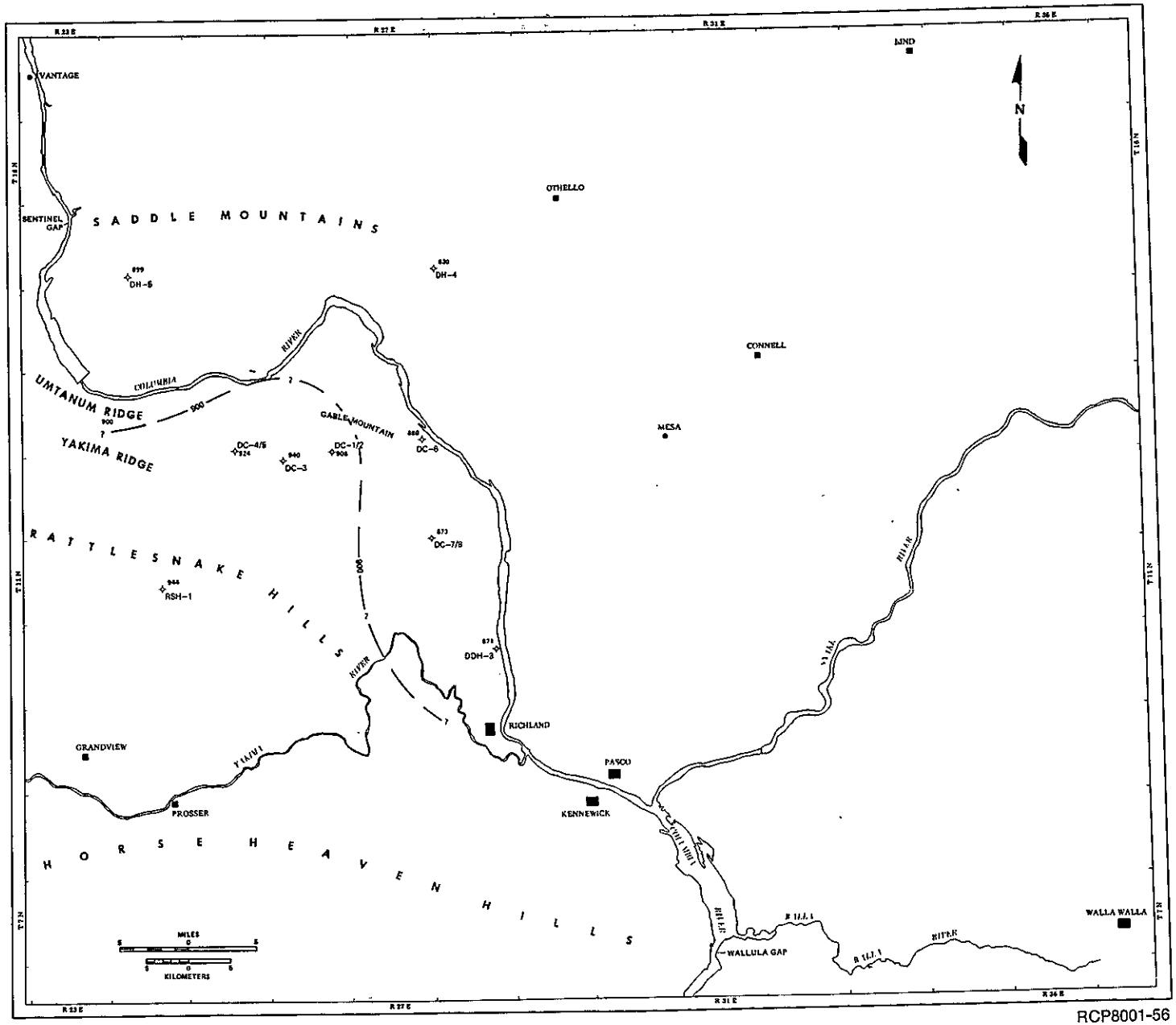

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FIGURE III-7. Preliminary Isopach Map, Sentinel Bluffs Sequence.

Two new magnetostratigraphic horizons, horizons T and S, were identified by Packer and Petty (1979) within the Sentinel Bluffs sequence. Horizon T was tentatively identified on the basis of inclination differences and correlated among five core holes in the Pasco Basin: DC-4; DC-6; DC-8; DH-4; and, DH-5, and to one surface section, the Sentinel Gap section. This magnetostratigraphic correlation appears more reliable in the northern Pasco Basin between DH-4, DH-5, and the Sentinel Gap surface section. Horizon S was also identified by Packer and Petty (1979) on the basis of inclination differences. It was correlated among four core holes: DC-2; DC-4; DC-6; and, DC-8; and two surface sections, Sentinel Gap and Emerson Nipple. The identification and correlation of horizon S is, overall, more definite than that of horizon T.

Several borehole geophysical log stratigraphic units have been identified in the Sentinel Bluffs sequence. These correlations are shown on Plate III-2. The borehole geophysical log correlations have been made among four boreholes: DC-2; DC-3; DC-4; and, DC-8; all are in the central Pasco Basin. These correlations are shown on Plate III-2.

Interpretations of rock (lava flow) stratigraphy have been made for the Sentinel Bluffs sequence and upper Schwana sequence in the central Pasco Basin (Figure III-8). These interpretations were made using the magnetostratigraphic correlations and borehole geophysical logs from the closely spaced boreholes in that area. As shown on Figure III-8, the Sentinel Bluffs sequence and upper Schwana sequence can be considered as a section containing a few uniformly thick "through-running" flows separated by thicker sequences of several flows within which some individual flows vary in thickness and probably pinch out within the Pasco Basin. These subdivisions have been informally named as follows: (a) upper Sentinel Bluffs sequence; (b) the middle Sentinel Bluff sequence through-runner; (c) the lower Sentinel Bluffs sequence; and, (d) the Umtanum flow, also a through-runner. The upper Sentinel Bluffs sequence, the middle Sentinel Bluffs sequence through-runner, and the lower Sentinel Bluffs sequence collectively constitute the total Sentinel Bluffs sequence, and the Umtanum flow is the uppermost unit in the Schwana sequence (compare Figure III-8 and Plate III-2).

The middle Sentinel Bluffs sequence through-runner is consistently 260 feet (±10 feet) (87 meters) thick in the central Pasco Basin boreholes. It contains a central vesicular zone that is locally brecciated, which indicates that it was probably emplaced as two flows or flow units. This central vesicular zone is well developed in DC-7 and DC-8 in the central Pasco Basin and more subdued in DC-4 and DC-5 in the western Pasco Basin. Logs through the unit show a high degree of internal correlative character, probably representing tiered columnar joints or laterally continuous intraflow structures.

Vantage Member (Ellensburg Formation). The Vantage Member, a sedimentary interbed, is exposed along the north face of Umtanum Ridge and the north face of the Saddle Mountains, and is penetrated by deep boreholes in the Pasco Basin (Figure III-9). Small, scattered exposures of the Vantage Member are present elsewhere in the southern and western Pasco Basin.

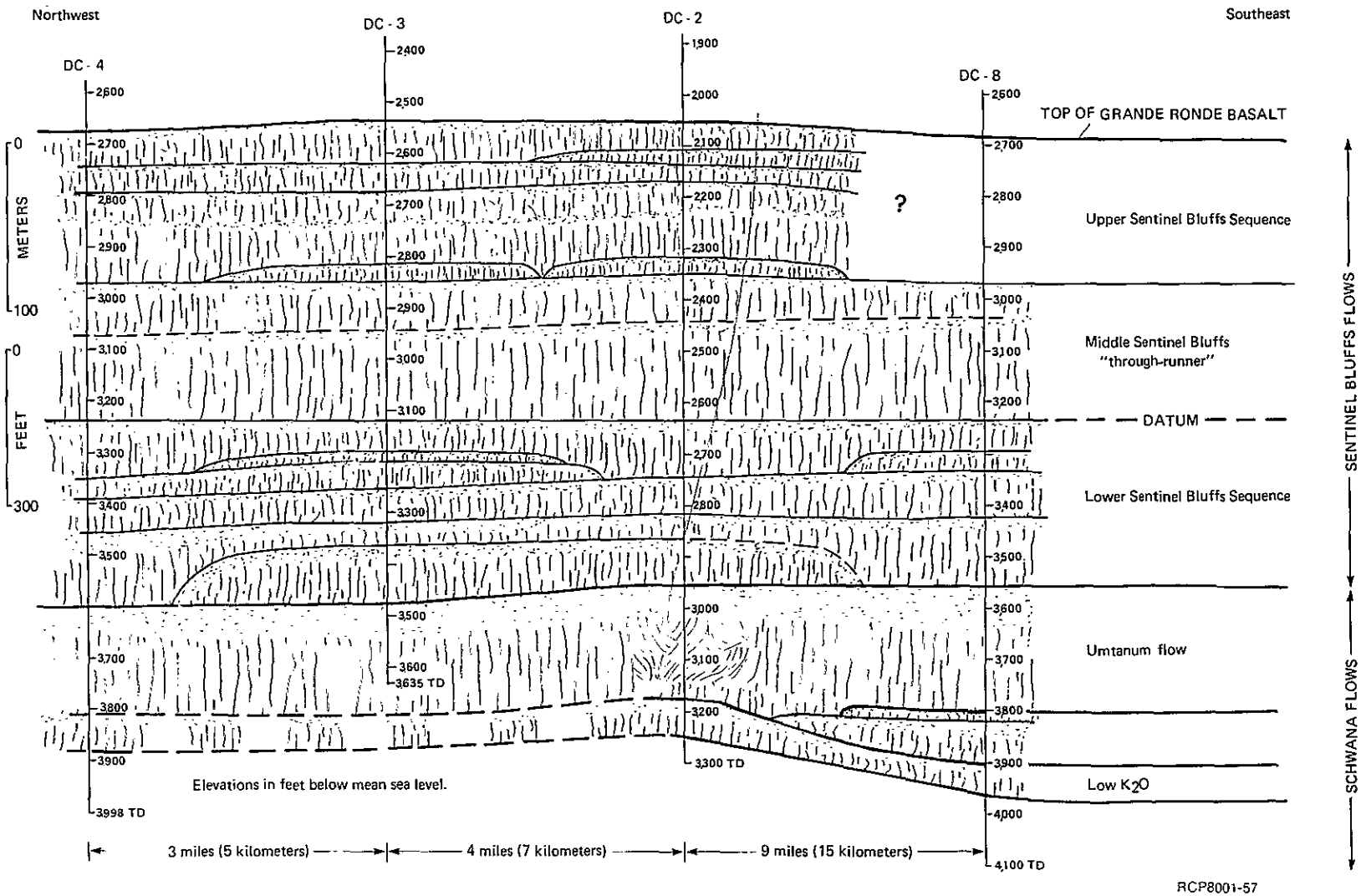

FIGURE III-8. Interpretation of Rock-Stratigraphic Units in the Sentinel Bluffs Sequence and Upper Schwana Sequence of the Central Pasco Basin.

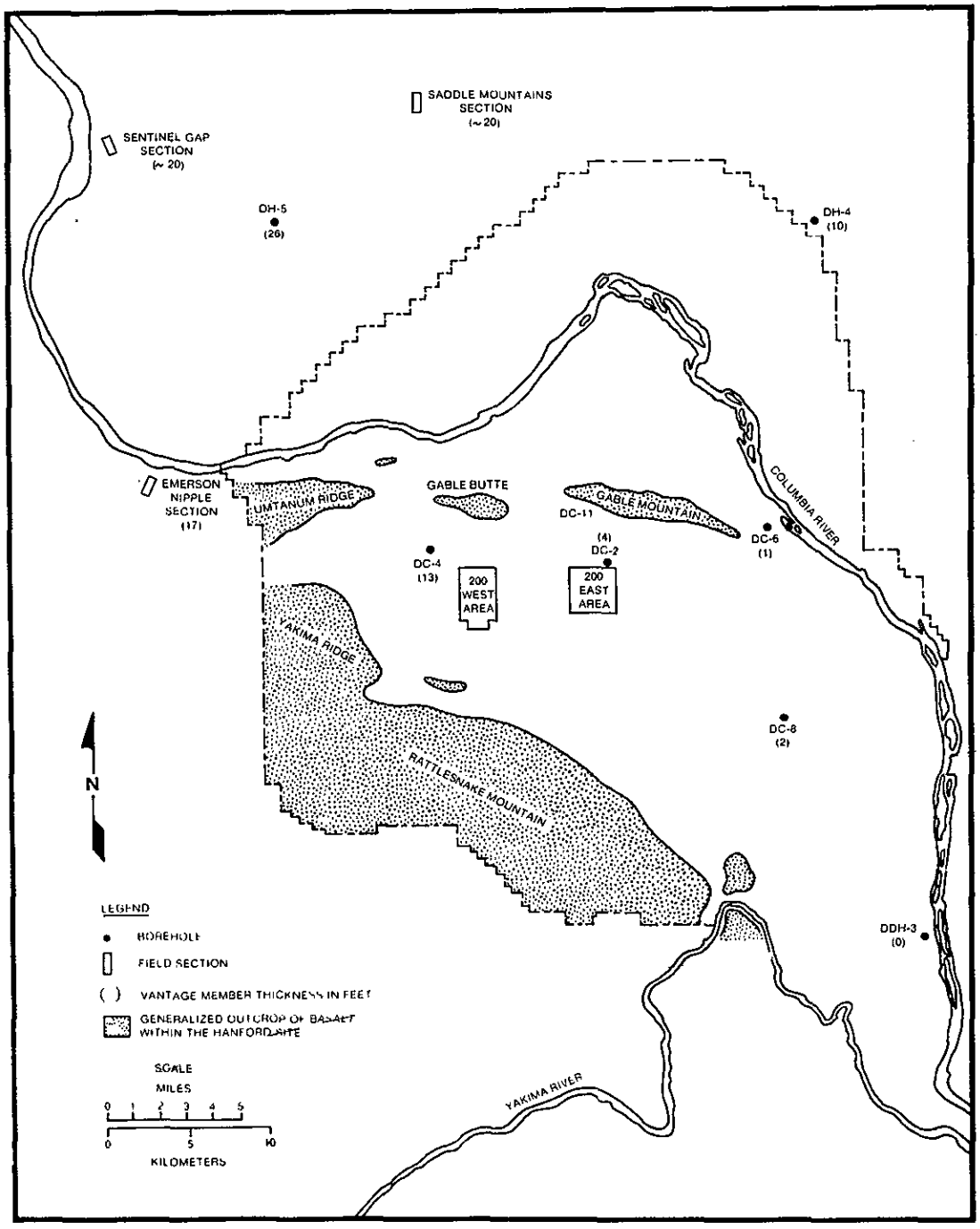

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FIGURE III-9. Vantage Member Thicknesses, Pasco Basin.

The drilled thickness of the Vantage Member varies from 0 to 26 feet (0 to 7 meters) and is greatest in the northwestern Pasco Basin where it is best represented in DC-4 and DH-5 (Figure III-9). In DC-4, it is 13 feet (3.9 meters) of black clay, clayey sandstone, and loosely consolidated sandstone. Small, but distinct shears with up to 4 inches (10 centimeters) offset are in the lower part of the unit, but not the upper. The Vantage Member is 26 feet (8 meters) thick in DH-5 and its lithology is similar to DC-4. In the central and southern Pasco Basin, the Vantage Member is a black clay, probably a partly devitrified volcanic glass. The Vantage Member is absent and the upper Grande Ronde Basalt is a saprolite locally within the Pasco Basin and across large areas east of the Pasco Basin (Swanson and Others, 1979b).

Wanapum Basalt

The Wanapum Basalt consists of three members in the Pasco Basin: (a) Frenchman Springs Member; (b) Roza Member; and, (c) Priest Rapids Member (Table III-1). The Frenchman Springs Member and Roza Member contain flows of only one chemical type, but the Priest Rapids Member contains flows of two chemical types.

The Wanapum Basalt occurs throughout the Pasco Basin. It has been completely penetrated by 12 core holes at 9 locations, and, at 5 locations, boreholes have been drilled to the top of the Wanapum Basalt (Table III-4). The Wanapum Basalt crops out extensively along Umtanum Ridge and in the Saddle Mountains and thick sections of Wanapum Basalt are exposed in the Rattlesnake Hills, especially on Rattlesnake Mountain, and at Wallula Gap (Plate III-1).

Correlation of the Wanapum Basalt across the Pasco Basin is shown on Plate III-2, a stratigraphic section, and Plates III-5a to 5g, a series of structural sections. The Wanapum Basalt thickens to the southwest across the central Pasco Basin (Figure III-10) in a pattern similar to that suggested for the Sentinel Bluffs sequence (Figure III-5). A northwest-trending zone of Wanapum Basalt thinning was mapped in the Saddle Mountains by Reidel (1978a). Thickness trends of the Wanapum Basalt across the Saddle Mountains were based on extrapolations of observations on the flanks of the Saddle Mountains structure. The structural and tectonic implications of this zone are discussed in the structure section of this chapter and in Chapter IV.

Results of a pilot study by Packer and Petty (1979) revealed potentially correlative magnetostratigraphic units in the Wanapum Basalt of the Pasco Basin. Packer and Petty (1979) measured polarity and inclination variations in the 12 Wanapum Basalt units penetrated by DC-2 (Figure III-11). Units DC-2/W-1 and DC-2/W-2 at the top of the Wanapum section have reversed polarity and are probably Priest Rapids Member flows. Unit DC-2/W-3 below the Priest Rapids flows has a flat inclination and is probably the Roza Member. The 9 Wanapum units below the Roza Member, DC-2/W-4 to DC-2/W-12, have normal polarity and show variations in their inclination. The uppermost 4 flows (DC-2/W-4 to DC-2/W-7) average about 60 degrees, the next 3 lower flows (DC-2/W-8 to DC-2/W-10) average about 40 degrees, the next lower flow (DC-2/W-11) is about

TABLE III-4. Drilled Thickness of the Wanapum Basalt, Saddle Mountains Basalt, and Elevations of the Top-of-Wanapum Basalt.

DRILL SITE	BOREHOLES CORE	BOREHOLES ROTARY	SADDLE MOUNTAINS BASALT THICKNESS* (Feet)	SADDLE MOUNTAINS BASALT THICKNESS* (Meters)	WANAPUM BASALT THICKNESS (Feet)	WANAPUM BASALT THICKNESS (Meters)	ELEVATION OF TOP-OF-WANAPUM (Feet)	ELEVATION OF TOP-OF-WANAPUM (Meters)
1	DDH-3		972	296	1,040	317	-758	-321
2	DH-4		424	129	1,055	322	496	151
3	DH-5		479	146	1,022	306	248	76
4	DC-2	DC-1	410	125	1,113	340	-361	-110
5	DC-4	DC-5	900	274	1,148	350	-771	-235
6	DC-6		722	220	1,083	330	-670	-204
7	DC-8	DC-7	867	264	1,115	340	-1,025	-313
8		DC-3	890	271	1,105	337	-678	-207
9		RSH-1	475	145	773	236	2,405	733
10	DB-8		779	238			-483	-147
11	DB-11		593	181			-223	-68
12	DB-12		435	133			50	15
13	DB-13		948	289			-613	-187
14	DB-14		925	282			-419	-128

*Includes interbeds.

Borehole locations are shown on Figure III-3.

All thicknesses are drilled thicknesses uncorrected for structural dip.

NOTE: This list is restricted to boreholes drilled by Rockwell Hanford Operations or the Atlantic Richfield Hanford Company. Information on other boreholes--some of which are known to penetrate the Wanapum Basalt--is being collected.

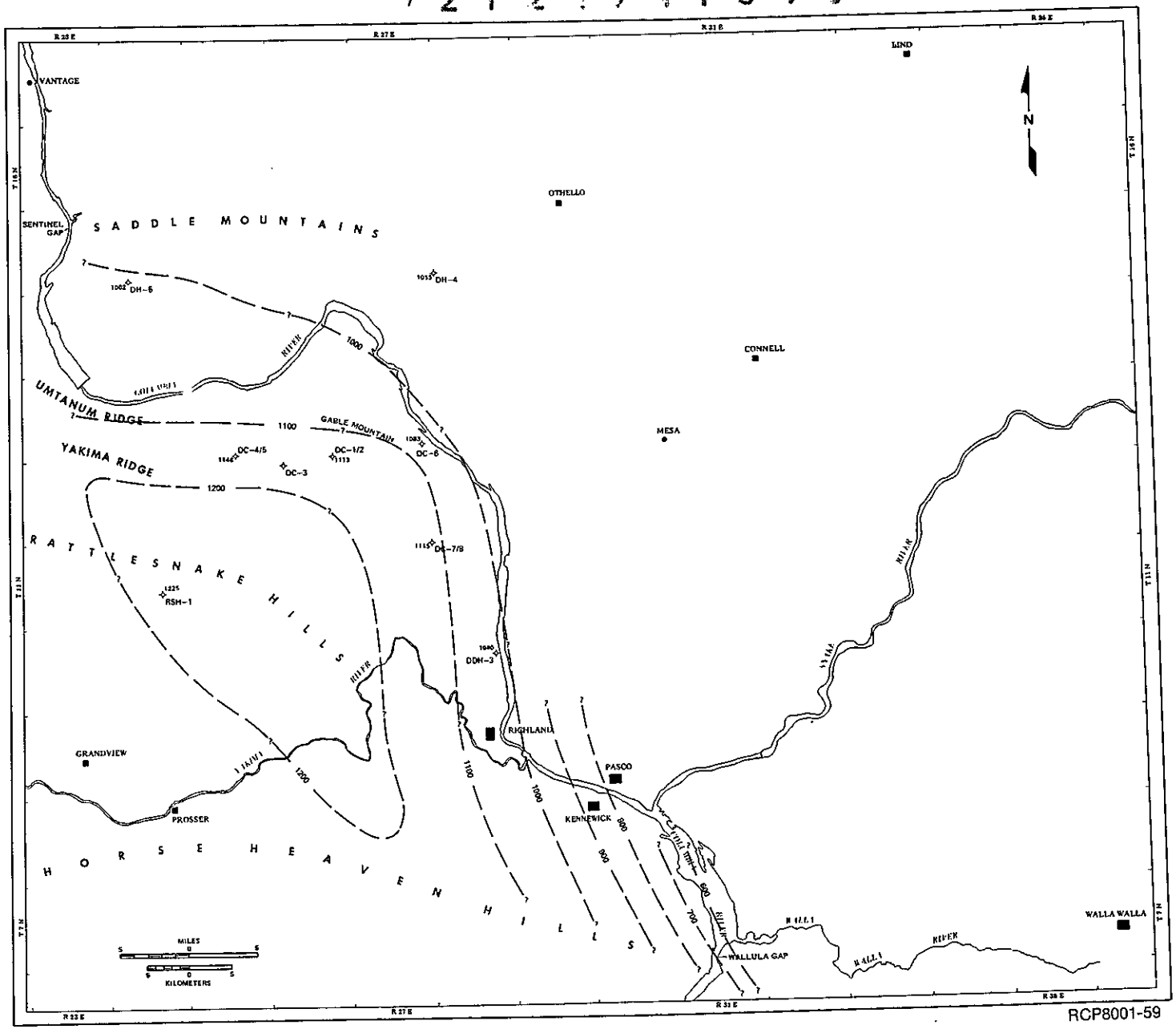
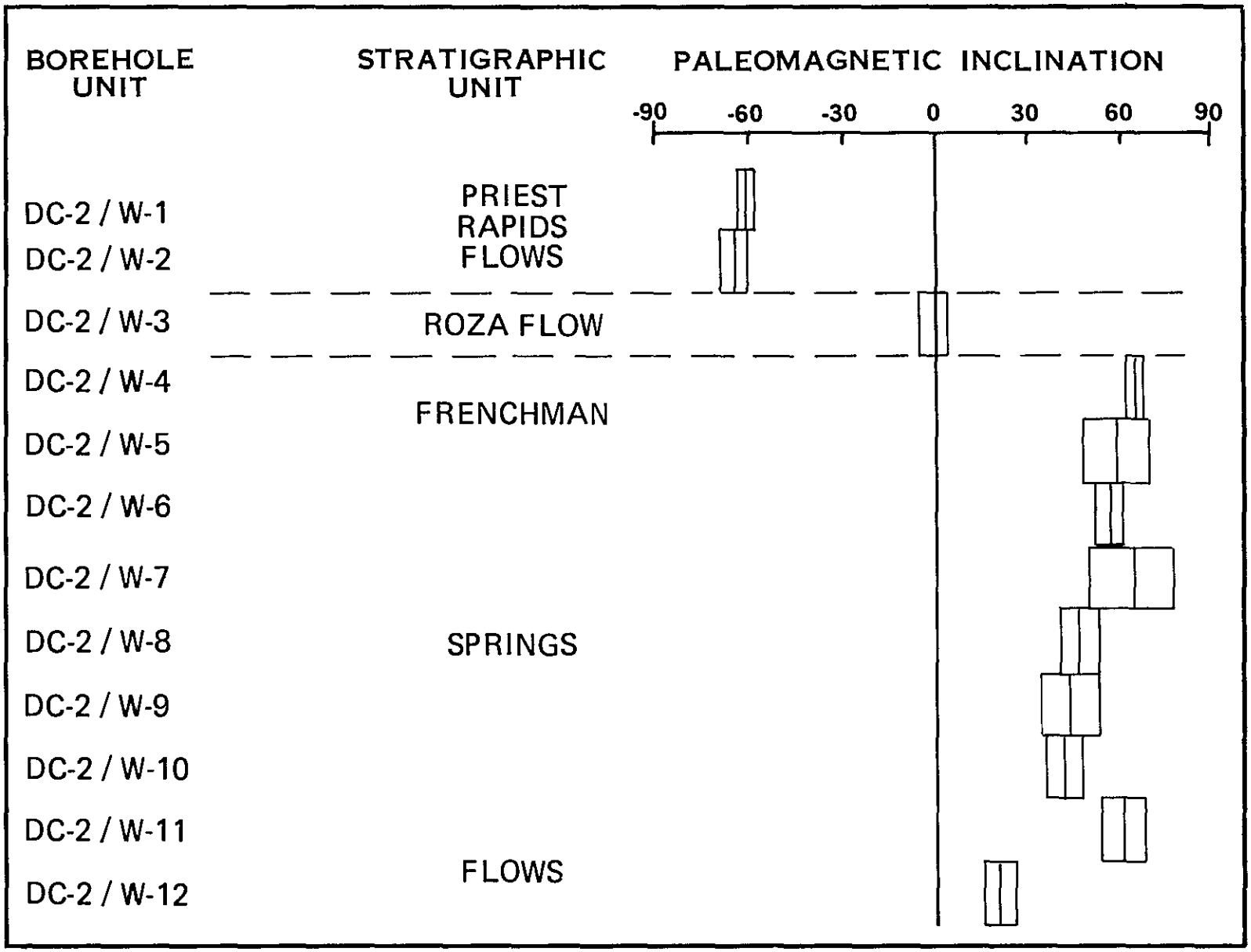


FIGURE III-10. Thickness Trends, Wanapum Basalt.



Note: Vertical dimension is not a scale of thickness.

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FIGURE III-11. Paleomagnetic Inclinations, Wanapum Basalt, Borehole DC-2 (after Packer and Petty, 1979).

60 degrees, and the lowermost flow (DC-2/W-12) has an inclination 20 degrees lower than any other Frenchman Springs flow in DC-2. The Frenchman Springs flows in DC-2 have a vertically changing pattern of inclination that indicates a good potential for magnetostratigraphic correlations, but because inclination measurements have not been made in the Wanapum Basalt units in other core holes, this is unconfirmed. However, the borehole geophysical log character of units DC-2/W-11 and DC-2/W-12 is correlative, and these two units have been correlated to nearby core holes as shown on Plate III-2. Thus, magnetostratigraphic correlations combined with borehole geophysical log correlations offer good potential for subsurface correlations of Wanapum Basalt.

Frenchman Springs Member. The Frenchman Springs Member is stratigraphically the lowermost unit of the Wanapum Basalt in the Pasco Basin and occurs throughout the basin. The map showing thickness trends of the Frenchman Springs Member (Figure III-12) depicts a pattern somewhat similar to the thickening pattern of the Wanapum Basalt. Near Vantage, the Frenchman Springs Member is approximately 350 feet (106 meters) thick (Myers, 1973), it gradually thickens toward the Saddle Mountains, and, from a zone near Sentinel Gap, it appears to abruptly thicken to the south and east. South of Othello, the Frenchman Springs Member is approximately 600 feet (183 meters) thick and is over 800 feet (244 meters) thick near the Rattlesnake Hills. The number of flows or flow units in the Frenchman Springs Member roughly correlates with the thickness of the unit. Near Vantage, there are 3 flows, but the number increases to between 8 and 10 near the center of the basin.

Correlation of individual flows within the Frenchman Springs Member is difficult because the flows are similar chemically and all have positive paleomagnetic polarity. As noted above, inclination variation combined with borehole geophysical logs offer good potential. Bentley (1977b) proposed use of between-flow variations in phenocryst abundance to identify and correlate Frenchman Springs flows, and named flows according to these abundances. During geologic mapping in the Pasco Basin, the Frenchman Springs flows were identified only as either phyric or aphyric (Plate III-1) and no names were used.

Roza Member. The Roza Member is stratigraphically above the Frenchman Springs and below the Priest Rapids (Figure III-1). Two flows occur throughout the Pasco Basin and, according to Bond and Others (1978), there might be three.

The thickness of the Roza Member varies across the Pasco Basin (Figure III-13). The Roza Member is thin in the southeastern Pasco Basin relative to the central Pasco Basin and it is interpreted to pinch out between the Pasco-Kennewick area and Wallula Gap. The Roza Member is thick in the central Pasco Basin, apparently along a northerly trend, and thins toward the Rattlesnake Hills and Saddle Mountains. Three zones of Roza non-deposition have been interpreted in the Saddle Mountains (Figure III-13): one zone near the west side of Smyrna Bench corresponds to the zone of thinning on the Wanapum isopach map; a second zone occurs near the east side of Smyrna Bench; and, a third occurs near Sentinel Gap.

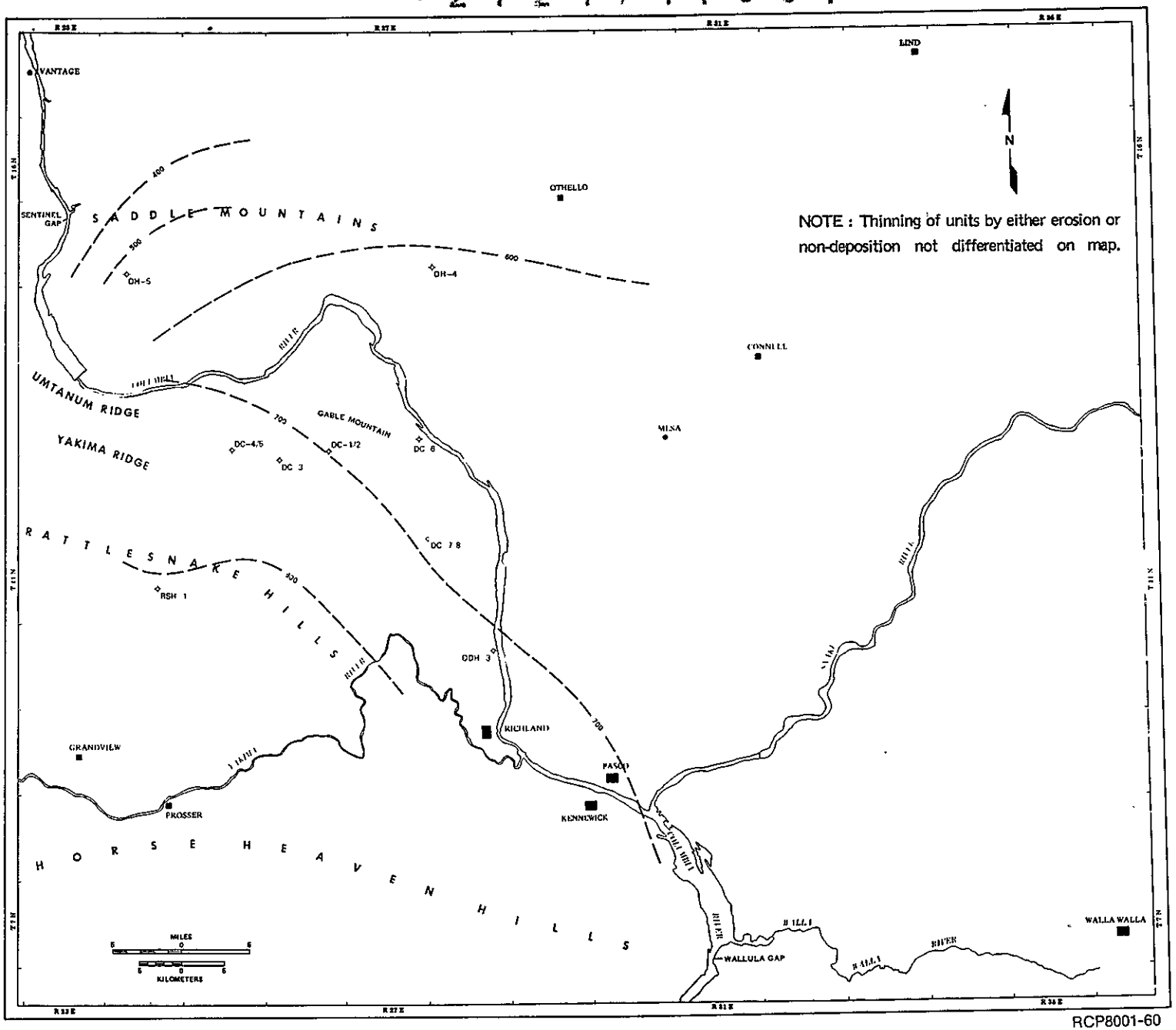


FIGURE III-12. Thickness Trends, Frenchman Springs Member.

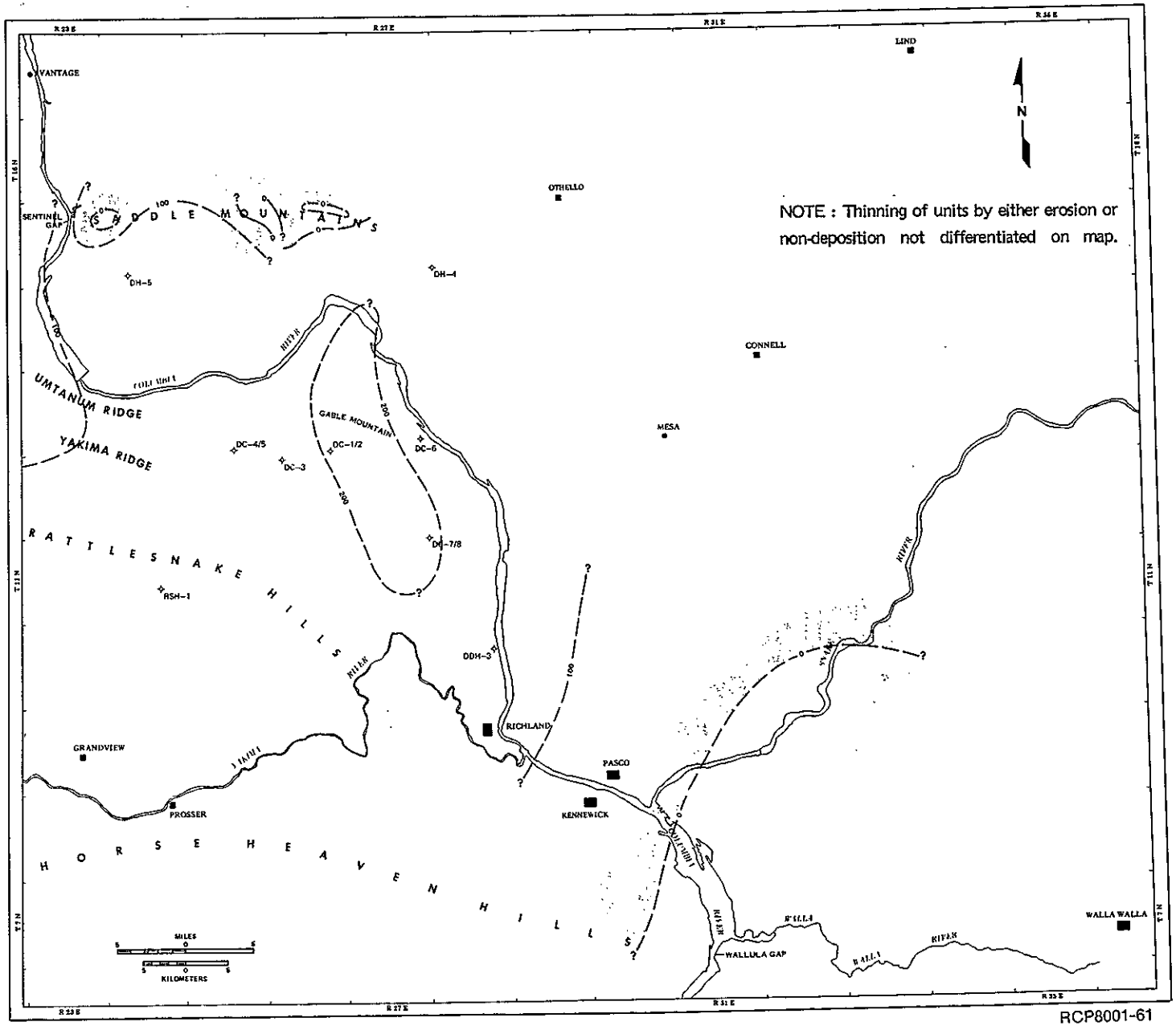


FIGURE III-13. Thickness Trends, Roza Member.

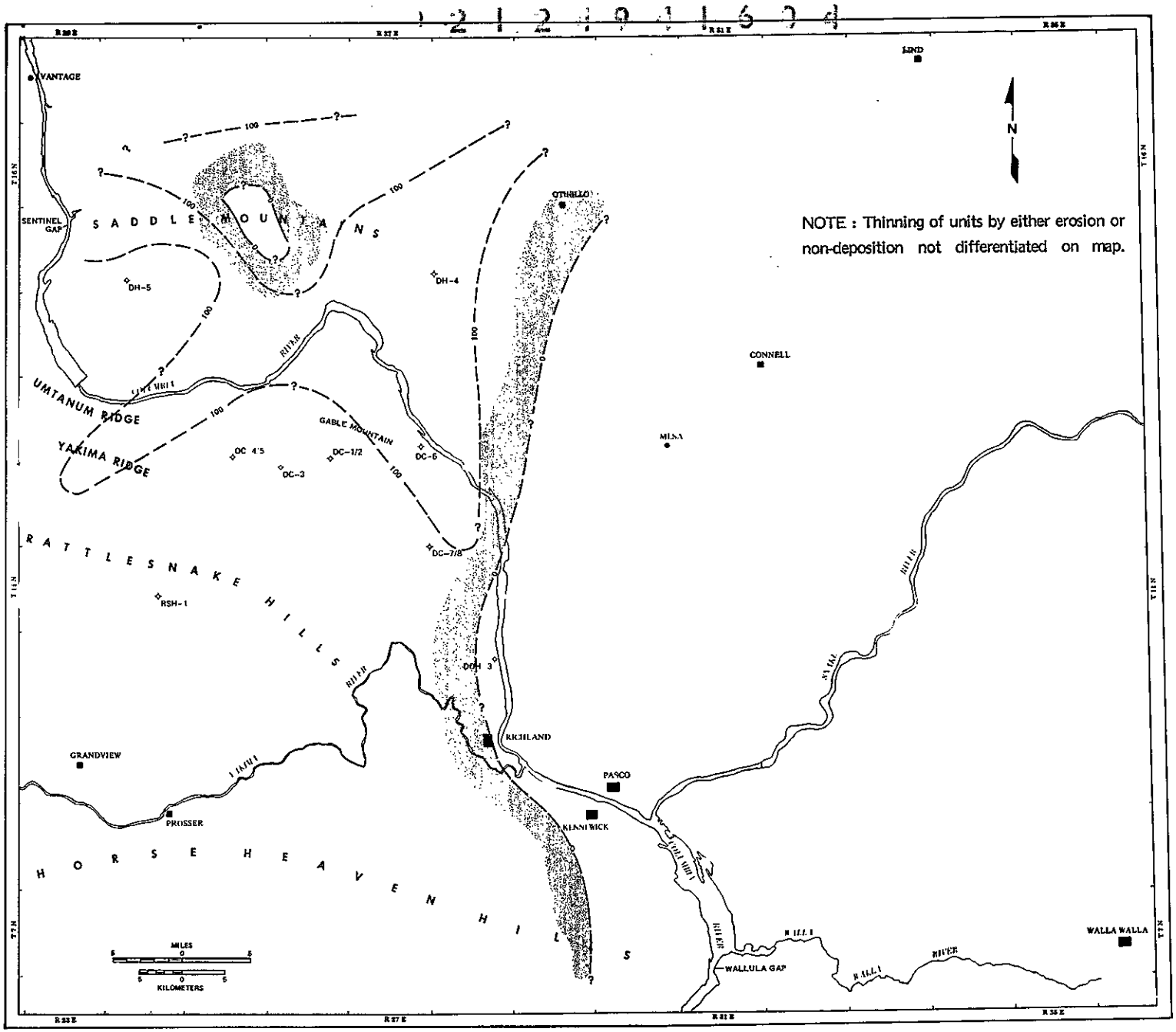
Priest Rapids Member. The Priest Rapids Member is the stratigraphically uppermost Wanapum Basalt unit in the Pasco Basin (Figure III-1). The Priest Rapids Member consists of one to two flows through most of the Pasco Basin, but locally there are apparently four flows. The Priest Rapids Member contains flows of two chemical types: the Lolo chemical type (Wright and Others, 1973); and, the Rosalia chemical type (Swanson and Others, 1979b).

The Rosalia chemical type flows are stratigraphically lowermost in the Priest Rapids Member. One Rosalia chemical type flow occurs throughout most of the basin, but between three and four flows occur between Priest Rapids Dam (Mackin, 1955) and DH-5. Rosalia chemical type flows are relatively thick in the northern and northwestern Pasco Basin, relatively thin in the central basin, and apparently pinch out along a northerly trend west of the Columbia River near DDH-3 (Figure III-14a). The location of the pinch out is uncertain to the north near Othello. The Rosalia chemical type is absent on the Saddle Mountains near Smyrna Bench (T15N, R25-26E).

Lolo chemical type flow is stratigraphically uppermost in the Priest Rapids Member. One Lolo chemical type flow occurs throughout the Pasco Basin. The Lolo chemical type flow pinches out in the northern Pasco Basin along an east-west trend of the Saddle Mountains (Figure III-14b) and in the southeastern Pasco Basin along a northeast trend parallel to the Snake River. The Lolo chemical type flow is thin near Smyrna Bench along a northwest trend, but thickens eastward toward Othello and southwestward toward the central Pasco Basin. It is relatively thin along a northwest trend subparallel to Rattlesnake Mountain and over the Rattlesnake Hills.

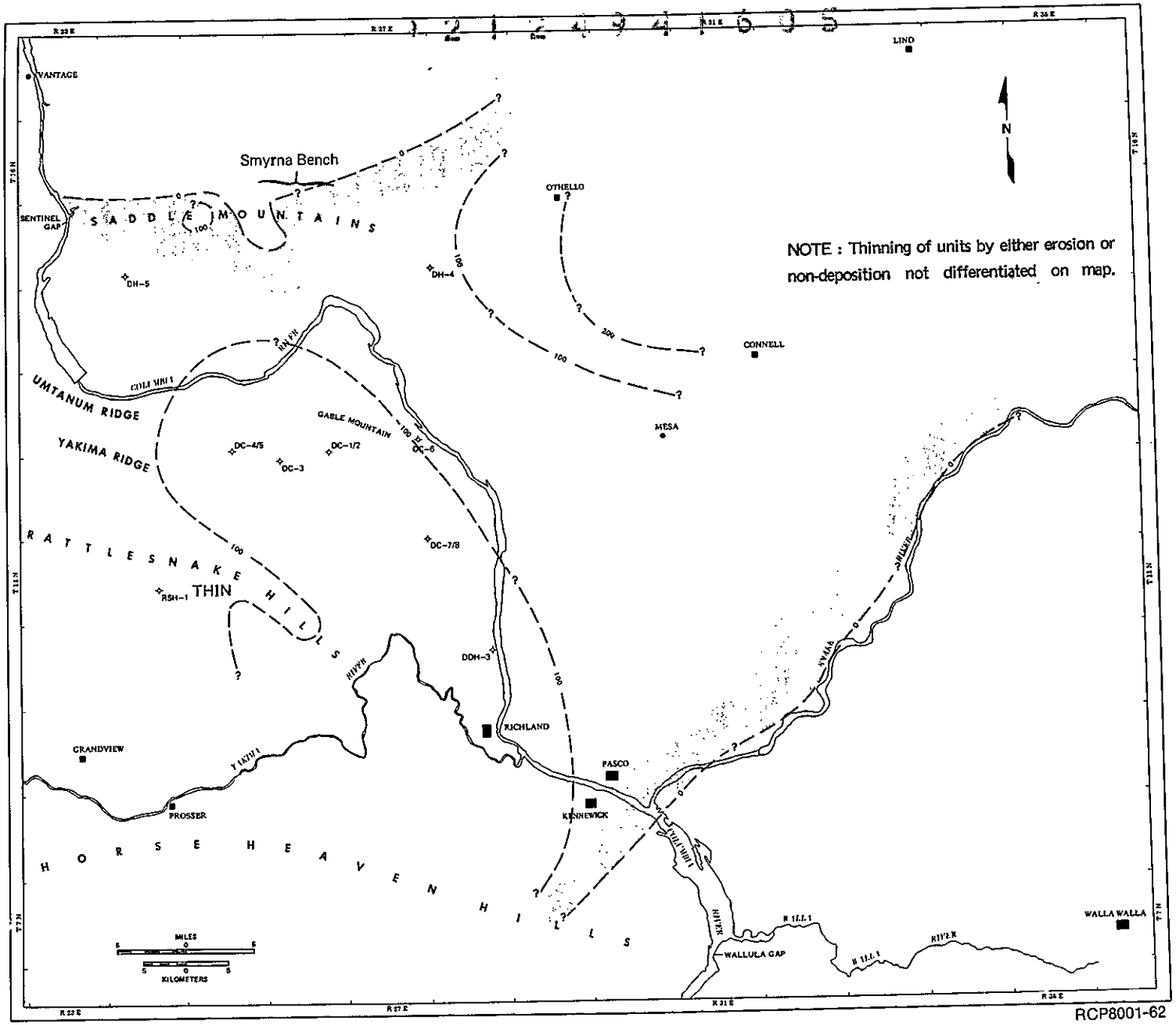
Mabton Interbed (Ellensburg Formation). The Mabton interbed is the most extensive and voluminous interbed within the Pasco Basin. The interbed is thickest along a northwest-trending axis subparallel to the Cold Creek Syncline (Figure III-15). The interbed thins in all directions away from this zone, but it continues across the crest of the Rattlesnake Hills where it is 83 feet (25 meters) in DH-2 and appears to be about 70 feet (21 meters) thick in Walla Walla Well Number 6, (an old Rattlesnake Hills gas field well).

Vertical lithologic changes in the Mabton interbed within the Pasco Basin are relatively uniform. From top to bottom, the unit consists of: (a) a well-indurated lapilli tuffstone, locally baked, and locally vertically fissured; (b) a very fine-grained tuffaceous, clayey, quartzitic sandstone; and, (c) a loosely consolidated quartzitic or arkosic sand or sandstone with interlayed diatomite or volcaniclastic sediments. No conglomerate facies has been detected in any core holes.



(a) Rosalia chemical type.

FIGURE III-14. Thickness Trends, Priest Rapids Member.



(b) Lolo chemical type.

Figure III-14 (continued)

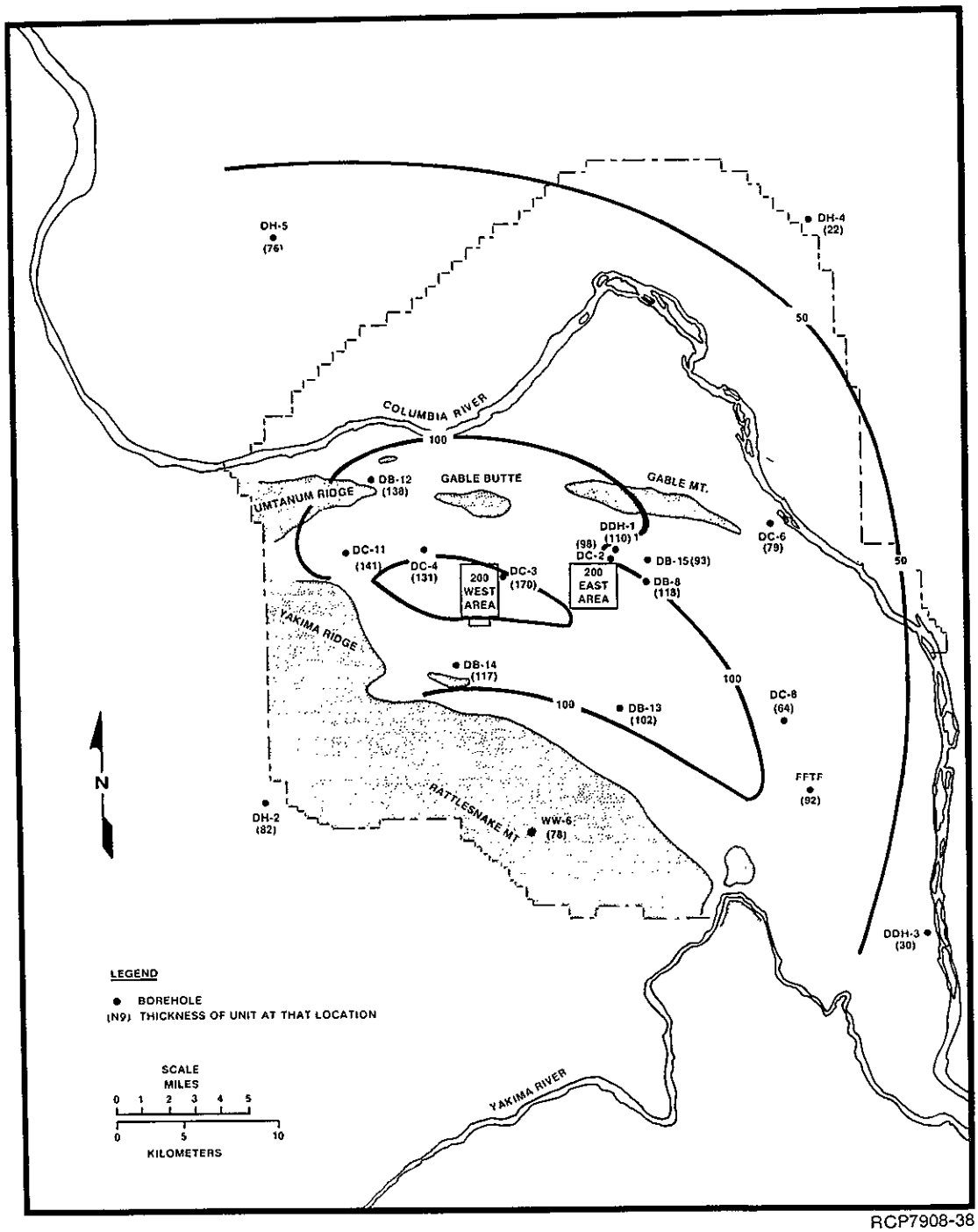


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FIGURE III-15. Thickness Trends, Mabton Interbed.

Saddle Mountains Basalt

The Saddle Mountains Basalt consists of seven members within the Pasco Basin: the Umatilla Member; Wilbur Creek Member; Asotin Member; Esquatzel Member; Pomona Member; Elephant Mountain Member; and, Ice Harbor Member. All members in the Pasco Basin contain flows of a single chemical type.

Flows of the Saddle Mountains Basalt occur throughout the Pasco Basin, but the unit thins and thickens more than the Wanapum Basalt. This is interpreted to be due in part to growth of the Yakima Folds during emplacement of the Saddle Mountains flows and, in part, to local removal by erosion of the upper part of the Saddle Mountains Basalt.

The Saddle Mountains Basalt is thickest in the center of the Pasco Basin between the Rattlesnake Hills and Gable Mountain (Figure III-16). It thins north toward the Saddle Mountains and south toward the Rattlesnake Hills and adjacent structures. A zone of apparent non-deposition or erosion in the Saddle Mountains occurs between Sentinel Gap and Smyrna Bench. An erosional channel is interpreted from well logs to be south of Kennewick, Washington.

Umatilla Member. The Umatilla Member is limited to the central and southern portions of the Pasco Basin (Figure III-17); it pinches out across the north-central Pasco Basin, but its southern limit is outside the Pasco Basin study area.

The greatest thickness of the Umatilla Member in the Pasco Basin is between the Horse Heaven Hills and Gable Mountain, with thinning over the Rattlesnake Hills. The Umatilla Member consists of one to two flows that probably entered the Pasco Basin from the southeast and thinned toward the north where it overlapped older units and pinched out.

Wilbur Creek Member. The Wilbur Creek Member is represented by the Wahluke flow in the Pasco Basin and is confined to a narrow zone in the northern basin (Figure III-18). The Wahluke flow is an intracanyon flow which entered the basin from the northeast near Othello, Washington, spread as a sheet-flow in the Eagle Lake area (this flow was originally called the Eagle Lake flow by Swanson and Others [1977]), flowed along the northern edge of the Umatilla Member (compare Figures III-17 and III-18), and out of the basin through a paleochannel exposed on Umtanum Ridge (Plate III-1).

Asotin Member. The Asotin Member in the Pasco Basin is represented by the Huntzinger flow and, like the Wilbur Creek Member, is confined to the northern Pasco Basin (Figure III-19). It probably entered the basin near the northeastern corner of the basin, based on reconnaissance mapping by Swanson and Others (1977). The growing Saddle Mountains formed its northern boundary, where it flowed into erosional channels. At one location in the Saddle Mountains (T15N, R23E), the flow invades the Ellensburg sediments. Its southern boundary is south of Gable Mountain, but the eastern extent is probably near Mesa, Washington. It

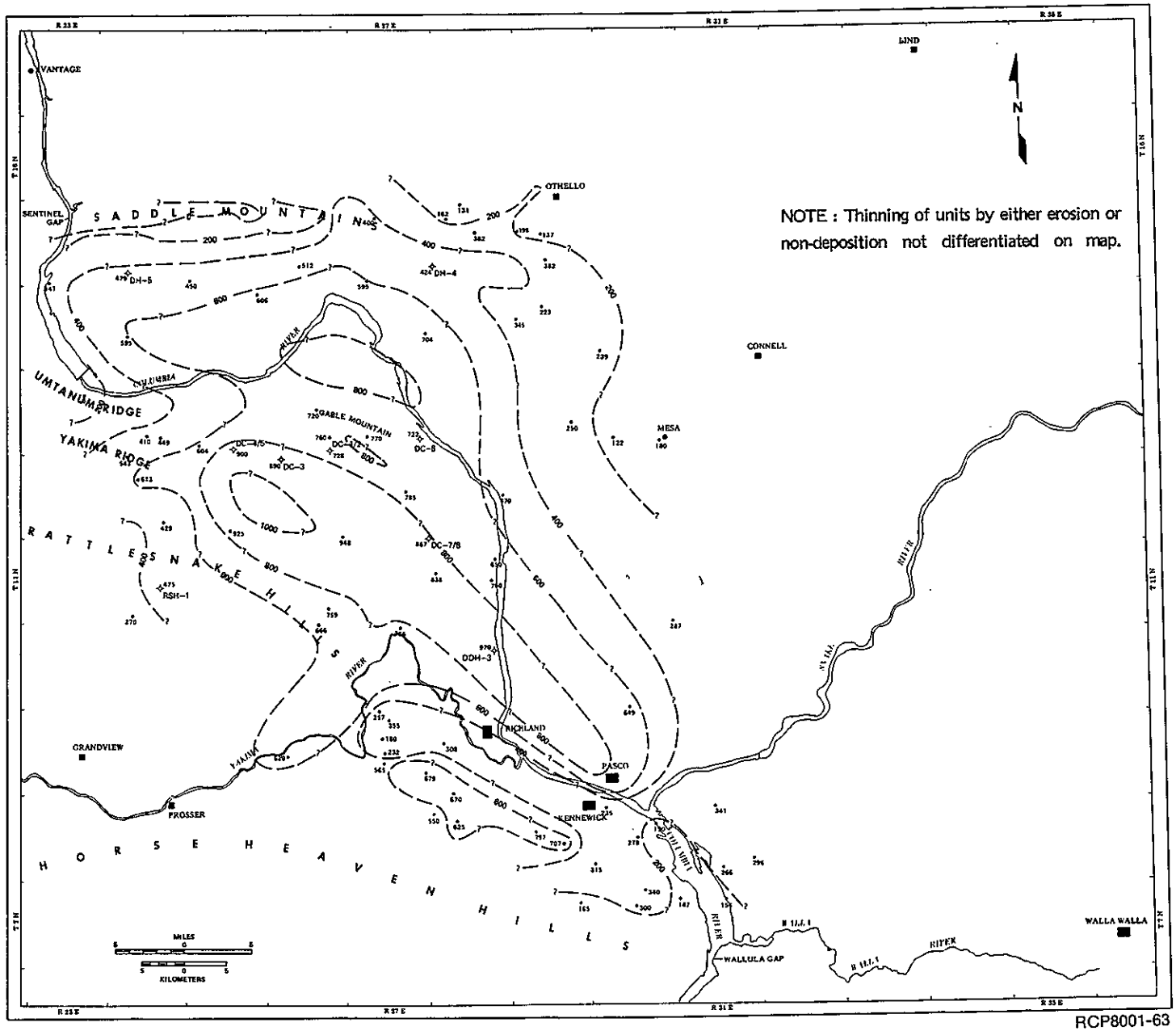

FIGURE III-16. Thickness Trends, Saddle Mountains Basalt.

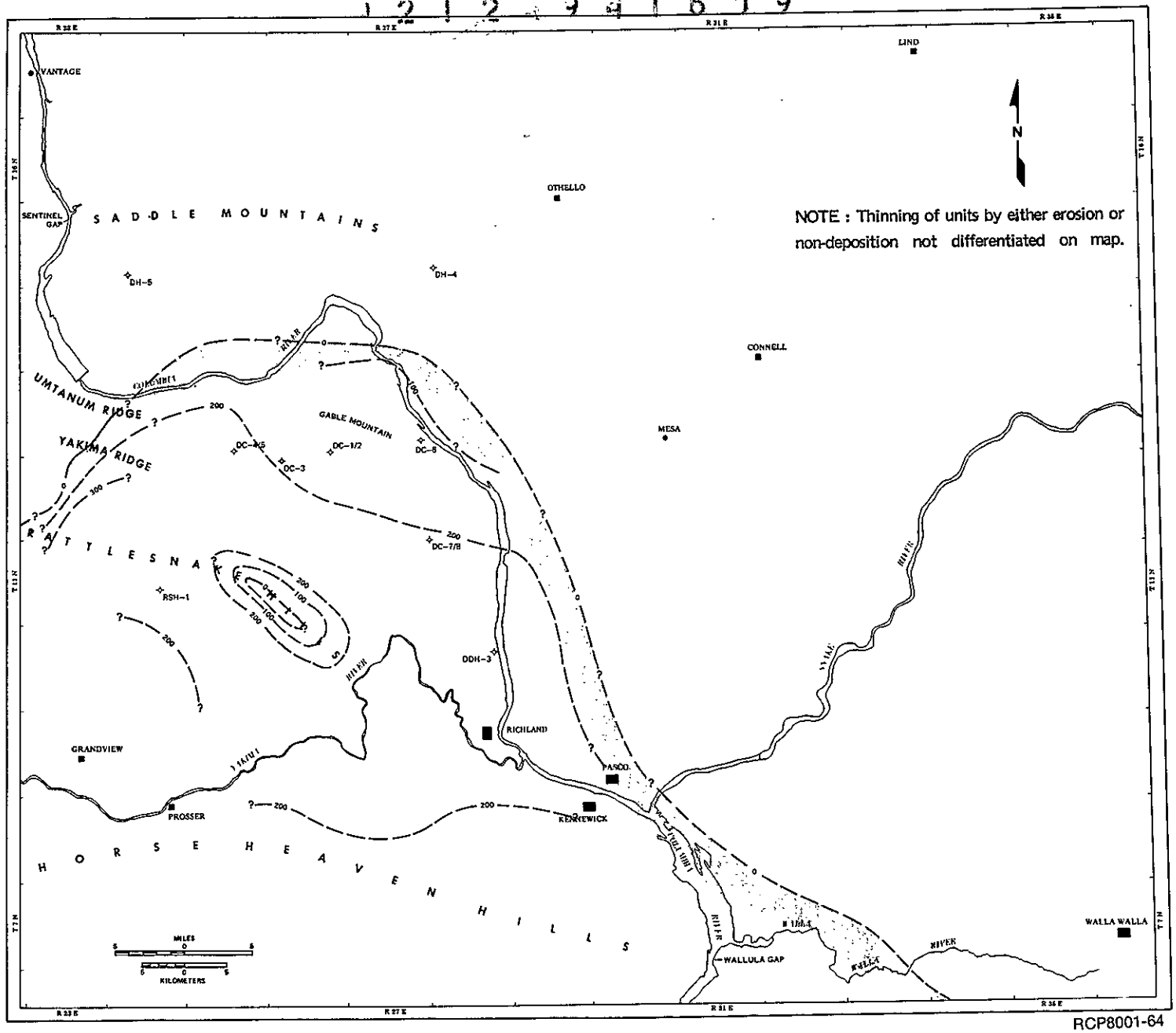

FIGURE III-17. Thickness Trends, Umatilla Member.

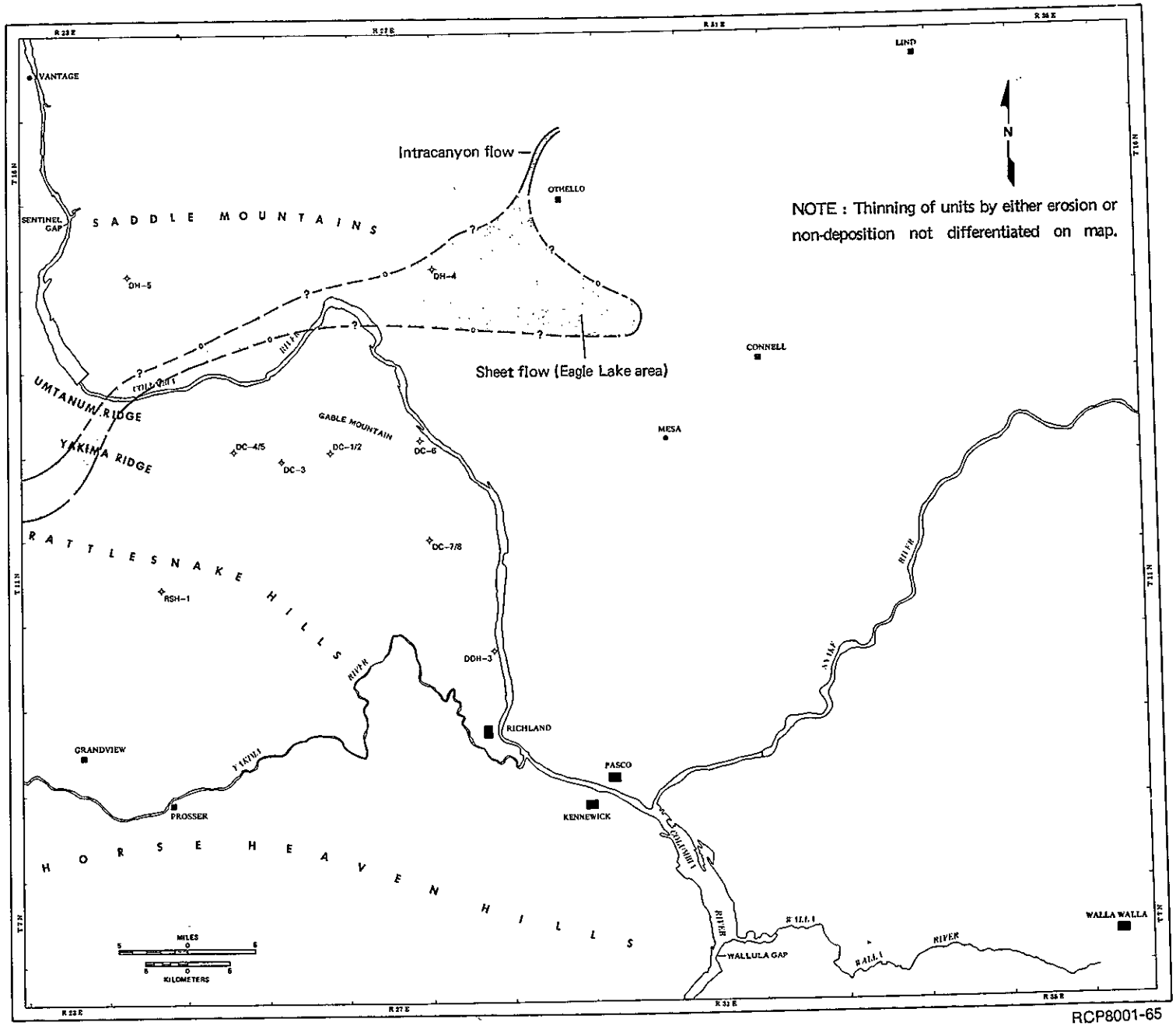

FIGURE III-18. Thickness Trends, Wilbur Creek Member.

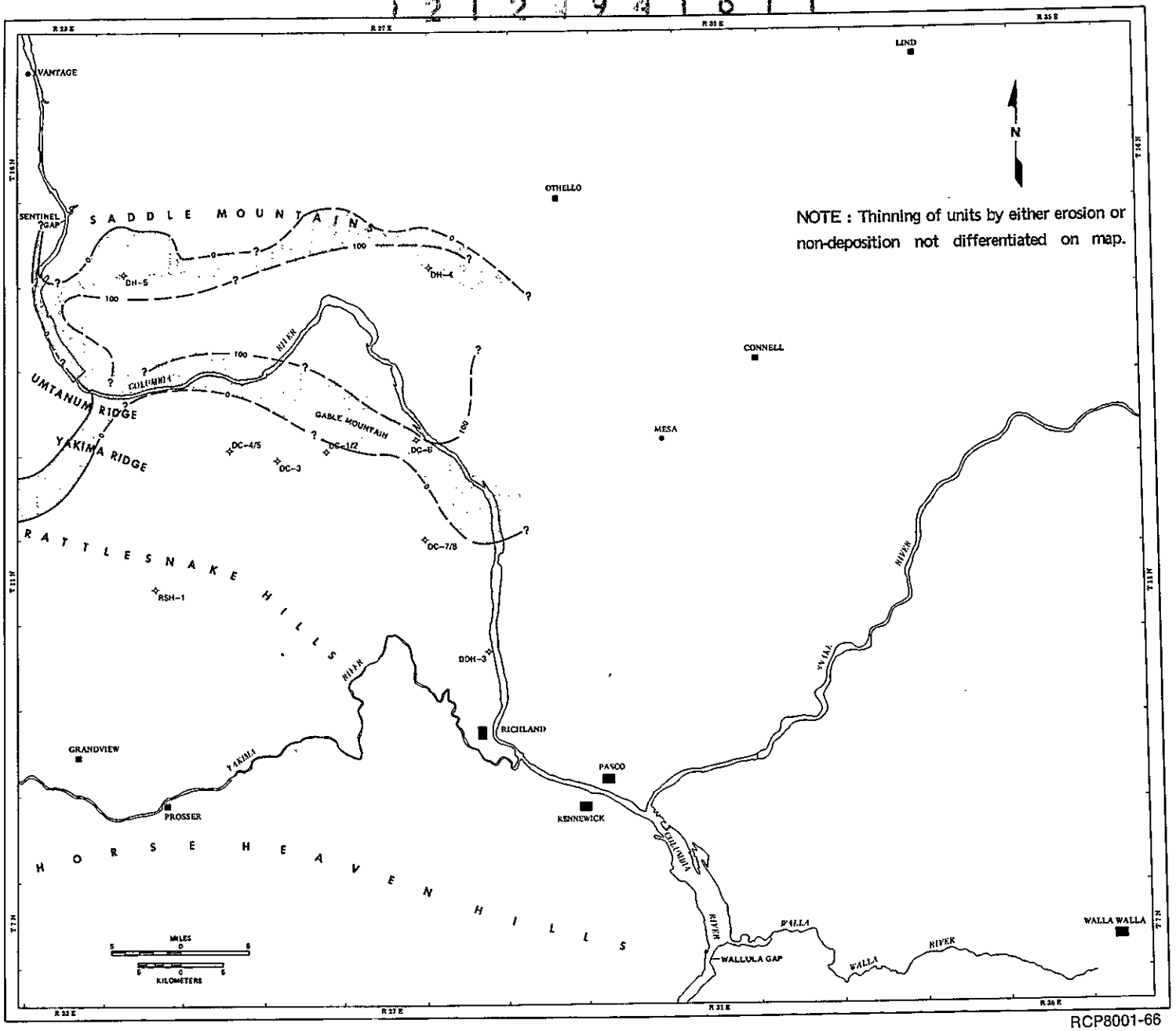

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FIGURE III-19. Thickness Trends, Asotin Member.

also flows out of the Pasco Basin in the paleochannel at the edge of the Umatilla flow through which the Wahluke also flowed. Core hole data indicate it overlapped the Umatilla Member near Gable Mountain and at DC-6.

Cold Creek Interbed (Ellensburg Formation). The Cold Creek interbed is interpreted as confined almost exclusively to the Cold Creek syncline area of the central Pasco Basin (Figure III-20). The interbed is thickest along a northwest axis generally coinciding with the syncline axis, and it pinches out to the north against the Umtanum-Gable Mountain structure and to the south against the Rattlesnake Hills structure. Core holes through the interbed reveal a tuffaceous to arkosic sandstone with a basalt cobble conglomerate facies composed of well-rounded and packed basalt cobbles in a black basaltic sand matrix.

The basalt cobble conglomerate facies might have a genetic relationship to the Huntzinger flow. Comparison of Figures III-19 and III-20 indicates that the margin of the Huntzinger follows an arcuate trend that is subparallel to the conglomerate facies trend. It is postulated that the Huntzinger flow may have dammed an ancestral river (perhaps the Snake River) with a flow-front margin about 100 feet (32 meters) high. The river eventually spilled over the basalt, which acted as a wide spillway, depositing boulders in a high-energy, plunge pool.

Esquatzel Member. The Esquatzel Member is represented by one, in places two, flow(s) in the Pasco Basin. It is confined to the central basin and is thickest between Yakima Ridge and Gable Mountain along a northwest trend (Figure III-21). The Esquatzel is interpreted to have entered the Pasco Basin from the east near Mesa, Washington. It pinches out northward between Gable Mountain and the Saddle Mountains structure and southward against the Rattlesnake Hills structure. Rattlesnake Hills, Yakima Ridge, and Umtanum Ridge apparently controlled its western extent, but it apparently poured out of the Pasco Basin along the same channel across Umtanum Ridge as the Wahluke and Huntzinger flows. Overlap of the Esquatzel flow onto the Umatilla Member flow suggests a wider channel than was used by the Wahluke and Huntzinger flows.

Selah Interbed. In this chapter, the term Selah interbed is used for that interbed lying stratigraphically below the Pomona Member and above the Esquatzel Member in the Pasco Basin. The stratigraphic relationships between the Selah interbed in the Pasco Basin and the Selah at its type locality at Selah Gap (Mackin, 1961) are not resolved. Lithologically, the Selah is a vitric tuff, locally silty or sandy, and in places fused to a perlitic vitric tuff by the overlying Pomona Member. Opaline silica and peperite are common at the Pomona contact. The areal distribution and thickness variation of the Selah interbed are shown in Figure III-22. The maximum thickness within the Pasco Basin is along a northwest-trending axis subparallel to the Cold Creek syncline beneath the 200 West Area (Hanford Site), where it probably is more than 70 feet (23 meters) thick.

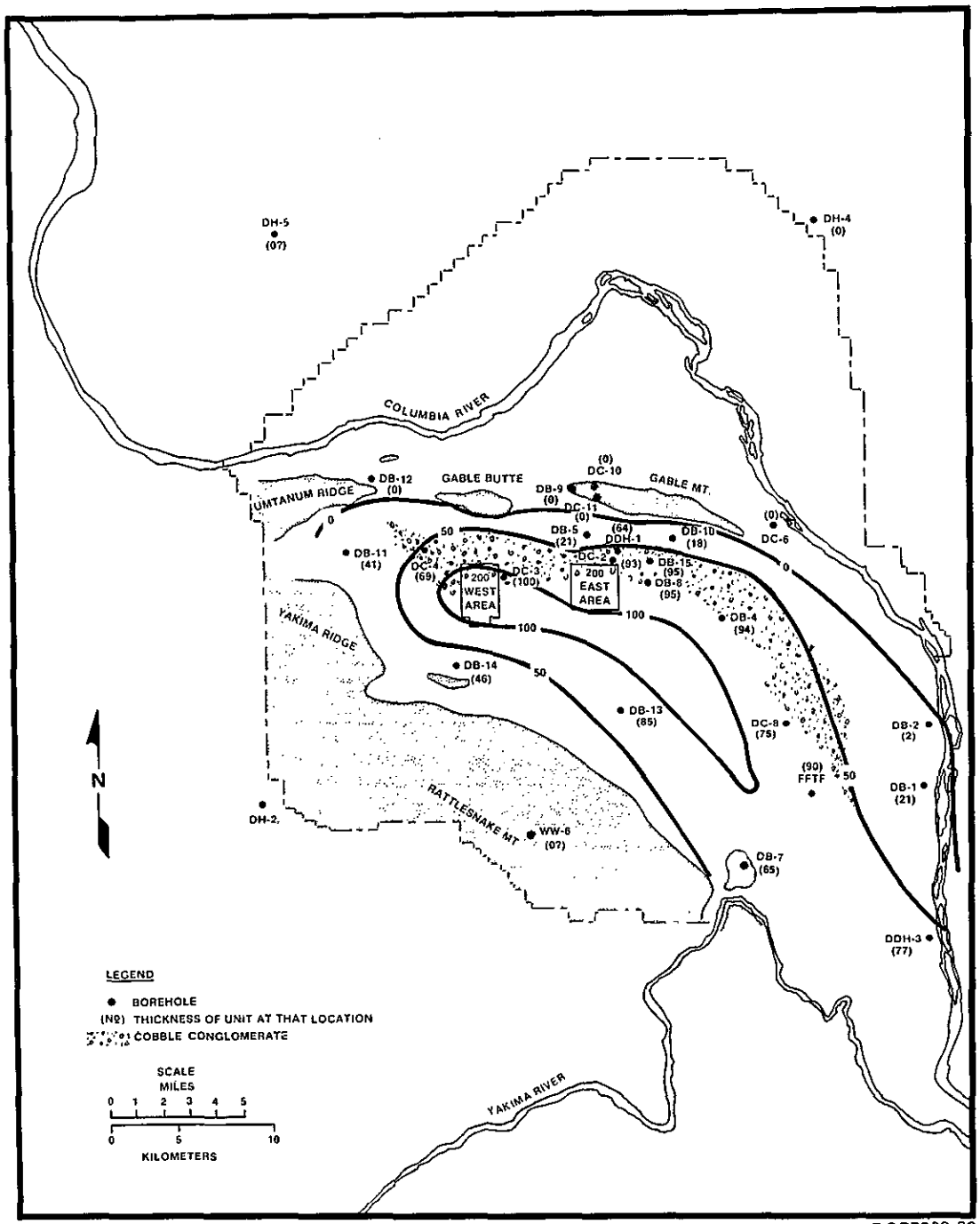

FIGURE III-20. Thickness Trends, Cold Creek Interbed.

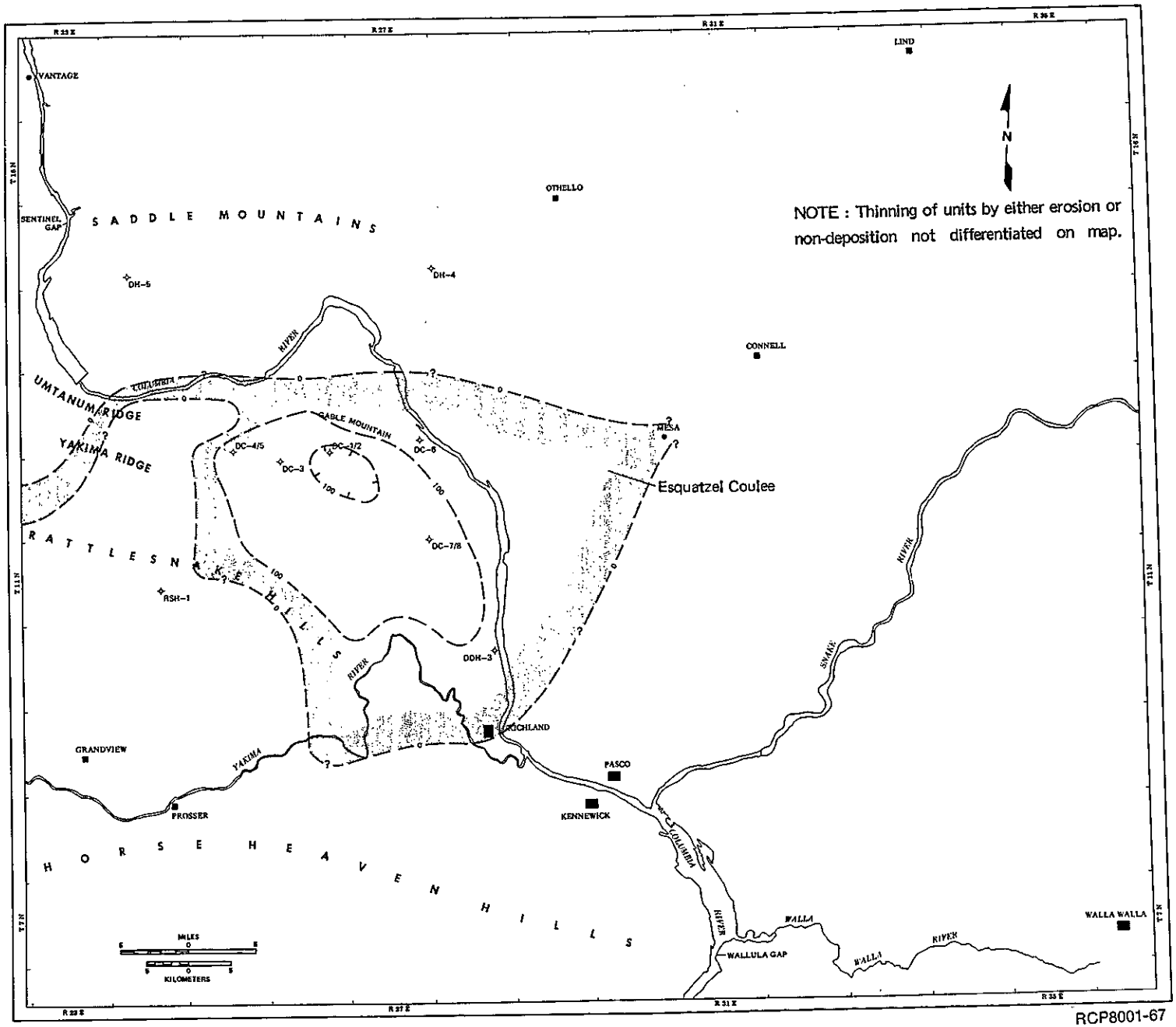

FIGURE III-21. Thickness Trends, Esquatzel Member.

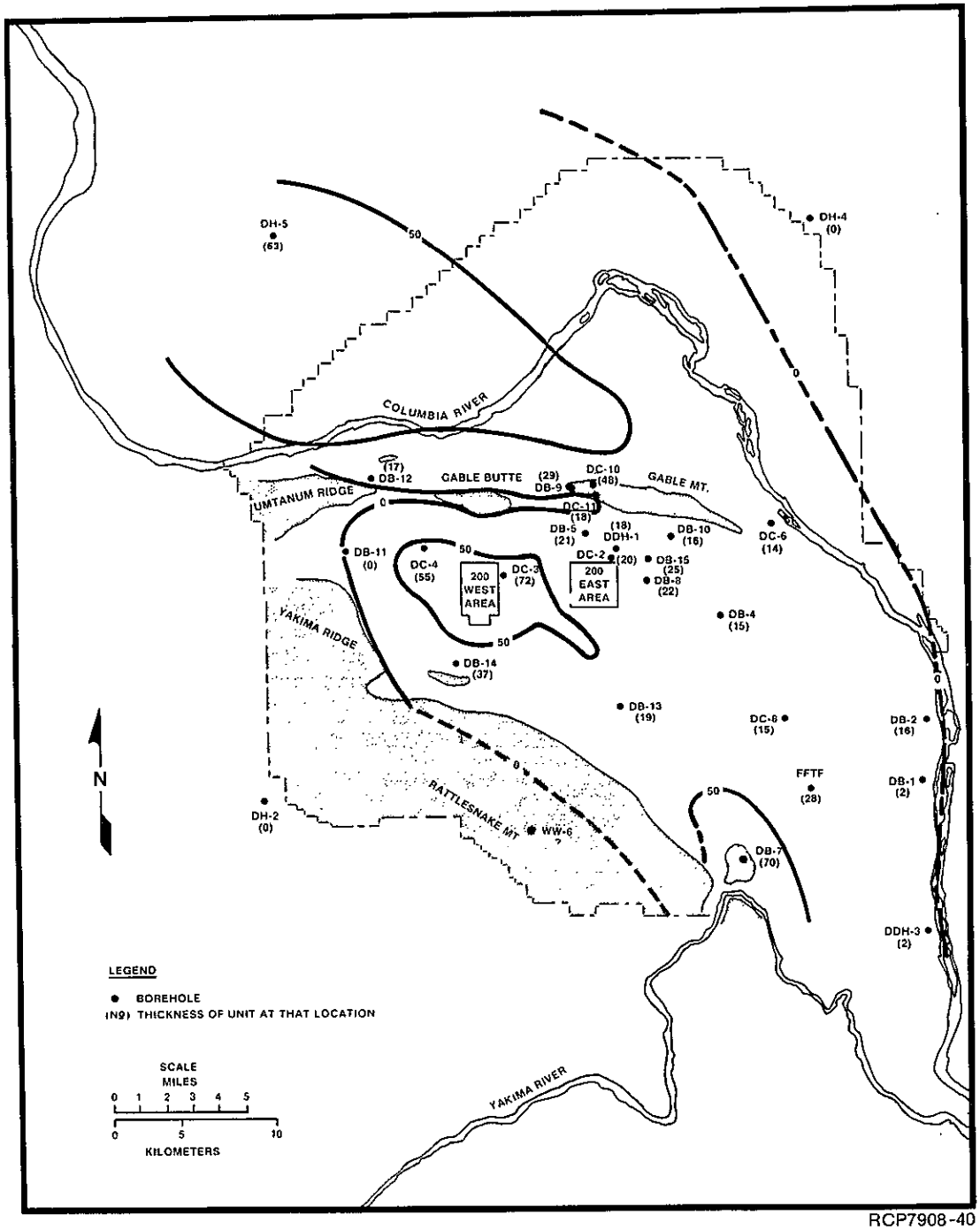

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FIGURE III-22. Thickness Trends, Selah Interbed.

Pomona Member. The Pomona Member is represented by one or two flows or flow lobes in the Pasco Basin. The lower flow has the greatest extent; the upper flow is more restricted (Figures III-23a and III-23b).

The lower Pomona flow pinches out against the Saddle Mountains in the northern Pasco Basin (Figure III-23a). Near Sentinel Gap (T15N, R23E), the lower Pomona flow invades Ellensburg sediments forming a peperite (Schmincke, 1964b). Its westernmost edge north of the Saddle Mountains is near Natural Corral (T14N, R23E) and the northeastern limit is west of Othello, Washington in the Drumheller Channels (T16N, R23E). The Pomona entered the basin from the east according to regional data by Swanson and Wright (1976). The lower Pomona's southeastern boundary is along the present Snake River. It thins over the Rattlesnake Hills and is not present on Umtanum Ridge or the easternmost part of the Horse Heaven Hills near Wallula Gap (T7N, R29-30E); otherwise, it occurs throughout the Pasco Basin. The greatest thickness of the lower Pomona is between the Rattlesnake Hills and Gable Mountain in the central Pasco Basin, and between the Rattlesnake Hills and Horse Heaven Hills in the southern Pasco Basin. The lower Pomona flow appears to have spread west as a sheet-flow beyond the present-day western margin of the Pasco Basin.

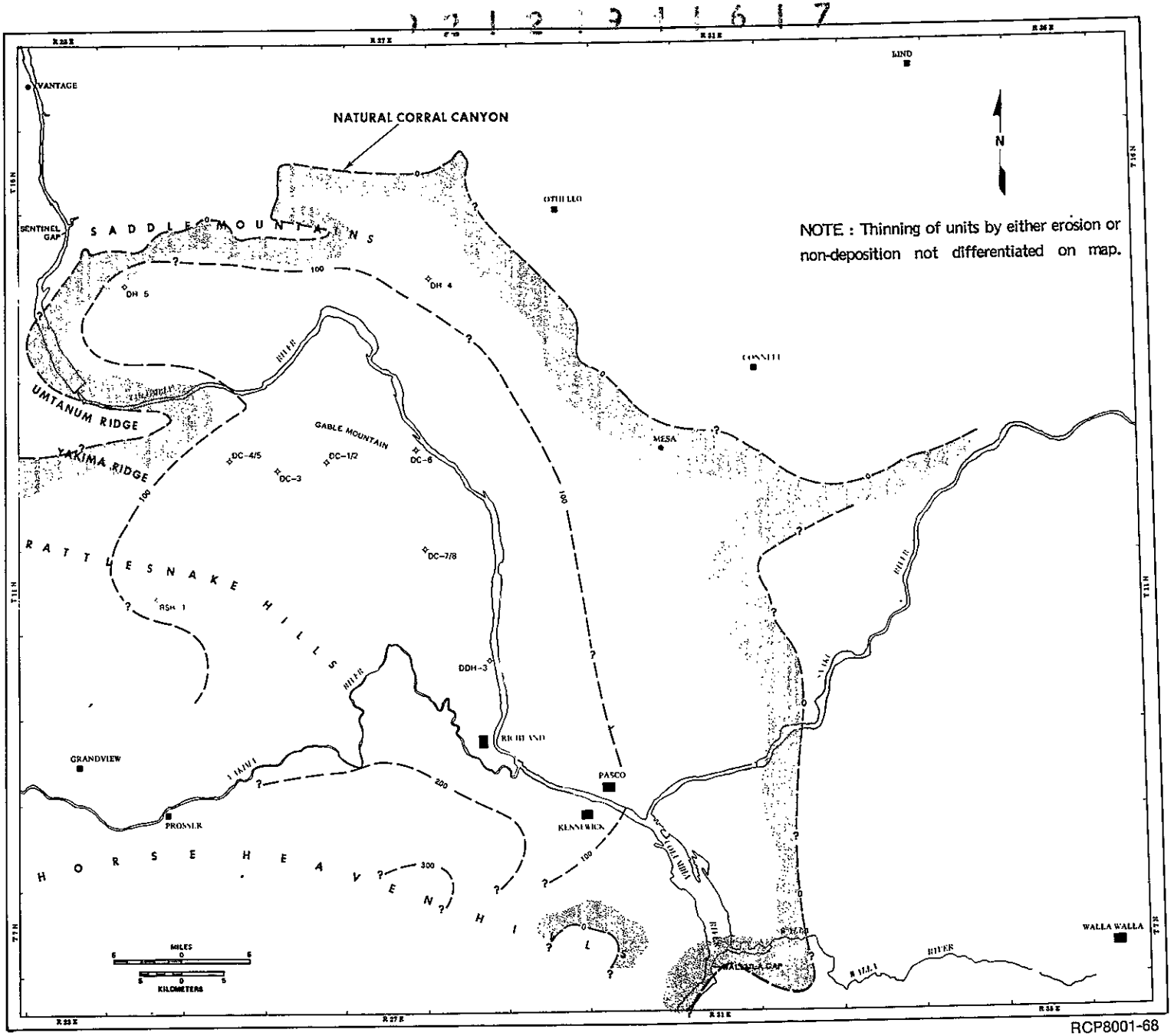
The upper Pomona flow (Figure III-23b) is restricted to two areas in the Pasco Basin; one is between the Saddle Mountains and Gable Mountain and the other is a narrow channel that parallels the course of the present Yakima River. The upper Pomona is interpreted here as a separate flow, but it might be nothing more than a local lobe or flow unit from the lower Pomona flow.

Bond and Others (1978) proposed a lower Pomona vent between Rattlesnake Hills and Prosser, Washington. This is currently considered unlikely because lower Pomona lava issuing from this vent would have to have flowed upstream to cover the Pasco Basin according to paleogeographic interpretations presented in this chapter.

Rattlesnake Ridge Interbed. The Rattlesnake Ridge interbed is a tuffaceous siltstone grading locally into a tuffaceous sandstone. In the northern Cold Creek syncline, the interbed has a 50-foot (16-meter) thick cobble conglomerate facies (Figure III-24) of mostly basaltic clasts. This is similar to the Cold Creek interbed. In DC-4, the conglomerate overlies a sandstone with granitic and andesitic clasts.

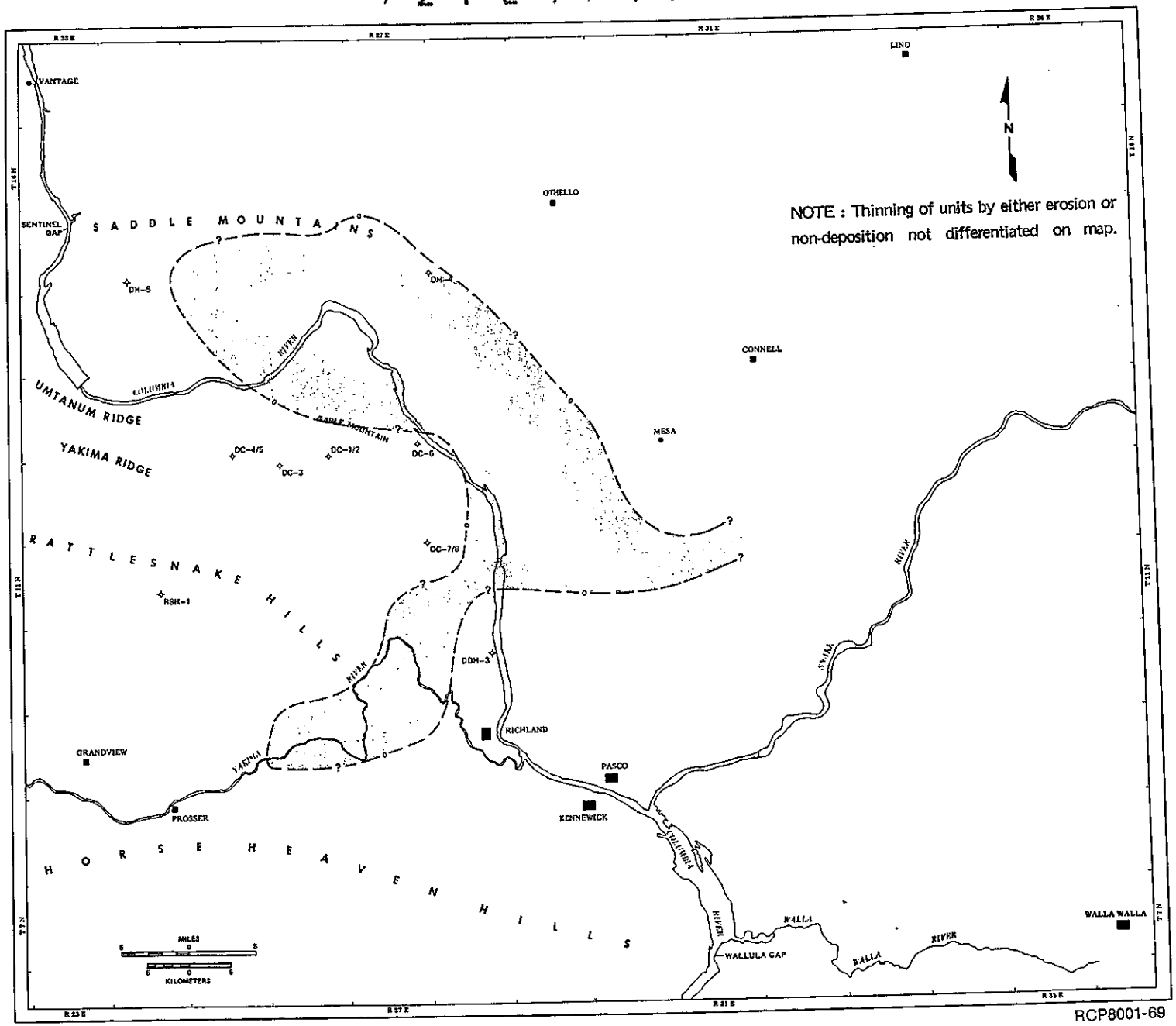
Elephant Mountain Member. The Elephant Mountain Member consists of two flows within the Pasco Basin. The distribution of the two Elephant Mountain flows is shown on Figure III-25a.

The lower Elephant Mountain flow pinches out along the south side of the Saddle Mountains, yet a small tongue extends along the north side of the Saddle Mountains (Figure III-25a). The lower Elephant Mountain flow is absent from the crest of the Saddle Mountains and Umtanum Ridge. The southeastern boundary of the flow is approximately parallel to the present Snake River Canyon. The Horse Heaven Hills mark the southern



(a) Lower flow.

FIGURE III-23. Thickness Trends, Pomona Member.



(b) Upper flow.

Figure III-23 (continued)

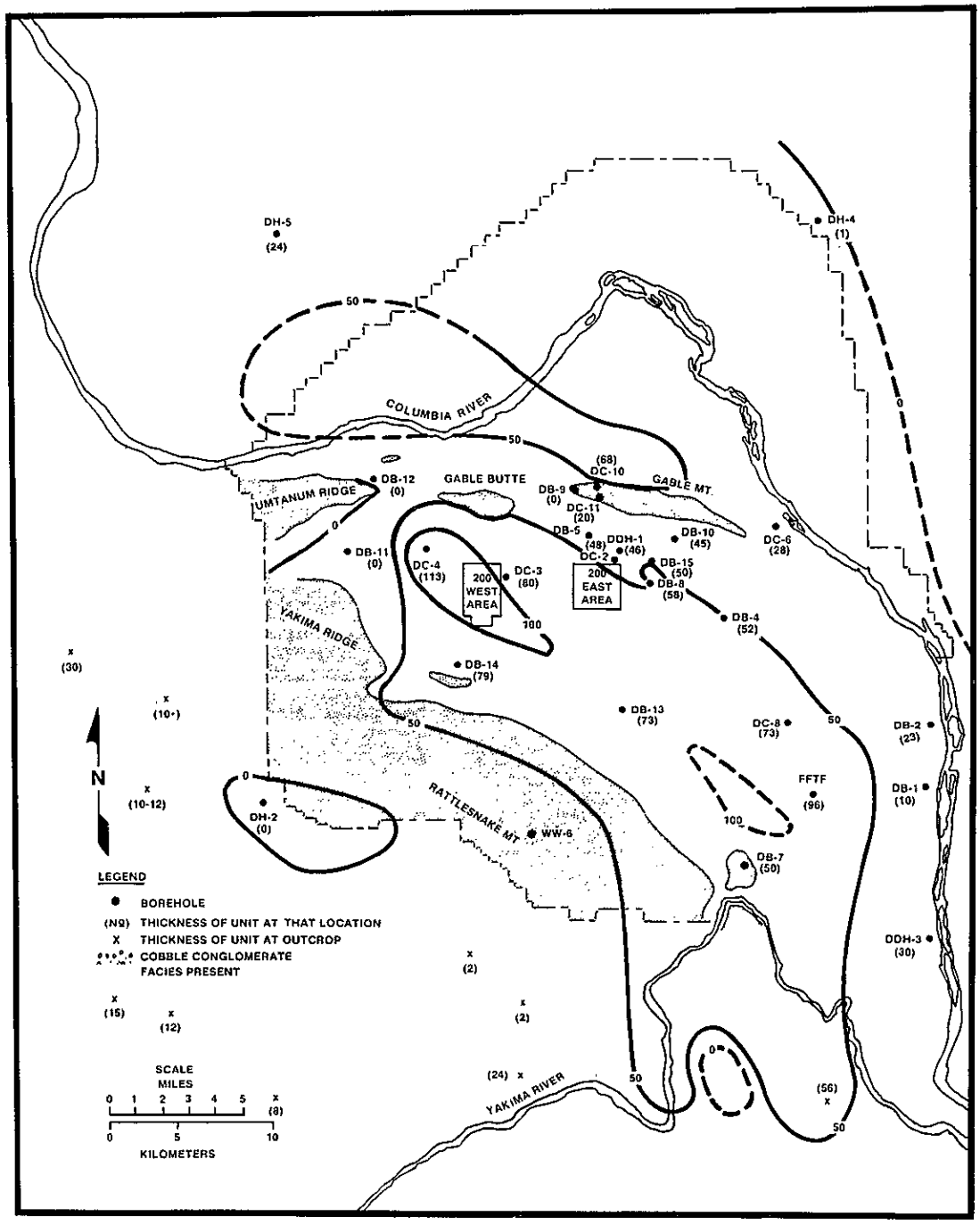


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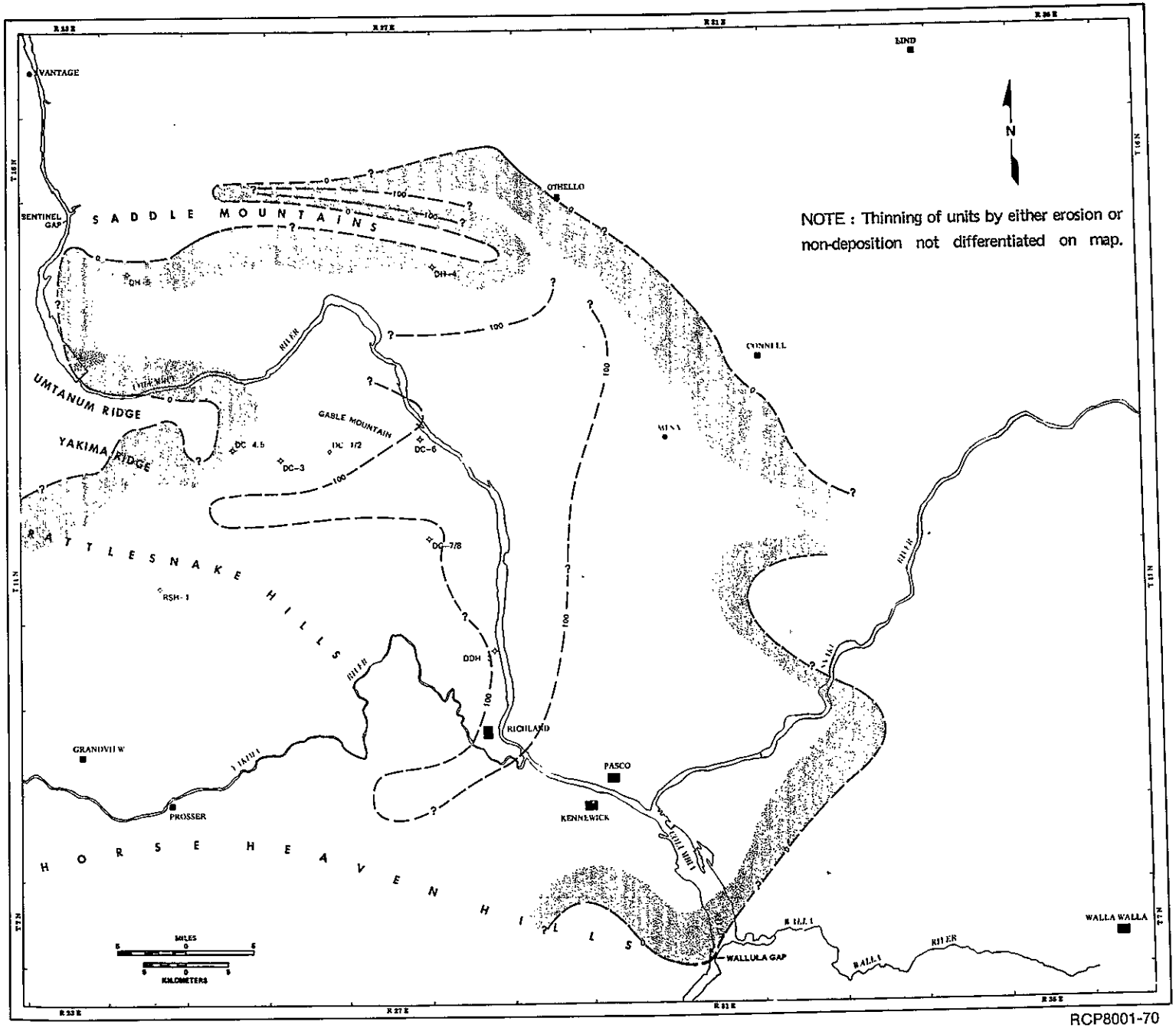
FIGURE III-24. Thickness Trends, Rattlesnake Ridge Interbed.



(a) Lower flow.

FIGURE III-25. Thickness Trends, Elephant Mountain Member.

boundary and the Columbia River north of Umtanum Ridge marks the westernmost extent of the flow in the northern Pasco Basin (Figure III-25a). Umtanum Ridge apparently formed a barrier. The greatest thickness of the lower Elephant Mountain flow occurs west of DC-8, between the Horse Heaven Hills and Gable Mountain. The flow thins over the Rattlesnake Hills, Gable Mountain, and east of the Columbia River, but (like the lower Pomona flow) appears to have spread west as a sheet-flow across the present-day western margin of the Pasco Basin.

The upper Elephant Mountain flow has a more restricted distribution than the lower Elephant Mountain flow except north of the Saddle Mountains (Figure III-25b). The eastern and southeastern boundaries of the upper and lower Elephant Mountain flow are approximately the same. The upper Elephant Mountain flow is restricted to a relatively narrow channel between Umtanum Ridge and Wallula Gap and is absent from part of the Rattlesnake Hills. The upper Elephant Mountain flow is relatively thick north of the Saddle Mountains and between the Horse Heaven Hills and Gable Mountain. Elsewhere, the upper Elephant Mountain flow is less than 50 feet (16 meters) thick and in no place more than 100 feet (32 meters) thick.

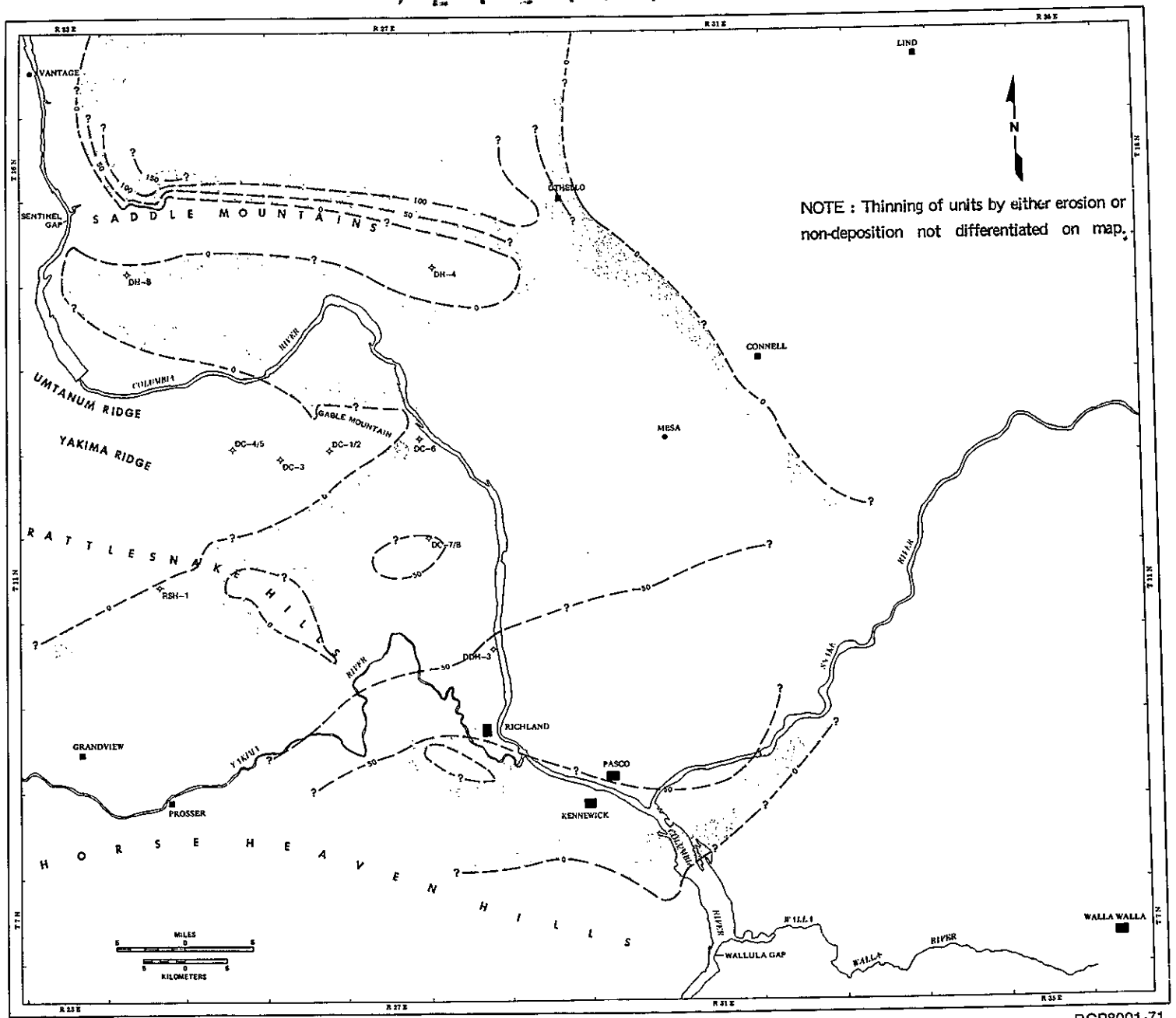
Ice Harbor Member. The Ice Harbor Member is confined to the present topographic low of the Pasco Basin (Figure III-26). The northernmost extent of the member is north of Basin City, Washington near the Bailie Boys' Ranch (T14N, R29E) where Swanson and Helz (1979) have mapped several dikes. The southern boundary is marked by the Horse Heaven Hills-Rattlesnake Hills uplift. The eastern boundary occurs near T8N, R34E.

Other Interbeds. A few discontinuous Ellensburg Formation interbeds occur within the Saddle Mountains Basalt. These include: (a) the Levey, a tuffaceous siltstone; (b) a vitric tuff from 2 to 6 feet (1 to 2 meters) thick separating two flows of the Esquatzel Member; and, (c) a thin, clay layer 0.5 foot (15 centimeters) thick, which is probably a devitrified glass, separating the Huntzinger flow from the Umatilla Member.

Ringold Formation

The Ringold Formation within the Pasco Basin (Figure III-27) is Pliocene age (Gustafson, 1973, 1978) and is divided into five units based on texture. From the base upward, these are: (a) basal gravel unit; (b) lower sand, silt, and clay; (c) middle gravel or conglomerate; (d) upper sand and silt; and, (e) a local fanglomerate facies. The middle, upper, and fanglomerate Ringold units crop out in the Pasco Basin.

Results from paleomagnetic investigations of the Ringold Formation are discussed by Packer and Johnston (1979). The magnetostratigraphy of a 460-foot (140-meter) composite section in the White Bluffs at Parsons Canyon-Ringold Flat has a 65-foot thick (20-meter) section of normal magnetic polarity at the base. This is overlain by approximately 360 feet



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(b) Upper flow.

Figure III-25 (continued)

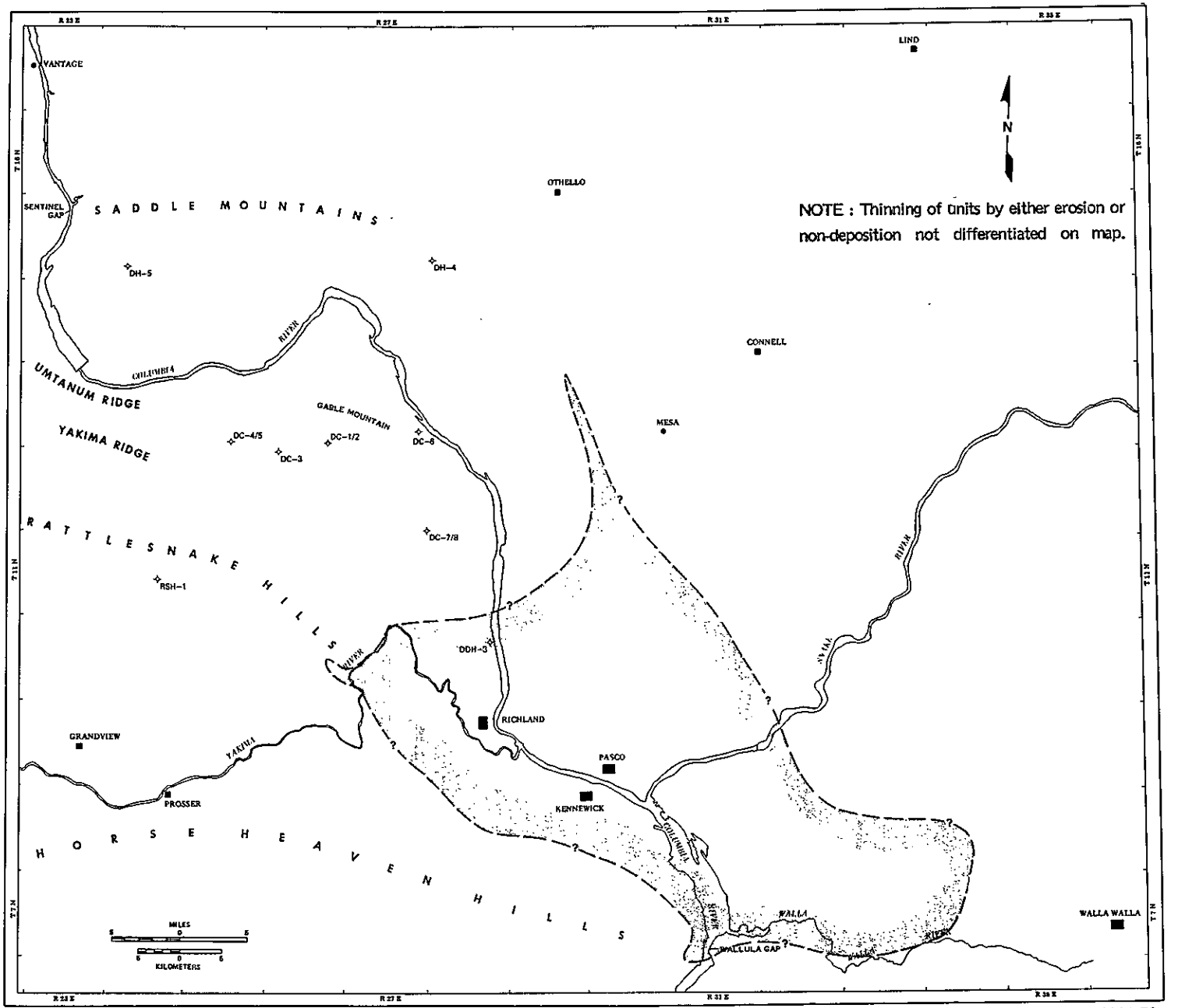

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FIGURE III-26. Thickness Trends, Ice Harbor Member.

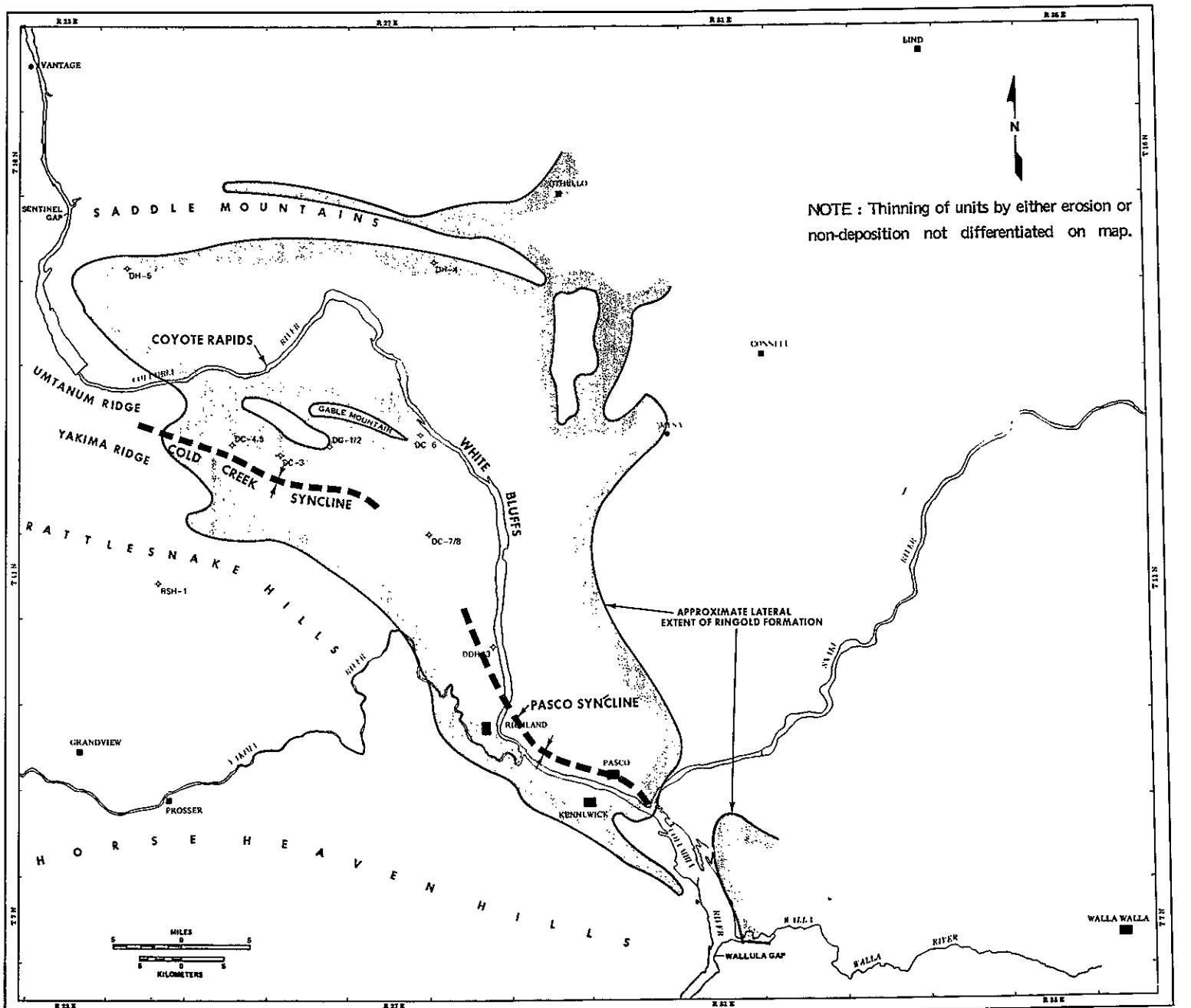

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FIGURE III-27. Generalized Lateral Extent, Ringold Formation.

(110 meters) of section having reversed magnetic polarity. The surficial caliche and loess have a normal magnetic polarity. The reversed magnetic polarity sequence of the upper Ringold unit in conjunction with paleontological data (Gustafson, 1973, 1978), which indicate a Blancan (Pliocene) fauna in the upper Ringold unit and a possible Hemphillian (Pliocene) fauna for the middle Ringold conglomerate, suggest that the reversed sequence is within the Gilbert Reversed Epoch. The Gilbert Reversed Epoch is approximately 3.32 to 5.12 million years ago.

Basal Ringold Unit. The basal Ringold unit (gravel) overlies the Columbia River basalt, but its conformability with the basalt is unknown. In the Cold Creek syncline, it is generally considered to be conformable (Routson and Fecht, 1979; Tallman and Others, 1979).

The basal Ringold is gravel supported by a coarse- to fine-sand matrix. Stringers and lenses of coarse to fine sand and silt are common throughout the thicker portion of the unit. The pebble-cobble fraction is primarily basalt, but also includes quartzite, granitic rocks, metamorphic rocks, and other lithologies with source areas outside the Pasco Basin. The sand matrix is composed primarily of quartz and feldspar, with local basaltic sand. Bedding forms are not distinguishable from the available borehole samples.

The basal Ringold unit occurs in the Cold Creek and Pasco synclines. In the Cold Creek syncline, south of the 200 East Area (Hanford Site), the gravel ranges in thickness from 50 to 150 feet (15 to 45 meters) (Routson and Fecht, 1979; Tallman and Others, 1979). In the Pasco syncline, the basal Ringold unit is much thinner, about 5 feet (1 meter) based on work by R. E. Brown for Rockwell Hanford Operations during 1978. These sediments were deposited as slope wash on the basalt surface and by streams flowing through the basin as evidenced by the presence of detritus derived from outside the Pasco Basin. The relatively consistent thickness, with negligible thickening in the axis of the Cold Creek syncline (Routson and Fecht, 1979), suggests that these gravels were deposited on a relatively undeformed surface, but thickness trends of the Rattlesnake Ridge interbed and Cold Creek interbed suggest prebasal Ringold deformation in the Cold Creek syncline.

Lower Ringold Unit. The nature of the contact between the lower and underlying basal gravel units is generally unknown. The texture of the lower Ringold unit is predominantly silty, coarse to medium sand to sandy silt with stringers of coarse to fine pebbles. It is composed of quartz, feldspar, mica, chlorite, and smectite. In core samples from beneath the Hanford Site, the unit is finely bedded to massive.

The lower sand and silt facies is present throughout most of the central Pasco Basin, except for the area around and immediately south of Gable Mountain-Gable Butte. The thickness ranges from zero on the flanks of anticlinal ridges to greater than 350 feet (106 meters) in the Cold Creek syncline. The upper surface of these facies generally decreases in elevation toward the Cold Creek syncline axis and increases in elevation near anticlinal ridges. The thickening of these low-energy,

flood plain, and lacustrine sediments in the Cold Creek syncline suggests that deposition was contemporaneous with and/or followed deformation of the syncline. The general slope of the upper surface is suggestive of deformation after lower Ringold time.

Middle Ringold Unit. The middle Ringold unit conglomerate facies overlies the lower or basal Ringold unit in the central Pasco Basin. The nature of the contact between these two units is not known. The middle Ringold unit consists of well-rounded pebbles and small cobbles with interstitial spaces filled with coarse to fine sand and silt. Lenses of silt and sand are present within the conglomerate. The conglomerate is moderately to well indurated with calcium carbonate and/or silica cement, but contains zones of poor induration. The non-basaltic gravel fraction is predominantly quartzite with metamorphic, granitic, and porphyritic volcanic rocks derived from outside the Pasco Basin. The basalt gravel fraction is Columbia River Basalt Group and is usually highly altered by hydration and physical disintegration. The total percent of basalt is highly variable and appears related to the proximity of basalt topographic highs during middle Ringold deposition. The sand fraction is predominantly quartz and feldspar, and the silt and clay-size fractions are quartz, feldspar, and smectite.

The middle Ringold conglomerate is present throughout most of the central Pasco Basin, except in the area north of Gable Mountain. It is greater than 350 feet (107 meters) thick in parts of the central Pasco Basin. Exposures are restricted to the southern part of the White Bluffs and at Coyote Rapids. The unit was probably deposited in a high-energy, fluvial environment.

Upper Ringold Unit. The silt, sand, and clay of the upper Ringold overlie the middle Ringold conglomerate unit and grade into it at the White Bluffs. The upper Ringold unit is a well-sorted, medium to fine sand, silt, and clay, with minor lenses of fine pebbles. It is more than 50 percent quartz and feldspar, with a relatively high percentage of calcite in caliche horizons. Quartz, feldspar, and mica are present in the silt fraction, and quartz, smectite, and mica are common in the clay-sized fraction. A caliche horizon commonly caps the upper Ringold. Other caliche horizons have been identified throughout the unit. More than 400 feet (122 meters) of upper Ringold are exposed in the White Bluffs. Here, the silt and clay layers typically are horizontally bedded with fine laminations and generally lack current structures. Sand units show horizontal layering and internal cross bedding. The sand, silt, and clay of the upper Ringold unit occur mainly east and north of the Columbia River. In the Hanford Site, south and west of the Columbia River, the upper Ringold unit is largely eroded and has been identified only in boreholes in and around the 200 West Area. The sediments of the upper Ringold unit were deposited in a low-energy, fluvial system with local lacustrine environments. The well-developed caliche horizon indicates that the surface of the upper Ringold unit was exposed to subaerial processes for a relatively long period of time.

Fanglomerate Unit. The fanglomerate facies consists of talus, alluvial fans, colluvium, and slope wash and it lies unconformably on the flanks of anticlinal ridges. The fanglomerate is composed of angular to subangular fragments of basalt and Ellensburg sedimentary rocks. It is generally poorly bedded, and clasts range in size from boulders to medium sands. The fanglomerate unit is extensively exposed on the north flank of the Saddle Mountains where it reaches thicknesses greater than 50 feet (15 meters). It is also exposed on the south flank of Gable Mountain where it is about 3 feet (1 meter) thick.

The fanglomerate facies is currently included in the Ringold Formation (after Grolier and Bingham, 1978). This assignment is made on the basis of apparent time equivalency; not similar depositional environments.

Hanford Formation (Informal Name)

Catastrophic Pleistocene flood deposits in the Pasco Basin are informally referred to as the Hanford formation (informal name). These glaciofluvial sediments were deposited as two facies, the Pasco Gravels (Brown, 1975) and the Touchet Beds (Flint, 1938a). The Hanford formation lies unconformably on the Ringold Formation and, locally, on the Columbia River basalt. The general lateral extent of the Hanford formation is shown in Figure III-28.

Both the Pasco Gravels and the Touchet Beds are cut by discordant zones of near-vertically stratified sediments known as clastic dikes. The genesis of these clastic dikes is poorly understood at this time. Clastic dikes that appear to have been filled from above have been observed by R. F. Black, but the origin of the fissures is not known. Additional studies are necessary to determine their relationship, if any, to seismic activity.

Pasco Gravels. The grain size of the Pasco Gravels varies from boulders to medium to fine sands. Clasts are basalt, granite, diorite, and porphyritic volcanic rocks with minor amounts of gneiss, schist, metasediment, and chert pebble conglomerate.

Bed forms in the Pasco Gravels are varied. The coarser deposits are commonly either foreset bedded and are associated with flood bars or they occur in horizontal beds as sheet deposits. Horizontally bedded, cross bedded, and finely laminated to massive sand deposits have been observed. The complex array of bedding forms is related to the changing energy environment of the catastrophic floods. The gravel and boulder facies were deposited by catastrophic floods within and near high-energy, flood-current channels. Sand facies were deposited in lower energy environments, generally protected from currents or during waning stages of floods.

The most extensive and thickest deposits of the Pasco Gravels are west of the Columbia River on the Hanford Site where they are generally 100 to 200 feet (33 to 60 meters) thick (Tallman and Others, 1979). East of the Columbia River, the Pasco Gravels are thin veneers in Ringold, Koontz, Esquatzel, and Smith Coulees, and the Othello Channels.

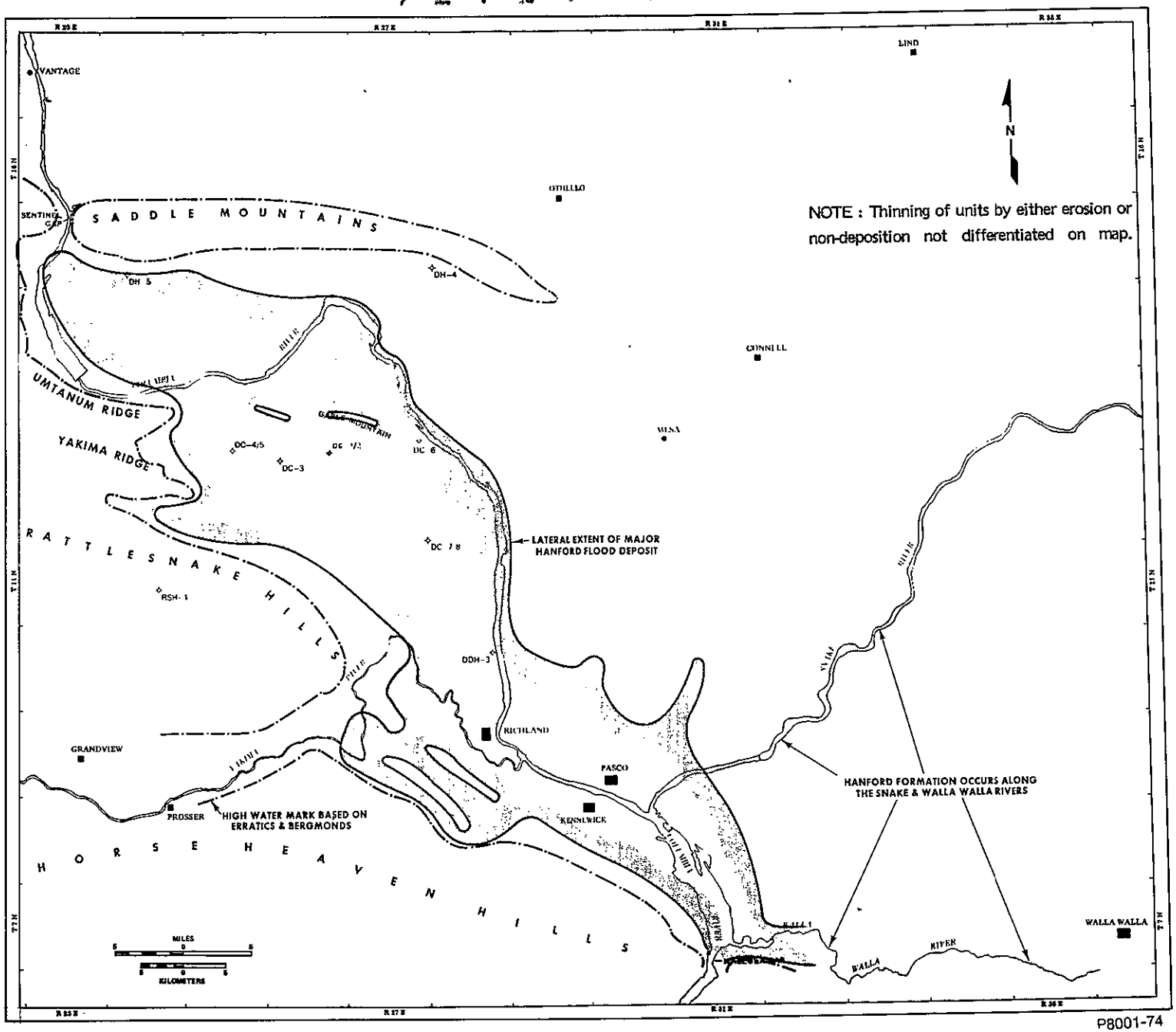

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FIGURE III-28. Lateral Extent, Hanford Formation (informal name).

The Pasco Gravels have been considered to be related to the last major Pleistocene catastrophic flood dated 13,000 years before present (Mullineaux and Others, 1977). Three dates on caliche, in what appears to be old flood gravels from Badger Coulee, were dated at 200,000 (+250,000-70,000), 220,000 (+380,000-70,000), and greater than 210,000 years before present using thorium-uranium dating methods (Tallman and Others, 1978). These dates suggest that at least one older, pre-Wisconsinan, flood is represented in the Pasco Basin.

Touchet Beds. The Touchet Beds are the rhythmically bedded fine-grained facies of the Hanford formation. They unconformably overlie the basalt and Ringold Formation and generally are in conformable contact with the Pasco Gravels. The contact between the Touchet Beds and the underlying Pasco Gravels is generally sharp and planar, but some channels are cut into the gravel and filled with Touchet Beds.

Touchet Beds are composed of silt to fine sand with stringers of coarse sand and gravels. The silt and sand, which are chiefly quartz and feldspar, commonly contain discrete but widespread ash layers. These rhythmically bedded sediments are interpreted as slackwater deposits. They are found mainly on the flanks of anticlinal ridges near the periphery of the basin. In Cold Creek Valley, the Touchet Beds are greater than 25 feet (7 meters) thick and commonly occur up to an elevation of 1,100 feet (335 meters) above mean sea level.

Surficial Deposits

Sand Dunes. Both active and stable sand dunes are in the Pasco Basin. They are mainly medium- to fine-grained quartz sand with minor amounts of silt. Some dunes contain a high percentage of basalt fragments. Volcanic ash, probably Mazama dated at 6,500 years (Fryxell, 1965), is present in stabilized dunes. Active dunes are in the central basin and to the north and west along the Columbia River. The south-central basin is covered with stabilized longitudinal dunes which trend southwest-northeast. The intervening blowouts associated with these dunes are covered with gravel lag, suggesting that these dunes are reworked sand of the Hanford formation.

Alluvium. Alluvial clay, silt, sand, and gravel of variable sorting and thickness are associated with streams in the basin and are mostly of Holocene age. The alluvium is reworked Hanford formation, Ringold Formation, Columbia River basalt, Ellensburg Formation, and loess. At elevations above catastrophic flood deposits, alluvium is derived from Columbia River basalt, Ellensburg Formation, and reworked loess, and may be of Pleistocene age. All alluvium below the elevation of the last major flood is of Holocene age.

Talus. Actively forming talus consists of angular clasts of Columbia River basalt and Ellensburg Formation at the bases of cliffs and on steep rock slopes such as the Saddle Mountains, Umtanum Ridge, Rattlesnake Ridge, and the Horse Heaven Hills. Pleistocene talus, infiltrated with loess and locally cemented with caliche, occurs locally.

Landslides. Landslide debris includes rotated blocks, slump blocks, earth slides, and flows. Larger, partly eroded, stabilized landslides and landslide complexes along these ridges are probably Pleistocene, but may be older. They probably began to form as soon as the ridge attained slopes sufficiently steep to be unstable. Holocene landslides of basalt are associated with anticlinal ridges and structures cross-cutting these ridges. Active landslides along the White Bluffs have been caused by infiltration of irrigation water into the Ringold Formation.

Loess. Loess deposits, consisting of wind-deposited silt and fine sand with some clay and volcanic ash, mantle much of the Pasco Basin. Most loess mapped in the Pasco Basin is Holocene, but several exposures of Pleistocene loess occur above the maximum Pleistocene flood level and may predate the flooding. The older loess is usually capped with caliche and is darker in color than the younger. A loess unit has been identified from core hole samples in the 200 West Area (Hanford Site) (Brown, 1960). It lies stratigraphically between the Pleistocene Hanford formation and the eroded surface of the Pliocene Ringold Formation.

Colluvium. Colluvium of silt, sand, gravel, and rock rubble is generally angular and composed of basalt, reworked Hanford and Ellensburg Formations, and loess deposits. It includes slopewash and mass wasting debris. Most colluvial deposits are Holocene age, but some at higher elevations may be Pleistocene.

BASALT LITHOLOGY VARIATIONS-GRANDE RONDE BASALT

This section summarizes the intraflow structures, petrography, and chemistry of Grande Ronde Basalt flows in the Pasco Basin. Lithology of the Grande Ronde Basalt is emphasized because it contains several thick flows and is a possible repository host rock.

Studies of intraflow structures and chemical variations in Grande Ronde Basalt flows have been performed: (a) to establish the general types of intraflow structures encountered in Grande Ronde Basalt to evaluate the kinds of lateral changes that occur in them and develop means for identifying intraflow structures in the subsurface; (b) to determine the vertical and horizontal variation in chemical composition of these flows to better distinguish flows, or groups of flows, and make more refined correlations between boreholes and from boreholes to outcrops; and, (c) to measure lithologic variations within flows.

Intraflow structures are primarily structures formed within basalt flows at the time of emplacement and cooling. Waste canisters emplaced within the interior of a basalt flow will be within some type of intraflow structure. Intraflow structures thus form rock masses which are the natural barrier nearest to the waste canister, and the character of the intraflow structures can influence ground-water flow paths and flow rates, sorption phenomena, and other waste-basalt interactions, as well as the mechanical integrity of the repository.

The scope of basalt lithology studies included detailed observations of fracture morphology and the intraflow structures in well-exposed surface sections of Grande Ronde Basalt. Fracture abundances were measured and the variations of texture with different intraflow structures were studied. Similar observations were made on cores from DH-5. Thin sections from one unit, interpreted to be a single flow, the Umtanum flow, were examined in all but two of the deep core holes. Major element chemical compositions of flows from all deep core holes in the Pasco Basin and from the surface sections described herein were studied. Trace element analyses were also studied from all but three of the deep core holes and from the Sentinel Gap surface sections.

Location of surface sections and core holes used in this study are shown in Figure III-29.

Deep core holes indicate the Grande Ronde Basalt in the Pasco Basin is at least 3,000 feet (1,000 meters) thick, and consists of at least 35 flows. These flows have an average thickness of 102 feet (34 meters) and range in thickness from 12 to possibly as much as 450 feet (4 to 150 meters) based on measurements in all core holes and surface sections.

Surface exposures of these flows show intraflow structures characterized by columnar jointing with internal variations in fracture abundance and column diameter. The upper one-third to one-quarter of each flow is typically vesicular, with vesicularity increasing toward the flow top. This increase in vesicularity most commonly culminates in a relatively thin, vesicular, rubbly flow top or flow-top breccia. Significant differences in intraflow structures, such as entablature and colonnade (Spry, 1962), occur from flow to flow, and these differences may be sufficiently regular to allow recognition of different types of intraflow structures.

The Grande Ronde Basalt is typically black to dark grey on fresh surfaces, and most flows are aphyric with intersertal to intergranular textures. The chief constituents are plagioclase (^{48}An to ^{65}An) clinopyroxene (augite, subcalcic augite, and pigeonite), and glass. Accessory minerals are titanomagnetite and ilmenite. Orthopyroxene and olivine are rare to absent. Numerous secondary alteration products include nontronite or other smectite clays, palagonite, calcite, opal, chlorophaeite, and thompsonite or other zeolites. Few Grande Ronde Basalt flows contain easily visible plagioclase phenocrysts, but a hand lens discloses tiny microphenocrysts in most flows.

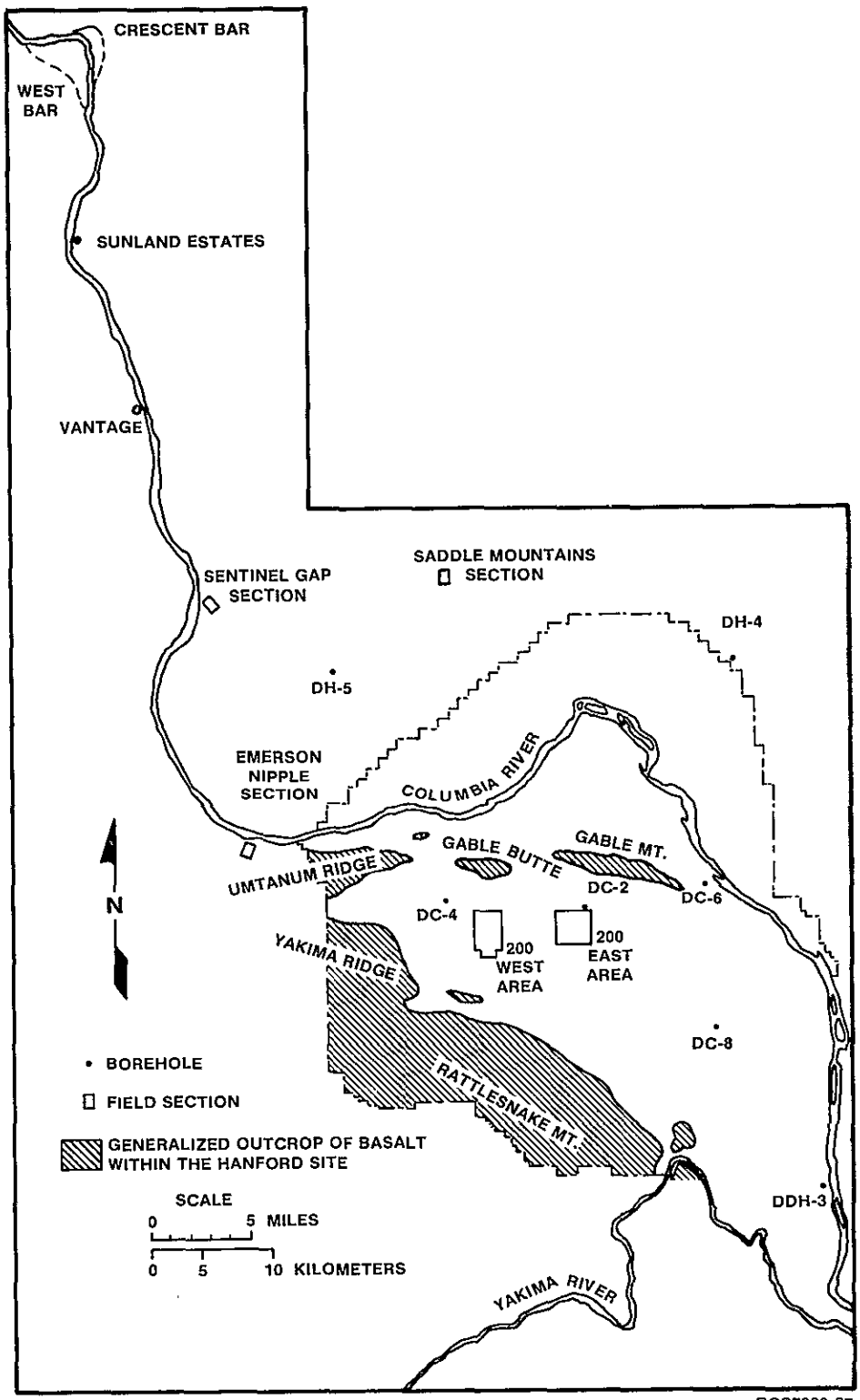


FIGURE III-29. Borehole Locations and Surface Sections Used in Study of Basalt Lithology Variations.

CHARACTERIZATION OF INTRAFLOW STRUCTURES

Common intraflow structures in columnar basalt flows, such as colonnade, entablature, platy jointing, and chisel marks, are discussed by Spry (1962). All these are represented in Grande Ronde Basalt flows in the Pasco Basin and are well exposed at Sentinel Gap and at the Emerson Nipple section (Plates III-3a, 3b, and 3c). Other intraflow structures, such as rubbly flow tops and pillowed zones also occur in Grande Ronde Basalt. Much of the data reported on the Sentinel Gap section are taken from Long (1978).

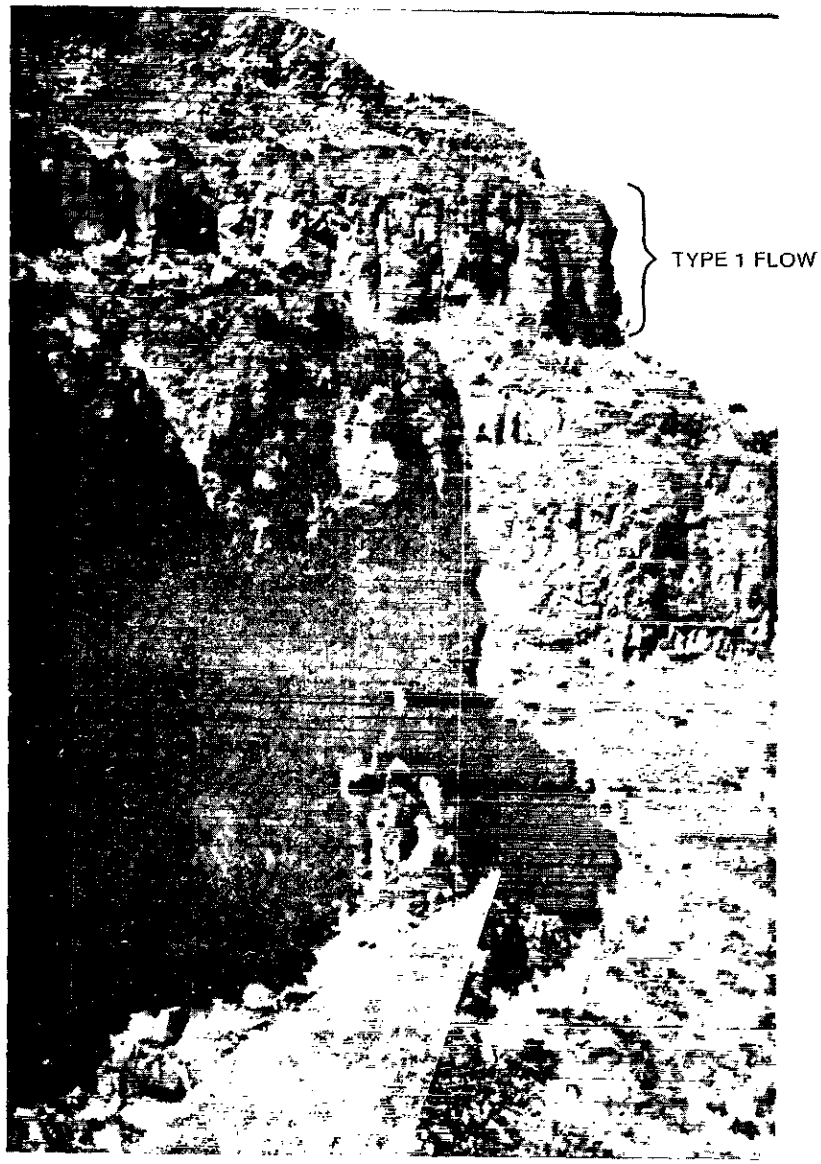
Sentinel Gap Section

(Composite of the Sentinel Bluffs sequence and Schwana sequence. Three basic types of flows with different internal flow structures are exposed in the Sentinel Gap section [Plates III-3b and 3c]). Photographs of these intraflow structures are shown on Figure III-30a, b, and c. Type 1 flows are relatively thin flows, 35 to 100 feet (10 to 30 meters) thick, consisting primarily of irregular, tapering columns 3 to 6 feet (1 to 2 meters) in diameter. These flows lack a distinct entablature and have a poorly developed vesicular flow top. Such flows are invariably diktytaxitic and contain vesicle cylinders. Type 2 flows are very thick flows (150 to 250 feet [45 to 76 meters]) showing columnar tiers of alternating entablature and colonnade-type columns in the lower one-half of the flow. These alternating tiers grade upward into a hackly entablature. Clinker flow top is common and vesicles are abundant in the upper one-third of the flow. Fanning of columns in the entablature occurs locally. Type 3 flows are moderately to relatively thick flows (95 to 200 feet [30 to 80 meters]), in which a sharp break between entablature and colonnade defines a marked difference in fracture abundance and column size. The colonnade in these flows commonly shows pinch-and-swell structure in the columns, and the entablature is a complex pattern of smaller, radiating columns. A crude upper colonnade caps the entablature of most flows.

Table III-5 classifies each of the flows in the Sentinel Gap section according to intraflow structure type. The columns in Type 1 flows (Figure III-30a) are irregular, four- to- five-sided, and relatively thick (average diameter about 4 feet [1.5 meters]). Cooling joints traverse the entire thickness of the flow. Vesicle cylinders extend from about 0.5 foot (0.2 meter) above the base to near the middle of the flow. Vesicles commonly occur in the upper third of the flow with vesicle diameter increasing upward to a thin flow top.

The Rocky Coulee flow is an example of a Type 2 flow (Figure III-30b). Hackly jointing characterizes the upper entablature. The lower one-third of the flow is alternating tiers of colonnade and entablature separated by platy, vesicular zones. The change from alternating tier or entablature and colonnade to hackly jointing of the upper entablature is coincident with the first occurrence of vesicles. The vesicles are commonly concentrated in layers where they are more abundant than elsewhere in the flow. The upper part of the flow is up to 30 feet (10 meters) thick and is locally pillowed. Thick flow lobes occur at the top of the flow and locally culminate in a red clinker flow top. The entablature columns of Type 2 flows (H and I on Plate III-3b) are tiered as in the Rocky Coulee flow,

9 2 1 2 1 9 1 1 6 3 4



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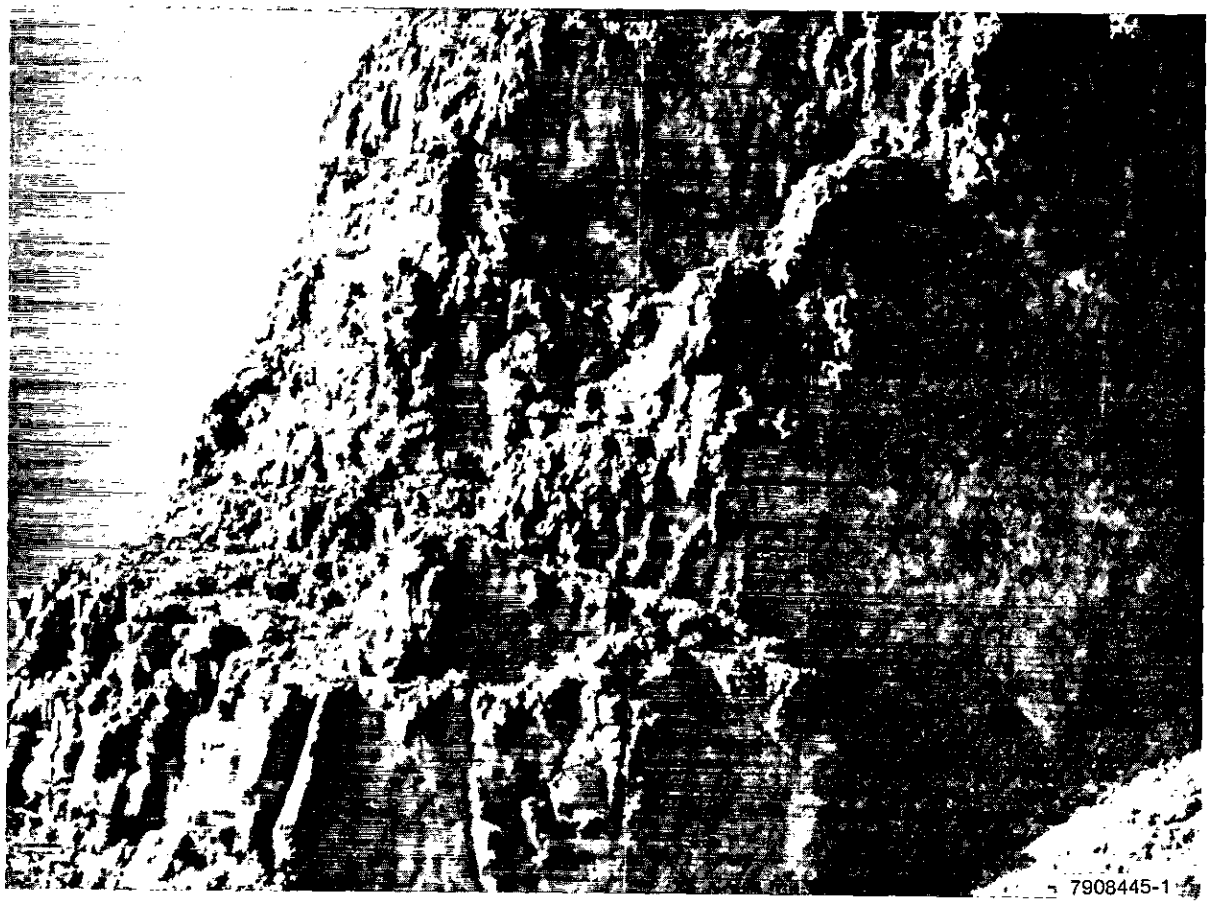
(a) Type 1 flow.

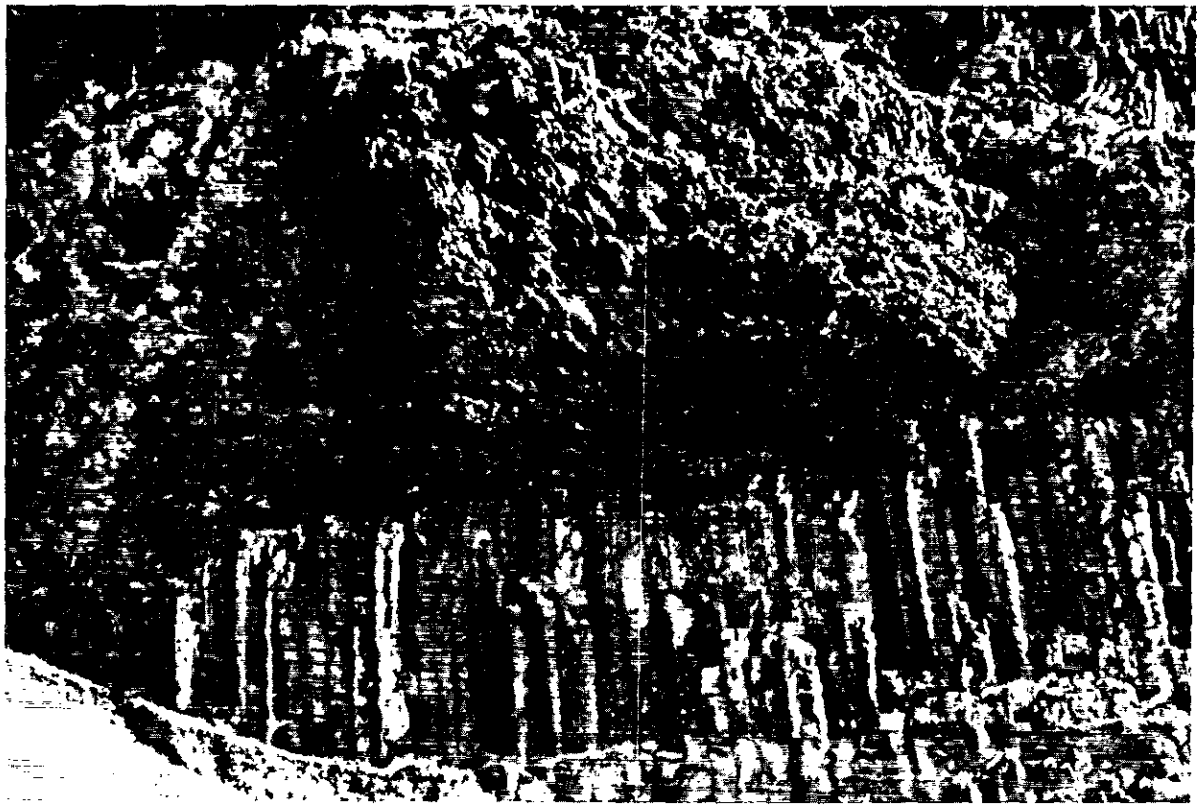
FIGURE III-30. Intraflow Structures.



(b) Type 2 flow.

Figure III-30 (continued)

9 2 1 2 1 9 1 1 6 3 5



7907836-10

(c) Type 3 flow.

Figure III-30 (continued)

TABLE III-5. Intraflow Structure Types within Sentinel Bluffs Sequence and Schwana Sequence Flows, Sentinel Gap Section.

FLOW	INTRAFLOW STRUCTURE TYPE
SG/GR-1 (Museum)	Type 1
SG/GR-2 (Rocky Coulee)	Type 2
SG/GR-3 (J)	Type 1
SG/GR-4 (I)	Type 2
SG/GR-5 (H)	Type 2
SG/GR-6 (G)	Type 1
SG/GR-7 (F)	Type 3 Gradational to Type 1
SG/GR-8 (E)	Type 3
SG/GR-9 (D or Umtanum)	Type 3
SG/GR-10 (C)	Type 3
SG/GR-11 (B)	Type 3
SG/GR-12 (A)	Not Exposed

9 2 1 2 1 9 1 6 3 7

but the hackly jointing is not developed. Vesicle layering, however, is strongly developed. Indeed, a marked break in vesicle abundance was picked as the contact between flows H and I by Taylor (1976). Cooling joints passed through this "contact" indicating that flows H and I are a single cooling unit at Sentinel Gap.

Flow E is typical of Type 3 flows. Figure III-30c illustrates the characteristically distinct boundary between entablature and colonnade in Type 3 flows. Columns in the colonnade are of relatively small to moderate size and have pinch-and-swell features. Column size is smaller and fractures are more abundant in outcrop in the entablature relative to the colonnade. Orientation of columns in the entablature appears chaotic, but, as noted by Spry (1962), the entablature in these flows can be thought of as consisting of a complex arrangement of rather simple units. For example, a common arrangement of entablature columns is to have adjacent groups of fanning columns with one group upright and the other inverted. Figure III-30d shows an inverted fan of columns surrounded by a hackly entablature. The entablature is commonly overlain by larger, irregular columns called the upper colonnade.

Emerson Nipple Section

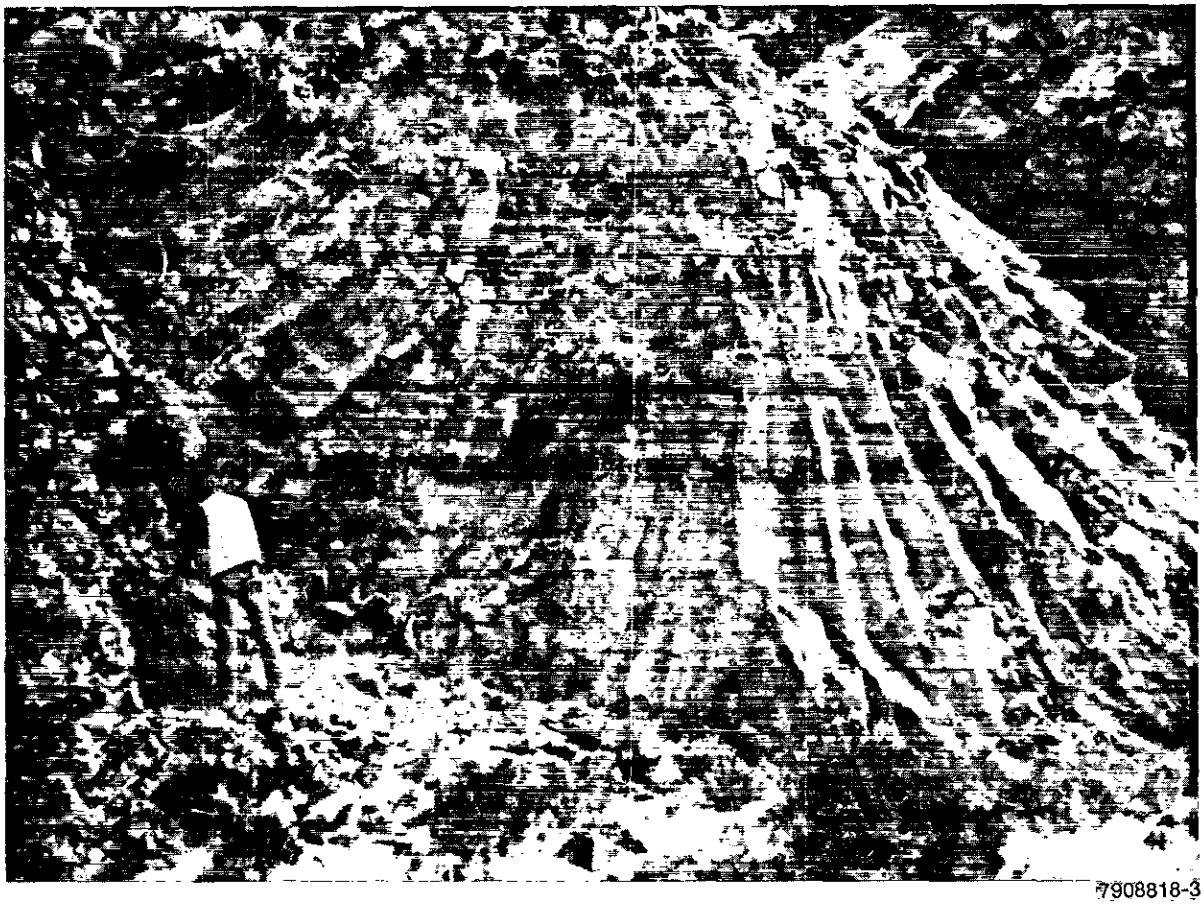
The Emerson Nipple section (Figure III-5b; Plate III-3a) is located on the north face of Umtanum Ridge (approximately 13 miles (21 kilometers) south of the Sentinel Gap section (Figure III-29).

The Grande Ronde flows at Emerson Nipple are correlated with those in the Sentinel Gap section as shown on Plate III-2. The intraflow structures are also similar, but a few intraflow features at Emerson Nipple do not occur at Sentinel Gap, and some flows at Emerson Nipple appear to be different or gradational from the three major types of intraflow structures at Sentinel Gap. For example, flow-top breccias 25 to 135 feet (8 to 42 meters) in thickness occur in two flows, EN/GR-10 and EN/GR-11 (Plate III-3a). Breccias of this thickness and exact character do not occur in the Sentinel Gap section. Also, gradational contacts between entablature and colonnade occur in tiered, Type 2 flows (EN/GR-3). Flow EN/GR-8 appears to be a Type 3 flow that is gradational to a tiered flow (Type 2) because it has extensive development of an entablature at the expense of the colonnade. Flow EN/GR-7 is a Type 2 flow gradational to a Type 3 because, although it exhibits a relatively sharp contact between entablature and colonnade, it is microvesicular and has columns typical of Type 3 flows. Flow EN/GR-9, on the contrary, has Type 2 characteristics which involve two flow units.

Table III-6 classifies each of the flows in the Emerson Nipple Section according to intraflow structure type.

Fracture Morphology

Certain fracture morphologies occur in nearly all flows (Spry, 1962). These include pinch-and swell along columns, ball-and-socket joints, chisel marks, and in the joints. Pinch-and-swell columns are shown in Figure III-31a. Columns in the flows of Sentinel Bluffs range from extremely well formed and regular to irregular and virtually nonexistent. Many of the column faces have pinch-and-swell structures. Almost all columns in the colonnade have at least some gently curving surfaces, but in some flows, these surfaces exhibit pronounced sinusoidal undulation.



(d) Inverted fan of columns.

Figure III-30 (continued)

TABLE III-6. Intraflow Structure Types within Sentinel Bluffs Sequence and Schwana Sequence Flows, Emerson Nipple Section.

FLOW	INTRAFLOW STRUCTURE TYPE
EN/GR-1	Type 1
EN/GR-2	Type 1
EN/GR-3	Type 2
EN/GR-4	Type 1
EN/GR-5	Type 2
EN/GR-6	Type 2
EN/GR-7	Type 2 Gradational to Type 3
EN/GR-8	Type 3 Gradational to Type 2
EN/GR-9	Type 3 Flow with Flow Units
EN/GR-10	Type 3 Gradational to Type 2 with Flow-Top Breccia
EN/GR-11 (Umtanum)	Type 3 with Extremely Thick Flow-Top Breccia
EN/GR-12	Type 1
EN/GR-13	Type 1
EN/GR-14	Not Exposed

9 2 1 2 1 9 1 1 6 1 0

7908818-4

(a) Pinch-and swell columns and stack of Dutch cheeses features.

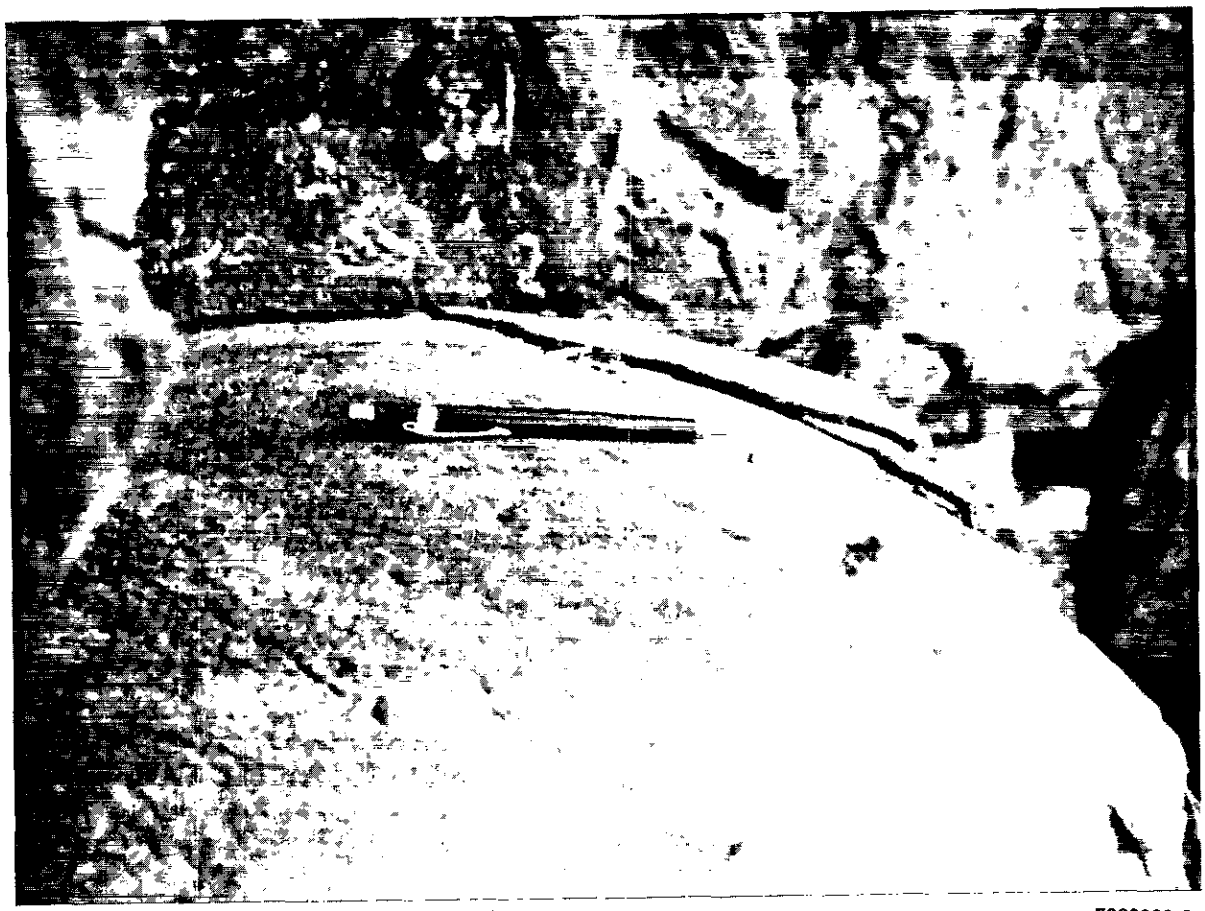
FIGURE III-31. Details of Fracture Morphologies.

Ball-and-socket joints (Figure III-31b) are in the colonnade of some flows with regular columns. Regularly spaced ball-and-socket and/or niche joints create a feature known as a "stack of Dutch cheeses" (Spry, 1962); note their presence in the upper part of the flow in Figure III-31a. Chisel marks are steps or grooves that occur on a scale of 1.5 feet to 0.5 inch (0.5 meter to 1.0 centimeter) that occur on fracture surfaces. A change in surface roughness along a fracture is associated with chisel marks (Figure III-31c) in the entablature. Early fractures have a substantially rougher surface than later surfaces (Long, 1978). However, as shown in Figure III-31d, both features can occur on essentially the same surface, suggesting that the fracture propagated in two stages as "fingers." A possible explanation is that surface roughness is controlled by the temperature at which the fracture forms in conjunction with the kind of texture developed in the rock before cracking. Recently, Ryan and Sammis (1978) suggested that differences in surface roughness occurring in fans on colonnade column faces represent elastic "smooth" and inelastic "rough" modes of fracturing. Differences in surface roughness on colonnade column faces generally are not as great as those shown in Figure III-31d, but following their suggestion, it seems reasonable that two modes of fracturing are involved. It is worth noting, however, that surface roughness differs in a general way from flow to flow and within flows. In Sentinel Bluffs flows, colonnade columns are generally smoother than many entablature columns, but areas of smooth fracturing in the entablature also occur and both the roughest and the smoothest fracture surfaces can occur in the entablature. Platy fracture zones (Figure III-31e) typically parallel the flow base and occur in almost all flows, but the degree and character of the development varies greatly from flow to flow. Some platy zones have distinct undulatory fractures; whereas, in others, platy zone fractures are curvilinear and subhorizontal. The origin of either type of platy fracture is not well understood, but is related to emplacement and primary cooling and perhaps enhanced by later deformation. Holmgren (1968) studied platy fractures in Columbia River basalt and concluded that they formed after the formation of the major vertical cooling joints. He ascribed them to alignment of elongated minerals and flattened vesicles in basalt. Locally, at Sentinel Gap, nearly horizontal, platy fracture zones occur which are interpreted as tectonic in origin. These are shear features that transect column tiers, and in places show brecciation and sigmoidal tension fractures (see structural analysis section of this chapter).

Nearly vertical, closely spaced fracture zones have been observed in the Grande Ronde Basalt flows at Sentinel Gap. It is unclear if these vertical fractures are primary or tectonic--or some combination. They certainly transect portions of the interior of individual flows and in some places may cross flow boundaries.

Basal Pillow Zones and Flow-Top Breccia

Basal pillow zones are an intraflow structure that forms when a basalt enters a lake or other body of water. Excellent examples of pillow lavas, pillow breccias, and palagonite tuffs occur within the Frenchman Springs Member (Mackin, 1961), but they are rare in the Grande Ronde Basalt at Sentinel



7908936-3

(b) Ball-and-socket joints.

Figure III-31 (continued)

7908936-2

(c) Chisel marks.

Figure III-31 (continued)

7908818-2

(d) "Rough" and "smooth" fracture surfaces.

Figure III-31 (continued)

(e) Platy fracture zone.

Figure III-31 (continued)

9 2 1 2 1 9 4 1 6 4 6

Gap. An example of a thin, basal, pillow zone in the Sentinel Bluffs flows is shown in Figure III-32. Pillowed zones occur in Grande Ronde flows near Vantage (Hole-in-the-Wall section, Bentley, 1977b) and farther north near the mouth of Moses Coulee (Fuller, 1927). Flow-top breccias occur in most flows, but are ordinarily limited to the upper 10 percent of a flow thickness. Some flows, however, exhibit flow-top breccias that constitute as much as 50 percent of the thickness of the flow. These breccias typically consist of massive, vesicular, and amygdaloidal clasts of basalt which range in size from 1 to 12 inches (2 to 30 centimeters) and are cemented or welded by up to a 20 percent matrix of fine-grained basalt. The clasts are angular to subrounded and locally are coated with a fine-grained, yellowish material. The degree of vesicularity is variable, but vesicular clasts predominate (75 percent) in the upper part of the breccia; whereas, in the lower part, vesicular and non-vesicular clasts are about equal in abundance. Lenses of columnar basalt occur sporadically in the breccias.

Lateral Variations

Long (1978) initially studied intraflow structures in only vertical sections at Sentinel Gap, in Core Hole DH-5, and later at Emerson Nipple. The characteristics of lateral variations in the intraflow structure within individual Grande Ronde Basalt flows are the subject of study by Long (now in progress). This study involves the examination of a well-exposed section of Sentinel Bluffs flows of Grande Ronde Basalt extending from Crescent Bar south to near Vantage, Washington (Figure III-29). Certain flows in this sequence are nearly continuously exposed for approximately 12 miles (20 kilometers) permitting direct observation of lateral changes in intraflow structures. Some preliminary conclusions from this study are given below.

Preliminary data suggest that intraflow structure Type 1 does not typically change laterally into Type 2 or Type 3 intraflow structures, but that a limited degree of gradation occurs between Type 1 intraflow structures and Types 2 and 3. This conclusion is based on surface tracing of flows with Type 1 intraflow structure over a distance of about 4 miles (7 kilometers) with no obvious transition to another intraflow structure type. However, correlative flows in the Sentinel Gap and Emerson Nipple sections do show somewhat different intraflow structures, including, in some cases, characteristics intermediate between intraflow structures Types 1 and 2. This implies that either intraflow structures change laterally to some degree or the proposed correlations are incorrect, even though they occupy identical stratigraphic positions and are otherwise indistinguishable. If such intraflow structure types do change, apparently they do so in a gradational fashion over a distance of as much as 12 miles (20 kilometers). Thick and thin flows appear to be continuous over the 12-mile (20-kilometer) distance studied and almost all flows are continuous over a 4-mile (7-kilometer) stretch that has been studied in detail. Preliminary examination of one locality south of Crescent Bar suggests that some flows terminate in this area and are at least partly replaced by others. In addition, limited data from the Sunland Estates area suggest that, between the Sunland Estates area and Sentinel Gap, the Umtanum flow pinches out.

FIGURE III-32. Basal Pillow Zone in Sentinel Bluffs Flows.

9 2 1 2 9 4 1 6 1 8

Pillow complexes are common in the Crescent Bar area making up to 50 percent of the thickness of some flows. Lateral changes in pillow palagonite complexes are abrupt. In one locality near Sunland Estates, a flow that is about 50 percent pillows becomes free of all pillows over a distance of 50 feet (15 meters) (Figure III-33). The flow lacks pillows over a distance of about 900 feet (300 meters) and, with similar abruptness, the pillow zones reappear to make up 50 percent of the flow. The total flow thickness remains constant across the abrupt change in the thickness of the pillowed zone.

The distribution of thick flow-top breccias in the Pasco Basin is not well defined. Their extent is limited to the north, by their absence from Sentinel Gap to Crescent Bar, and to the east and southeast by their absence in all core holes in the Pasco Basin except DC-8. It is possible that the thick flow-top breccia in the Umtanum flow lies along a northwest trend from Emerson Nipple to DC-8.

The origin of flow-top breccia is uncertain, but Waters suggested to Rockwell Hanford Operations in 1978 that they result from dammed drainages spilling over parts of the flow while still molten, causing convective overturn of the material in the upper part of the flow with attendant rapid chilling and brecciation. If this is the case, one might expect the breccia zones to occupy channel-like areas in the plane of the flow. There is some suggestion that such areas would lie to the west and south of the present Pasco Basin during Grande Ronde time. This is based on the concept of the Columbia Plateau consisting of a broad, gentle paleoslope extending to the proto-Cascade Range, which would mean that most major drainages would have been farther west than the present Pasco Basin. This is suggested by the Sentinel Bluffs isopach (Figure III-5) and by the apparent northwest trend of the margin of the Umtanum breccia. An alternative hypothesis suggested by D. A. Swanson to Rockwell Hanford Operations in 1979 is that the Umtanum flow-top breccia is a near-vent breccia localized along a northwest-trending dike source. This is consistent with our limited knowledge of the distribution of the Umtanum breccia. Future work is planned to compare the Umtanum flow-top breccia with known near-vent breccias.

Variations in thickness of entablature and colonnade are in evidence in exposures near Sunland Estates. One such feature, discussed previously, involves the presence or absence of a pillow zone. Other intraflow structure changes occur in the Crescent Bar area: (a) relatively rapid change in position of an entablature-colonnade contact; (b) presence or absence of upper colonnade; and, (c) presence or absence of thin flow lobes near the tops of relatively thick flows. An example of rather abrupt thinning of a colonnade in the Sunland Estates area is shown in Figure III-34. The majority of flows near Sunland Estates appears to be more regular than the one shown in the Figure III-34. Thinning of the colonnade in most flows occurs in a less radical fashion, typically over distances of about 150 feet (50 meters).

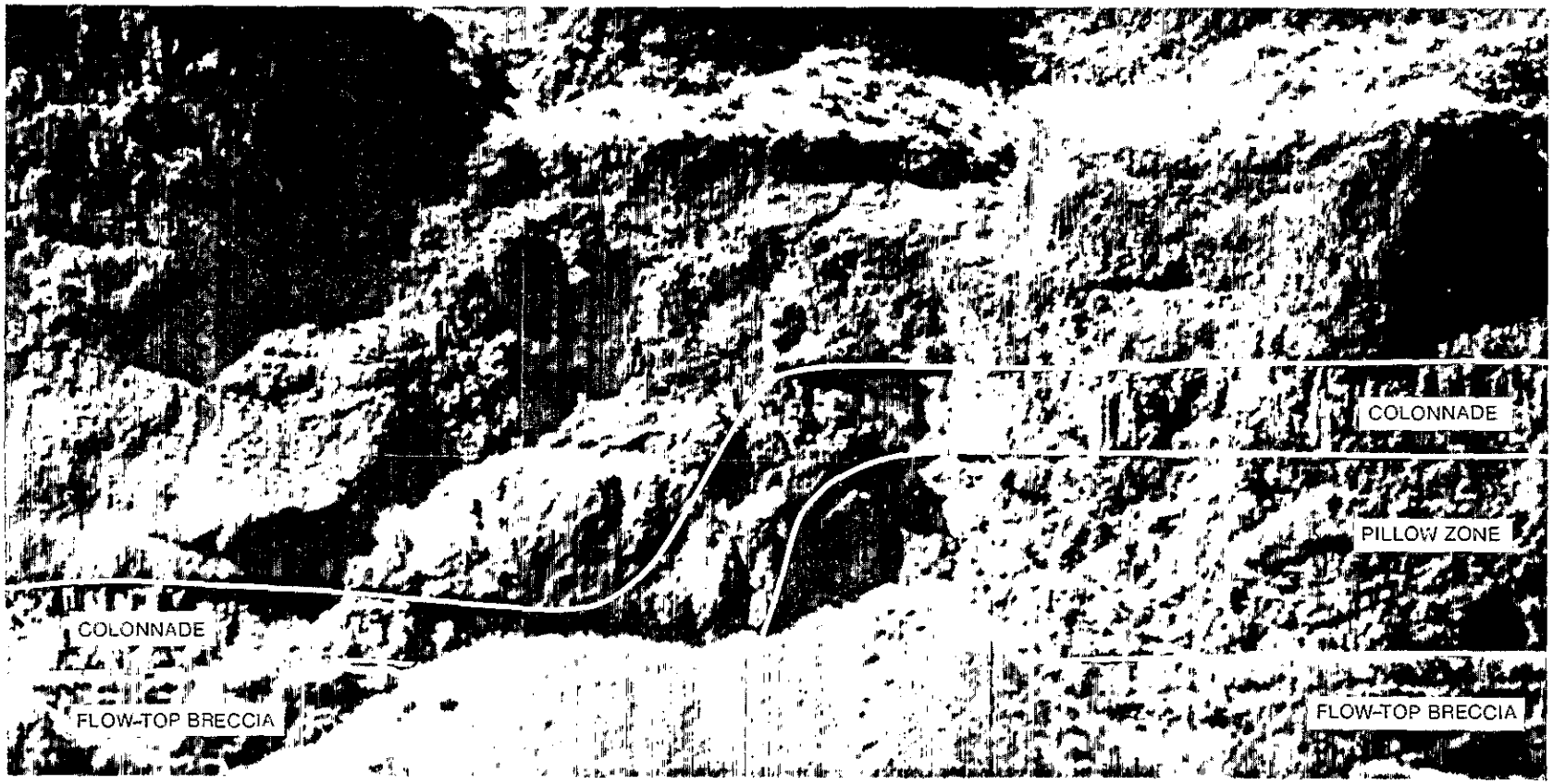


FIGURE III-33. Abrupt Lateral Pinch-Out of Pillow Palagonite Complex.

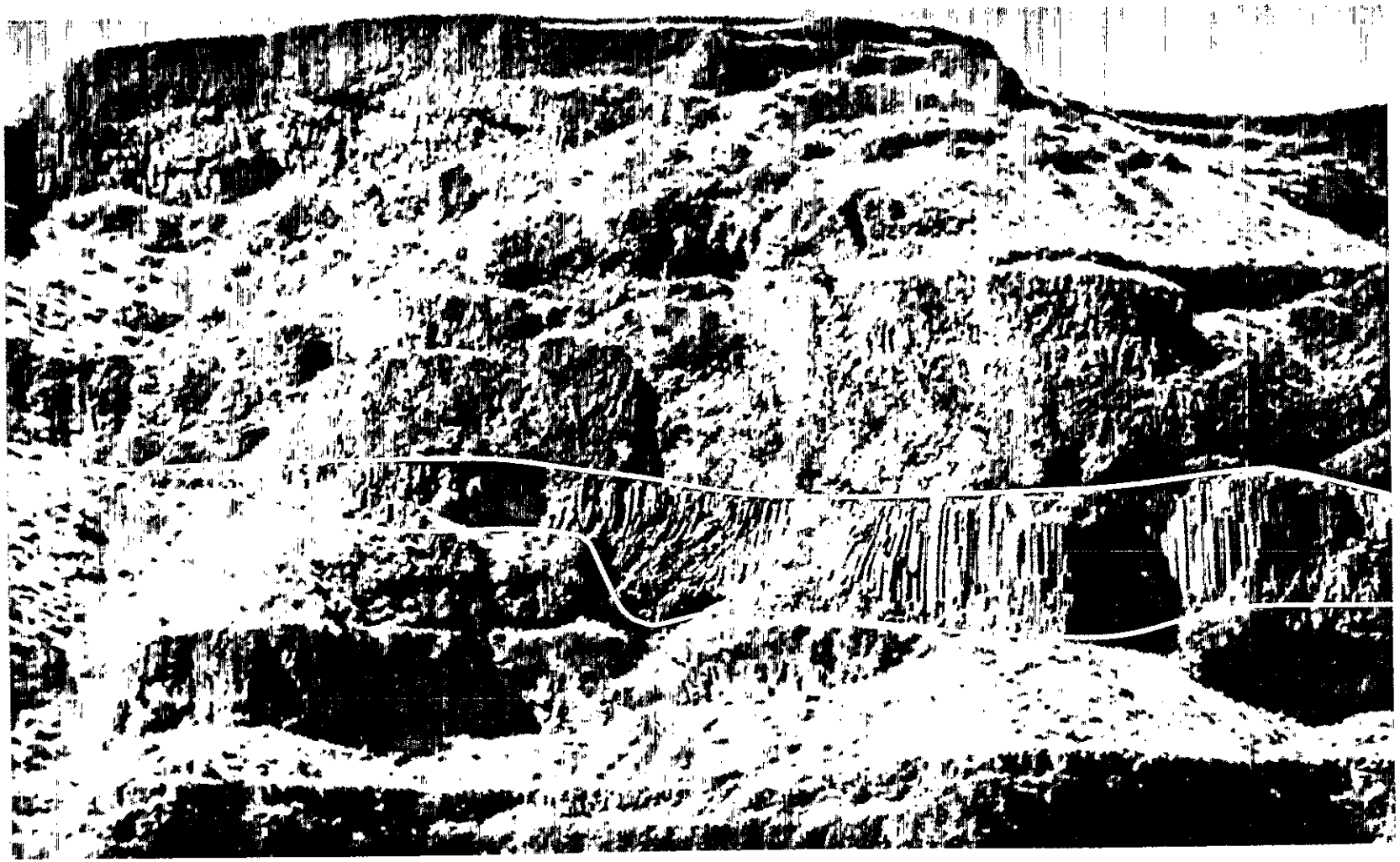


FIGURE III-34. Lateral Pinch-Out of Colonnade (Sunland Estates).

Local changes in jointing pattern of entablature and colonnade commonly occur, many with periodic spacing. One of the most obvious examples is fanning or radiating columns. These intraflow structures are particularly well exposed in the Umtanum flow at the Emerson Nipple section, where they have a radial and concentric jointing pattern with the appearance of a filled lava tube and have a periodic spacing of about 250 feet (75 meters) over an exposure of about 650 to 1,000 feet (200 to 300 meters). In some places, alternating, inverted, and upright fanning columns occur, again with fairly regular spacing. Near Sunland Estates, fanning columns are less common and less regular in their spacing than at Sentinel Gap and Emerson Nipple.

Fracture Measurements

Fracture logs were made both in surface basalt exposures and on basalt cores. The purpose of these measurements was two-fold: (a) to determine if fracture characteristics can be used to identify intraflow structures, especially the contact between the entablature and colonnade; and, (b) to provide data on fractures that might be of utility to hydrologists in estimating permeability and fracture porosity in basalt flows in the Pasco Basin.

A fracture, as logged in drill core, was defined as any subplanar or planar crack either filled or unfilled which transects or partially transects the core. Some of the fractures are clearly drilling or hammer breaks and these have been excluded. Most core fractures are narrow (less than 0.05 inch [1 millimeter]) and contain some kind of filling. Even relatively wide fractures are generally filled, but some have visible porosity and may be permeable. The mineralogy of the fracture filling was not determined, but analyses by Ames (in BWIP, 1978) indicate they are mostly montmorillonite. Unfilled fractures generally have narrow apertures (less than 0.05 inch [1 millimeter]), but rare fractures or fissure openings are 0.25 to 0.5 inch (6 to 12 millimeters) in width and are unfilled, only partly filled, or have fillings that have been differentially leached.

Of the 1,454 fractures logged in 3 Grande Ronde Basalt flows from DH-5, 85 percent were filled and 15 percent unfilled. The percentage of filled fractures for each flow logged is as follows: Museum--87 percent; Rocky Coulee--77 percent; and, Flow E--86 percent.

Results from core fracture measurements are shown graphically in Figure III-35 as the average number of fractures per foot plotted against position in the DH-5/GR-1 flow, the DH-5/GR-3 flow, and the DH-5/GR-8 flow. The only consistent feature appears to be a decrease in maximum fracture abundance near the base of each of the three flows. This feature is most distinct for the DH-5/GR-8 flow about 30 feet (10 meters) above the base of the flow, but even for this flow, scatter in the plotted points makes the position change in fracture abundance uncertain. It is possible, although, that the change does correspond to the contact between entablature and colonnade.

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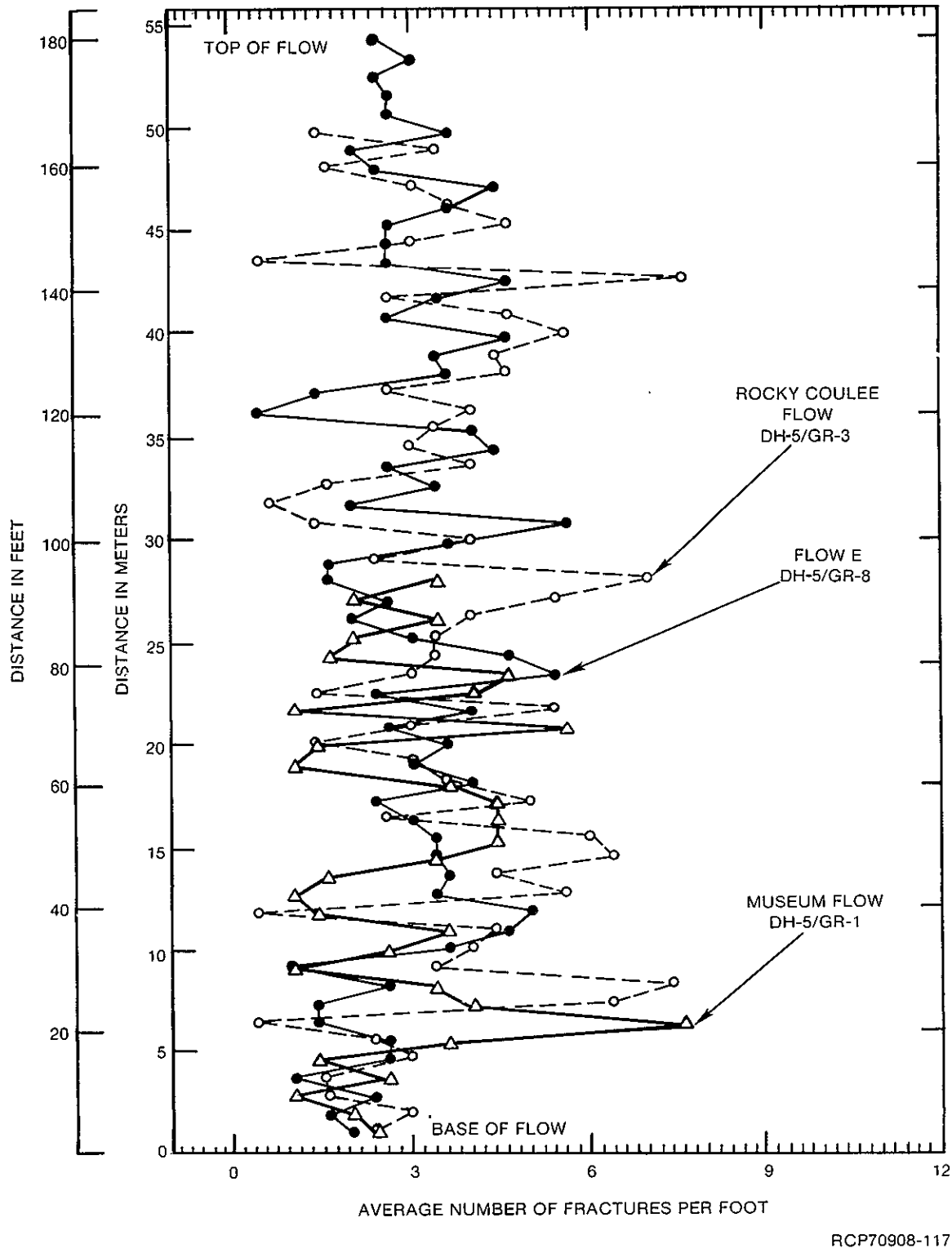

FIGURE III-35. Fracture Measurements, Core Hole DH-5.

Similar plots were made for other drill core fracture characteristics, such as percentage of fractures with greater than 60-degree-dip and maximum fracture length (Long, 1978), but these revealed no entablature-colonnade contact.

Plots of fracture abundance from surface exposures are shown in Figure III-36. From the diagram, it is possible to locate the actual fracture abundance toward the top, which is consistent with the lack of entablature and crudely tapered columns in this Type 1 flow.

The Rocky Coulee flow, SG/GR-2, shows a more irregular distribution of fracture abundance slightly below the entablature-colonnade contact (Figure III-36). From the diagram, it is possible to locate the actual position of the entablature-colonnade contact to within 3 feet (1 meter). This location is consistent with the observed location of the contact. Furthermore, the fracture abundance in the entablature is definitely greater than that in the colonnade and this is, again, consistent with actual inspection of the two parts of the flow.

Plots of fractures with greater than 60-degree-dip versus position in the flow were also made for the surface data (Long, 1978). These plots show much scatter, and no correlation with intraflow structure type or contacts.

Textural Variations

Petrographic observations indicate a strong correlation between certain basalt textures and intraflow structures. Two textural features that change markedly across sharp entablature-colonnade contacts are: (a) a decrease in the volume percent of glass from entablature to colonnade; and, (b) a decrease in abundance and size of crystallites in that glass from entablature to colonnade (Figure III-37a and III-37b). These textural changes also appear to correlate with the diameter of columns within a given flow. Thus, the basal colonnade, the upper colonnade, and areas of local colonnade development within the entablature can be distinguished from one another by lower glass content and fewer crystallites in the glass of the colonnade relative to the entablature. The texture of the glass varies considerably, but in five cases examined, the glass content always increases going from the colonnade into the entablature and the size and abundance of microlites increase.

Diktytaxitic flows, such as the Museum flow (Type 1), have a poorly developed entablature, are relatively coarse grained, and have a lower glass content than Type 3 flows. Where they do have a poorly developed zone of smaller columns at the top, they have a higher percentage of tachylitic glass. This textural change is gradual, where the change in column diameter is gradual.

Shape and grain size of opaque phases also vary with position in a flow. Plagioclase and clinopyroxene morphology also changes slightly through a flow, but these changes appear to be related to the extent of crystallization. That is, the shape and size of plagioclase and clinopyroxene in the entablature of a flow are mostly indistinguishable from those of the colonnade where the entablature has crystallized more completely.

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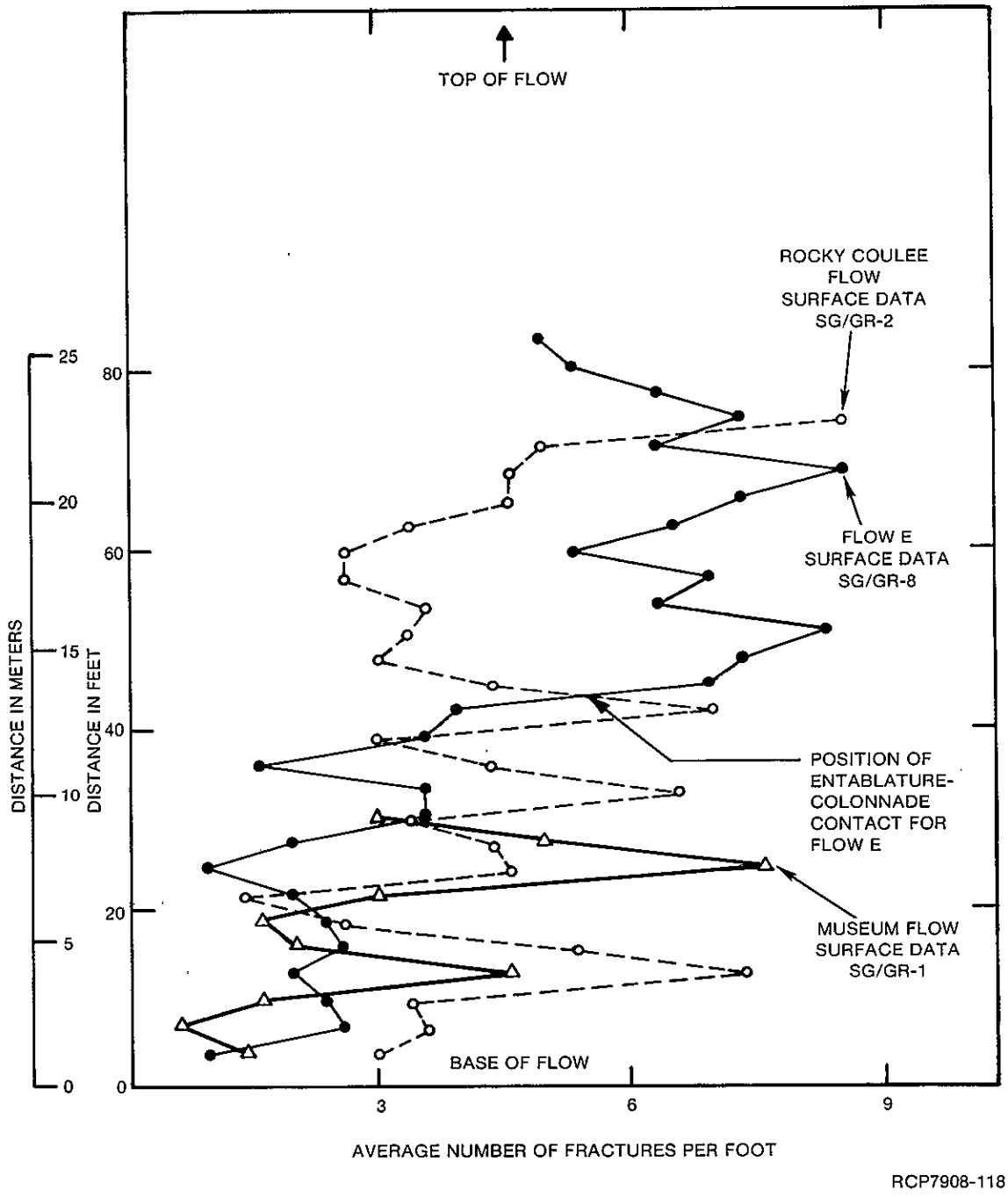
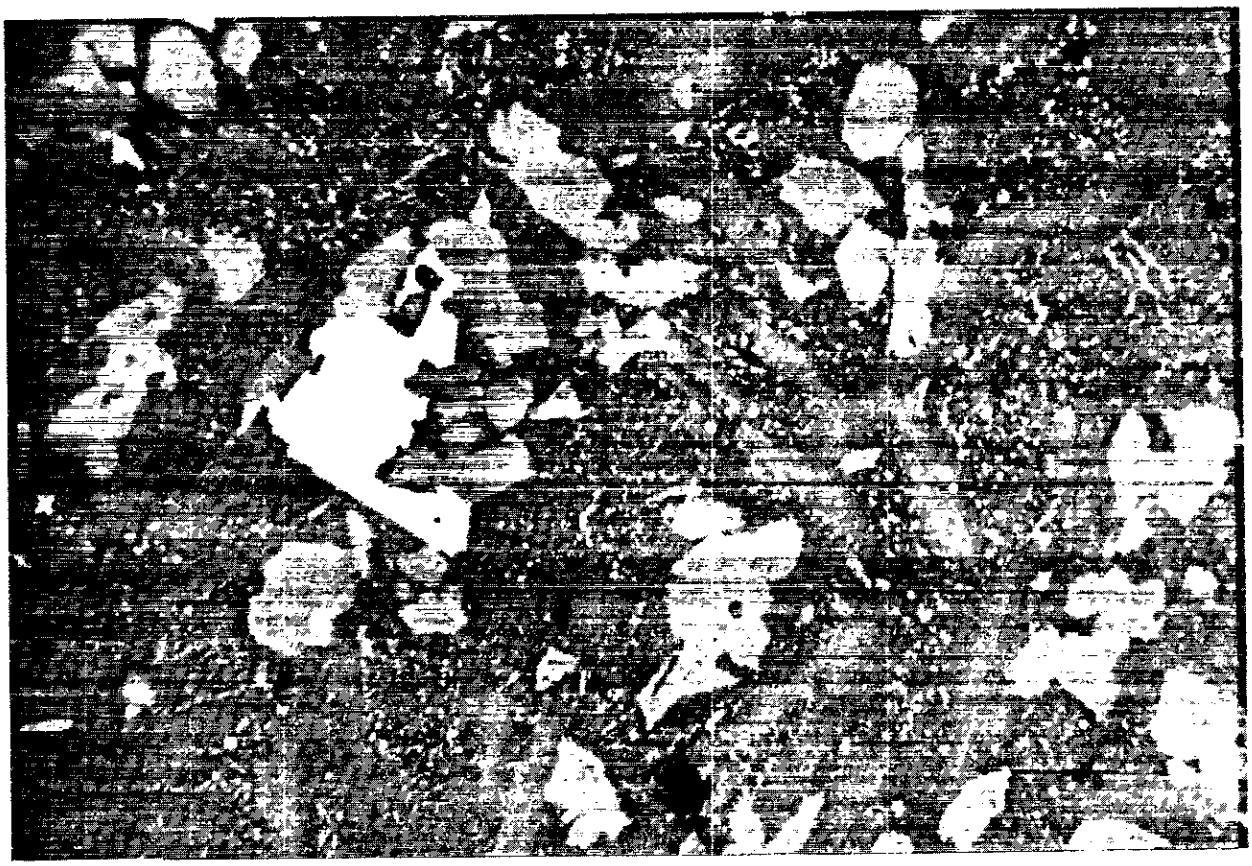


FIGURE III-36. Fracture Measurements, Sentinel Bluffs Flows at Sentinel Gap Surface Exposure.



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(a) Reflected light, Sample C2249 (width of photomicrograph is 0.6 millimeter).

FIGURE III-37. Photomicrograph, Umtanum Flow at Umtanum Ridge (Entablature).

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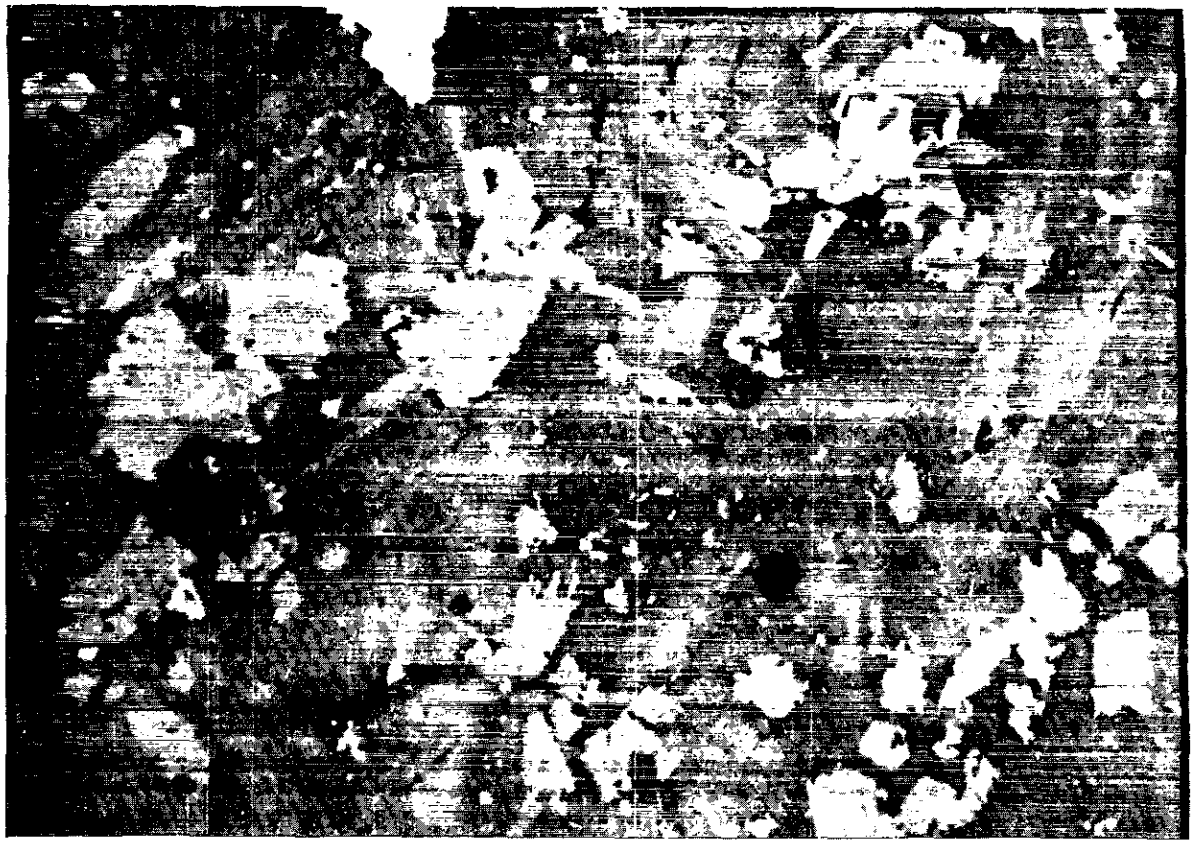

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(b) Reflected light, Sample C2250 (width of photomicrograph is 0.6 millimeter).

Figure III-37 (continued)

Textural data from thin sections of core can thus accurately define the contact between entablature and colonnade, and can also provide quantitative information on fracture abundance. A relationship between fracture abundance and basalt textures exists because fracturing responds to mechanical properties of the rock which are, in turn, controlled by rock texture. Because glass has a substantially different mechanical property than crystalline materials, the glass content is probably the most important parameter. A consequence is that texture actually provides information on fracture abundance over a much larger volume surrounding a drill core than does counting the fractures in the core.

Magnetic Properties

Previous work by Coe and Others (1978), Beck and Others (1978), and Packer and Petty (1979) has shown that the mean inclination of remanent magnetization differs sufficiently between flows in parts of the Schwana and Sentinel Bluffs sequences to be useful for correlations. Measurement of additional magnetic parameters, especially magnetic intensity, magnetic susceptibility, saturation magnetization, stability characteristics, and characteristics of susceptibility anisotropy, might help to recognize intraflow structures. Accordingly, the above parameters were determined for three prominent Grande Ronde Basalt flows by Beck for Rockwell in 1979. Beck concluded from the results of the test that the measured parameters are not an unequivocal guide for recognizing intraflow structures in Grande Ronde Basalt.

Intraflow Structures within the Umtanum Flow in the Pasco Basin Subsurface

Interpretation of the intraflow structures in the Umtanum flows in the Pasco Basin subsurface has been made using textural data, visual observation of core and surface sections, and density logs (Figure III-38). Reconnaissance textural data were collected from DC-2, DC-4, DDH-3, and DH-4, and detailed textural information was collected from DH-5, Emerson Nipple, and Sentinel Gap. Density logs are available from all core holes. Visual observation was made of surface sections and basalt core from core holes was examined. An interpretation of these data is displayed graphically in Figure III-38. The Umtanum has a uniform thickness overall, about 240 feet (80 meters), except for DH-4 where the flow has thinned markedly.

The flow-top breccia of the Umtanum varies in thickness reaching its greatest known thickness at the Emerson Nipple section where it is more than 100 feet (33 meters) thick. A thin, pillowed zone is at the top of the Umtanum flow at Sentinel Gap. Below the pillowed zone at Sentinel Gap is a thin and poorly exposed upper colonnade not present at Emerson Nipple, probably because of the thick flow-top breccia. An upper colonnade, 25 feet (12 meters) thick, is interpreted to exist in the top of the Umtanum in DH-5 based on basalt textures, particularly the presence of evenly distributed, large magnetite or titanomagnetite grains that characterize the upper colonnade of many Grande Ronde Basalt flows. Lack of thin sections from the upper part of the other flows in the other core holes prevents recognition of upper colonnade features elsewhere in the subsurface. The upper 30 to 75 feet (10 to 25 meters) of the Umtanum--including its flow-top breccia--are typically vesicular. This vesicularity can be observed directly in outcrop and core and indirectly on borehole geophysical logs such as the density log.

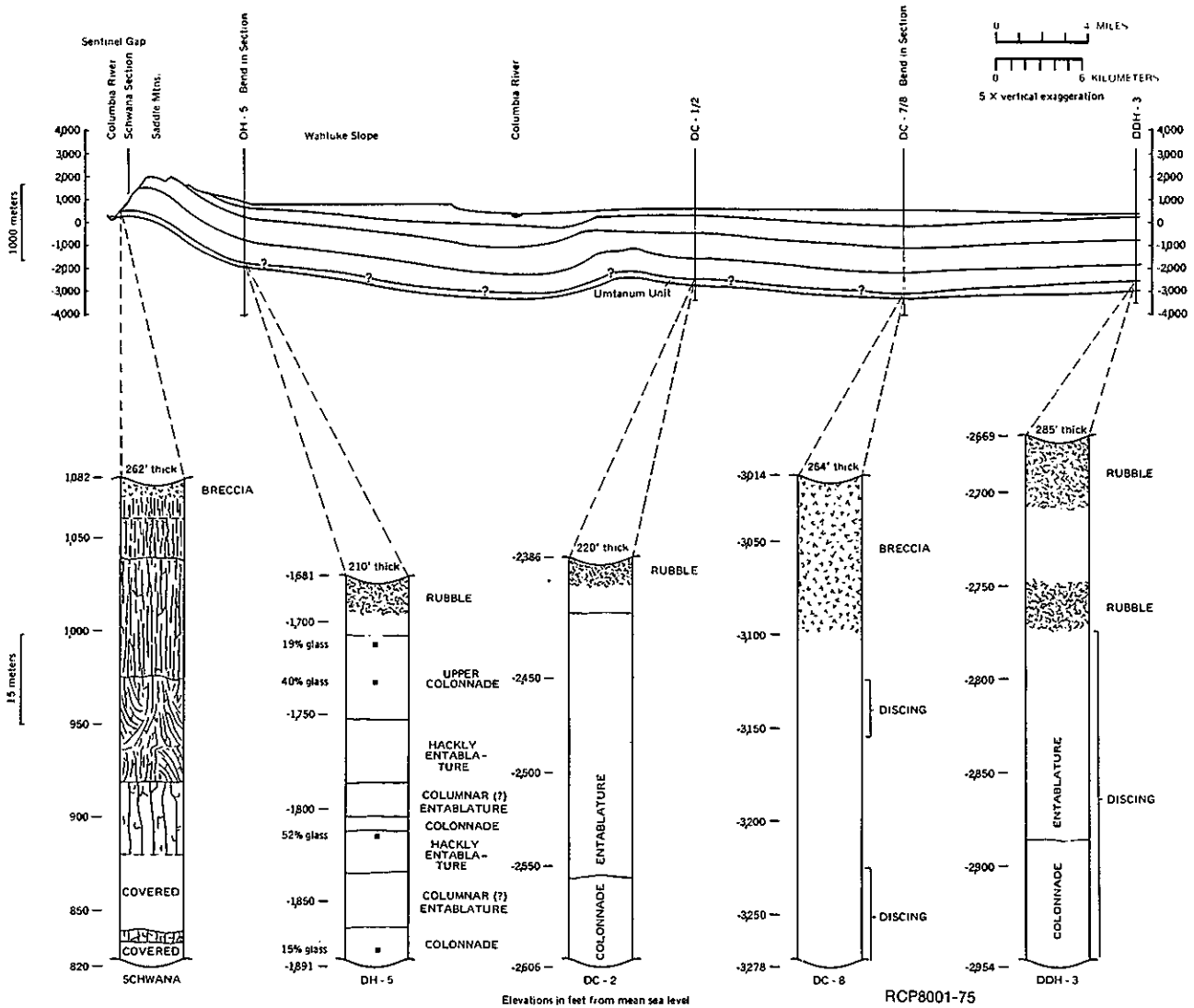

FIGURE III-38. Interpretation of Intraflow Structures in the Umtanum Flow across the Pasco Basin.

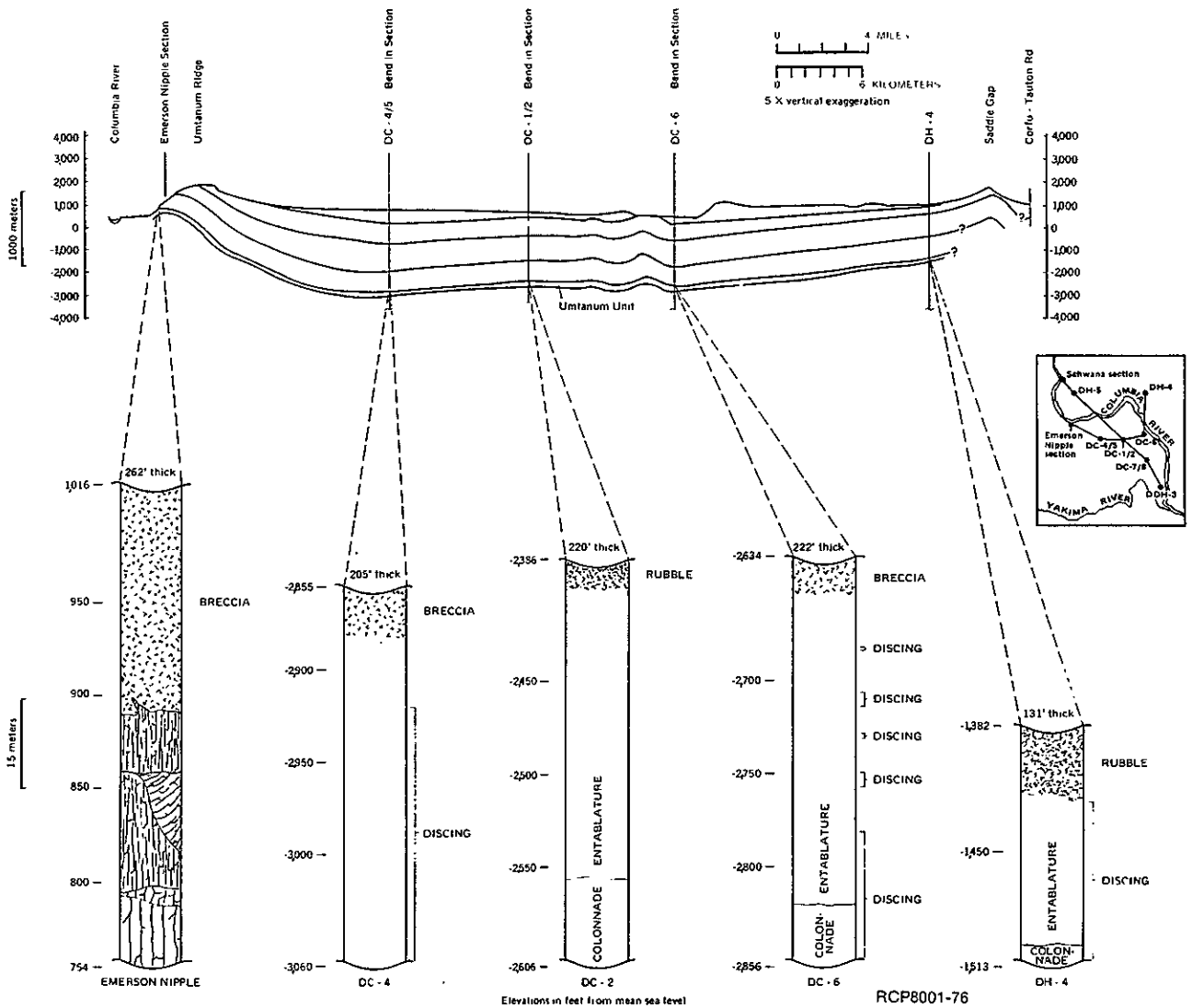

Figure III-38 (continued)

The middle, thickest portion of the Umtanum is commonly the entablature (Figure III-38). In DH-5, however, textural interpretations based on samples taken at 5- to 10-foot (1.5- to 3.0-meter) intervals indicate the upper colonnade is underlain by an entablature of 2 distinct column diameters and then by a thin colonnade (Figure III-38). This sequence is then repeated to the base of the flow. These data suggest that the Umtanum unit in DH-5 is more like a tiered or Type 3 flow than a Type 2 flow. Such intraflow structure details are not known from other core holes because thin sections are not yet available for the upper parts of the Umtanum flow. Thin sections are available from the lower colonnade-entablature contact in the other core holes and were studied to locate the contact shown in Figure III-38.

The colonnade of the Umtanum flow is relatively thick at Sentinel Gap, thins in DH-5, Emerson Nipple, and DH-4 (although, as a percentage of total thickness, it is larger in DH-4 due to the relatively small total thickness of the flow there). The colonnade thickens in DC-2, but is relatively thin in DC-6. In DDH-3, the colonnade is substantially thicker again. The contact between the entablature and colonnade is ordinarily very sharp, but is apparently gradational over about 6 feet (2 meters) in DDH-3.

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Variation in Chemical Composition

Vertical variations in chemical composition were determined using major element data from three flows exposed at Sentinel Gap: SG/GR-1 (Museum flow); SG/GR-8 (Flow E); and, SG/GR-9 (Flow D, Umtanum unit) (Figure III-39; Plates III-3b and 3c). These flows were selected because they represent the range of chemical composition and intraflow structure variation observed in Grande Ronde Basalt flows. In addition, a preliminary examination of the chemical variability within flows in a single locality indicated that these flows covered the range of that variability. These variations are displayed graphically in Figure III-39 and listed as the mean and one-standard-deviation in Table III-7. The standard deviation is a measure of dispersion and, even though there is covariance between many elements (Reidel, 1978b) in the Grande Ronde Basalt, it provides a numerical comparison of confidence limits on the average flow composition. These data demonstrate significant variation in the chemical composition among these flows for most elements, but for other elements, all or much of the variation in some flows can be accounted for by analytical variation. Examples of the latter case are SiO_2 in SG/GR-8 and Al_2O_3 in SG/GR-9. Flows SG/GR-8 and SG/GR-9 both show approximately the same, fairly limited, internal variation; whereas SG/GR-1 shows significantly more internal variability. This latter flow is diktytaxitic with vesicle cylinders, and this greater chemical heterogeneity appears to be characteristic of these types of flow. In general, the Types 2 and 3 flows have vertical chemical homogeneity similar to SG/GR-8 and SG/GR-9. These data demonstrate that vertical chemical variability within Grande Ronde flows at Sentinel Gap is substantially less than differences between major groups of flows and between certain single, chemically distinct flows and the flows that surround them. This does not, however, address the problem of lateral chemical variations.

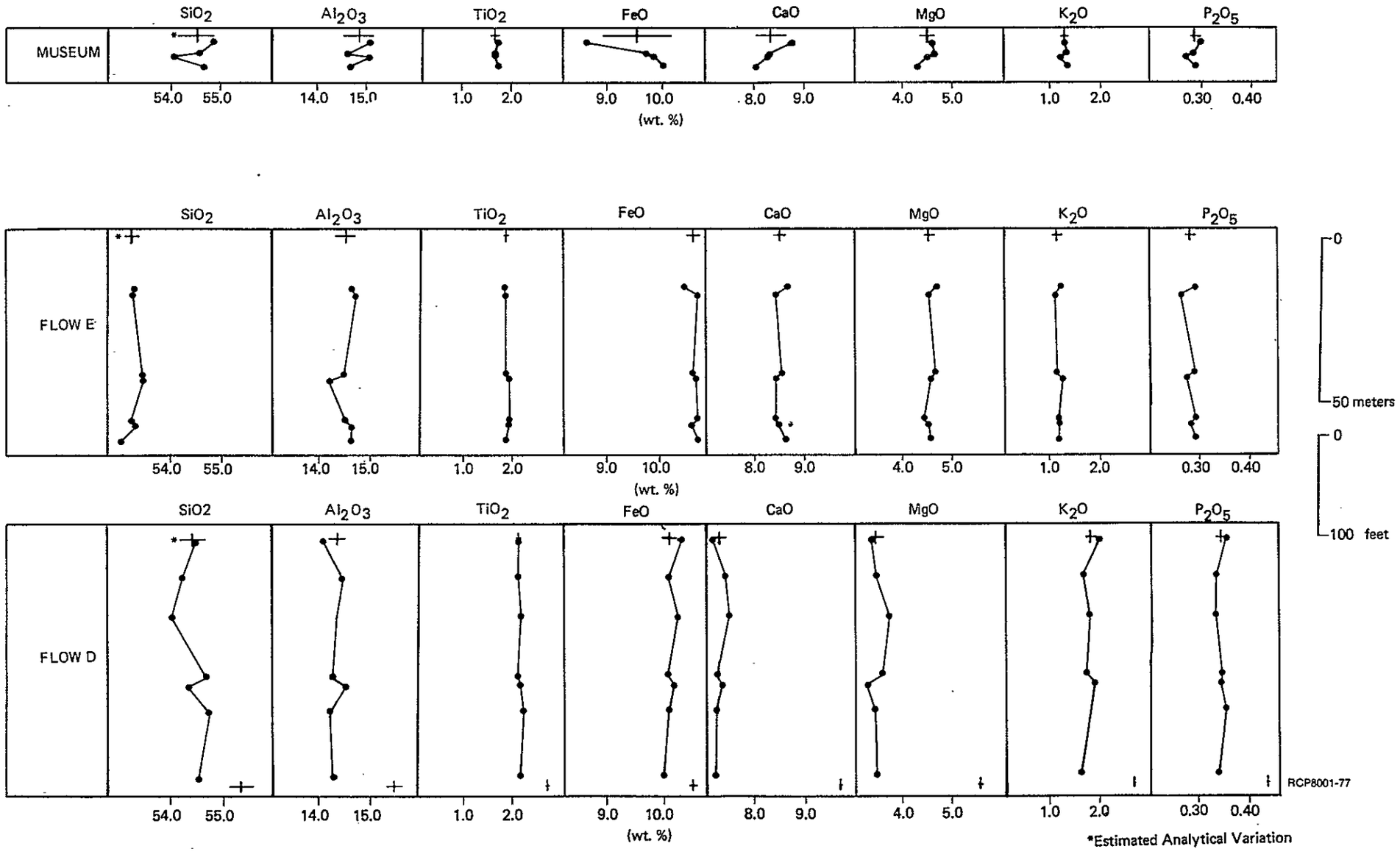

FIGURE III-39. Vertical Variation in Chemical Composition within Three Grande Ronde Basalt Flows at Sentinel Gap.

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TABLE III-7. Variations in Major Element Chemical Composition within Three Grande Ronde Basalt Flows at Sentinel Gap.

OXIDE	MUSEUM FLOW				FLOW E				UMTANUM UNIT				ANALYTICAL PRECISION
	Sentinel Bluffs		Pasco Basin		Sentinel Bluffs		Pasco Basin		Sentinel Bluffs		Pasco Basin		
	$\bar{X}$	σ	$\bar{X}$	σ	$\bar{X}$	σ	$\bar{X}$	σ	$\bar{X}$	σ	$\bar{X}$	σ	
SiO_2	54.19	0.37	54.20	0.48	53.50	0.42	53.58	0.31	54.62	0.16	54.59	0.28	0.27
Al_2O_3	14.52	0.25	15.05	0.39	14.80	0.23	14.80	0.32	14.37	0.12	14.59	0.31	0.14
TiO_2	1.69	0.07	1.69	0.06	1.89	0.06	1.91	0.05	2.15	0.04	2.15	0.05	0.01
FeO	9.97	0.17	9.55	0.47	10.54	0.31	10.56	0.26	11.12	0.09	11.15	0.24	0.08
CaO	8.41	0.12	8.59	0.33	8.33	0.14	8.53	0.19	7.20	0.05	7.21	0.16	0.05
MgO	4.76	0.34	4.79	0.39	4.89	0.35	4.64	0.19	3.53	0.16	3.45	0.11	0.05
K_2O	1.23	0.07	1.15	0.24	0.95	0.17	1.07	0.13	1.62	0.04	1.65	0.16	0.04
P_2O_5	0.28	0.02	0.29	0.02	0.28	0.02	0.28	0.01	0.34	0.01	0.35	0.01	0.02

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Lateral variations in chemical composition were examined using the same three flows used for vertical variations. These three flows were correlated to core wells and the Emerson Nipple section. Then, data from these same three flows in core wells and in surface sections were averaged and a standard deviation was calculated for each element in the data set for each flow. The validity of this test depends on the correctness of the correlation of these flows among core holes and surface sections. The correlation (Plate III-2) utilizes chemical composition and stratigraphic position relative to major chemical changes. SG/GR-8 and SG/GR-9, for example, lie on either side of the magnesium break, and SG/GR-9 has nearly unique major element chemical composition. SG/GR-1 is the top flow of the Grande Ronde Basalt, which leaves open the possibility that more than one flow is involved. If this is the case, it is not supported by lateral chemical variation data.

The data are displayed in Figure III-40 and presented numerically in Table III-7. They show a slight increase in the standard deviation over the vertical variation at Sentinel Gap for most elements. This may be caused by a slight, but real, lateral variation, or it may reflect the larger total population of analyses in the data set for lateral variation, which causes a greater probability of observing the maximum variation found in a flow; probably, some of both factors are involved. For other elements, there is very little change in the standard deviation between the vertical and horizontal variation estimates. In either case, this preliminary evaluation demonstrates the statistical significance of recognition of major chemical differences between Grande Ronde Basalt flows in the Pasco Basin.

STRUCTURE

GENERAL

The purpose of this section is to describe the major geologic structures within the Pasco Basin study area. An attempt is made to separate the relatively objective information obtained from surface mapping, drilling, and geophysical surveys from the more subjective interpretations of subsurface structures made utilizing that information.

The Pasco Basin is within the Columbia Plateau geological province and is underlain by basalt flows of the Columbia River Basalt Group and associated sedimentary rocks. On the basis of structure, the Columbia Plateau geological province is divided into three subprovinces: (a) the Yakima Fold Belt; (b) the Palouse; and, (c) the Blue Mountains Uplift (see Regional Geology, Chapter II).

Most of the Pasco Basin study area is within the Yakima Fold Belt subprovince. The basin itself is defined in part by the Yakima Folds. The Pasco Basin study area (Figure III-1) includes the Pasco Basin proper and also extends slightly beyond the Pasco Basin to the northeast

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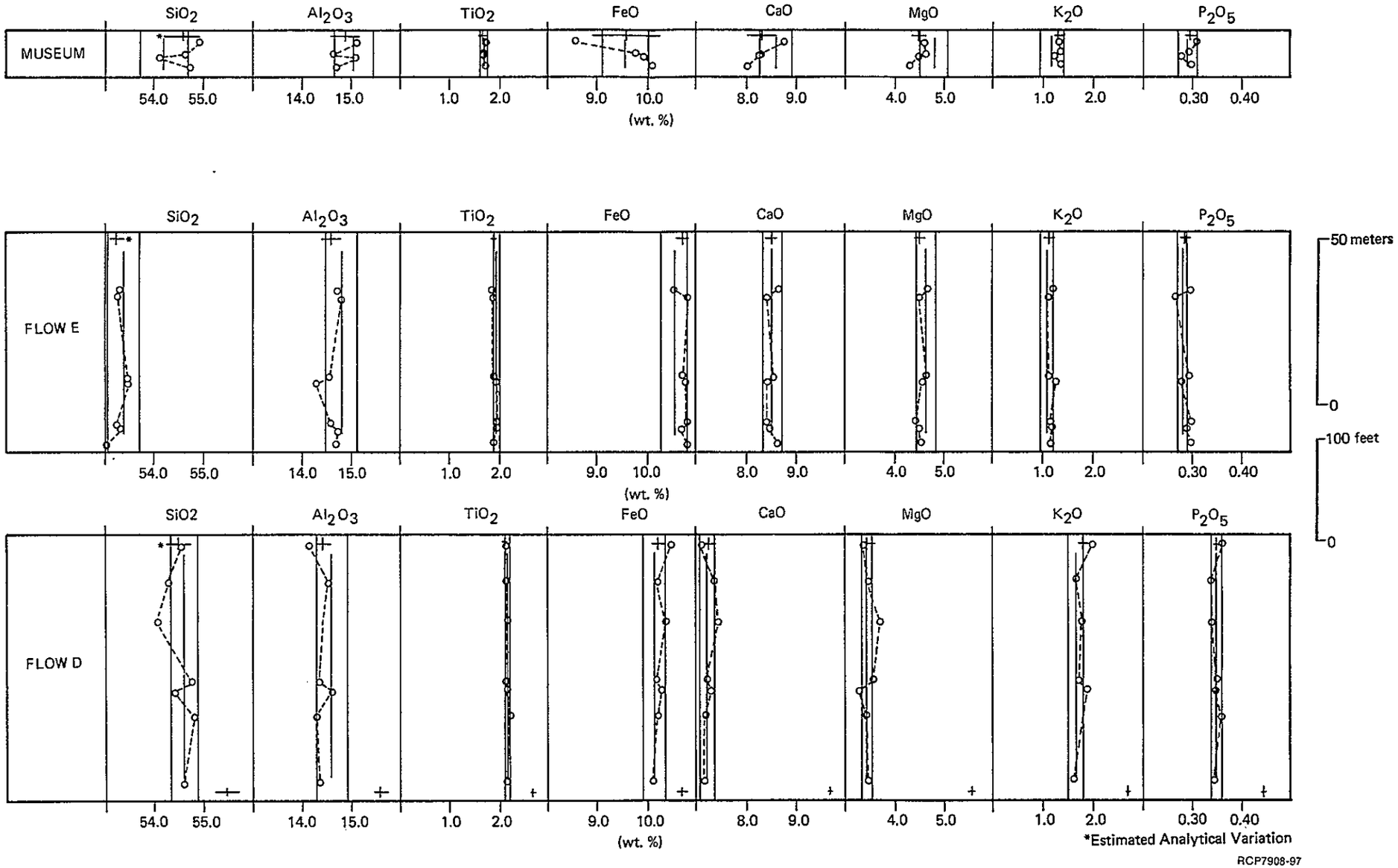

FIGURE III-40. Lateral Variations in Chemical Composition within Three Grande Ronde Basalt Flows within the Pasco Basin. Dashed lines connecting open circles are vertical variations from Figure III-39. Vertical lines represent mean and standard deviation of lateral variation in each flow.

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and to the east into the Palouse subprovince. The Pasco Basin study area also extends beyond the Pasco Basin to the south and southwest, but remains within the Yakima Fold Belt subprovince. The Pasco Basin study area thus includes the boundary between two major subprovinces within the Columbia Plateau geological province; the Yakima Fold Belt subprovince, and the Palouse subprovince.

The geologic map (Plate III-1) and cross sections (Plate III-5) indicate that the Yakima Fold Belt within the Pasco Basin study area can be broadly described as consisting of five main structures: (a) the Saddle Mountains structure; (b) the Umtanum Ridge-Gable Mountain structure; (c) the Yakima Ridge structure; (d) the Rattlesnake Hills structure; and, (e) the Horse Heaven Hills structure (Figure III-41). Topography strongly mimics structures with major anticlines generally forming ridges.

Folds within the Pasco Basin trend east-west in the northwestern part of the basin and northwest in the southeastern part of the basin. Structural relief on the folds decreases toward the eastern side of the basin. In general, the folds are asymmetric and open to tight. They are eroded into sharp to rounded ridges, separated by broad alluviated valleys developed in the intervening synclines. Some synclines are broad and flat-bottomed, but the troughs of others are rounded. The sense of fold asymmetry is such that the steeper limb of an anticline is usually the north limb; however, the reverse is true locally. Overturning and thrusting of thin basalt layers were observed in some hinge zones. Culminations and depressions are common along fold hinges and produce variations in structural relief and plunging hinge lines. The maximum fold amplitude observed is approximately 3,000 feet (640 meters). Wavelengths vary from 3 to 12 miles (15 to 20 kilometers), and also vary between folds along their trends. In places, each major fold within the Pasco Basin has smaller subsidiary folds on its limbs or in its hinge regions. These major and subsidiary folds are distinguished only by their relative size and are referred to as first-order and second-order structures, respectively; they are not necessarily temporally or genetically related. The crest lines of first-order folds do not everywhere coincide with their hinge lines because of the asymmetry of the larger first-order structures and the presence of second-order structures. But second-order folds are commonly coincident with the crest lines of first-order structures. The term "monocline," as used in this report, refers to a change in the degree, but not the direction, of dip on a fold limb. Some first-order structures are "box" folds in profile and monoclines, as used in this report, are commonly one of the multiple hinges of the "box" folds. These monoclines are described as separate, second-order folds, however, because of their extent and because their box-fold geometry changes along strike.

The structural geology of the Pasco Basin is presented in the four sections that follow. Frequent references are made to the following diagrams: (a) compilation geologic map of the Pasco Basin (Plate III-1); (b) aeromagnetic maps of the central Pasco Basin (Plates III-6a to 6d);

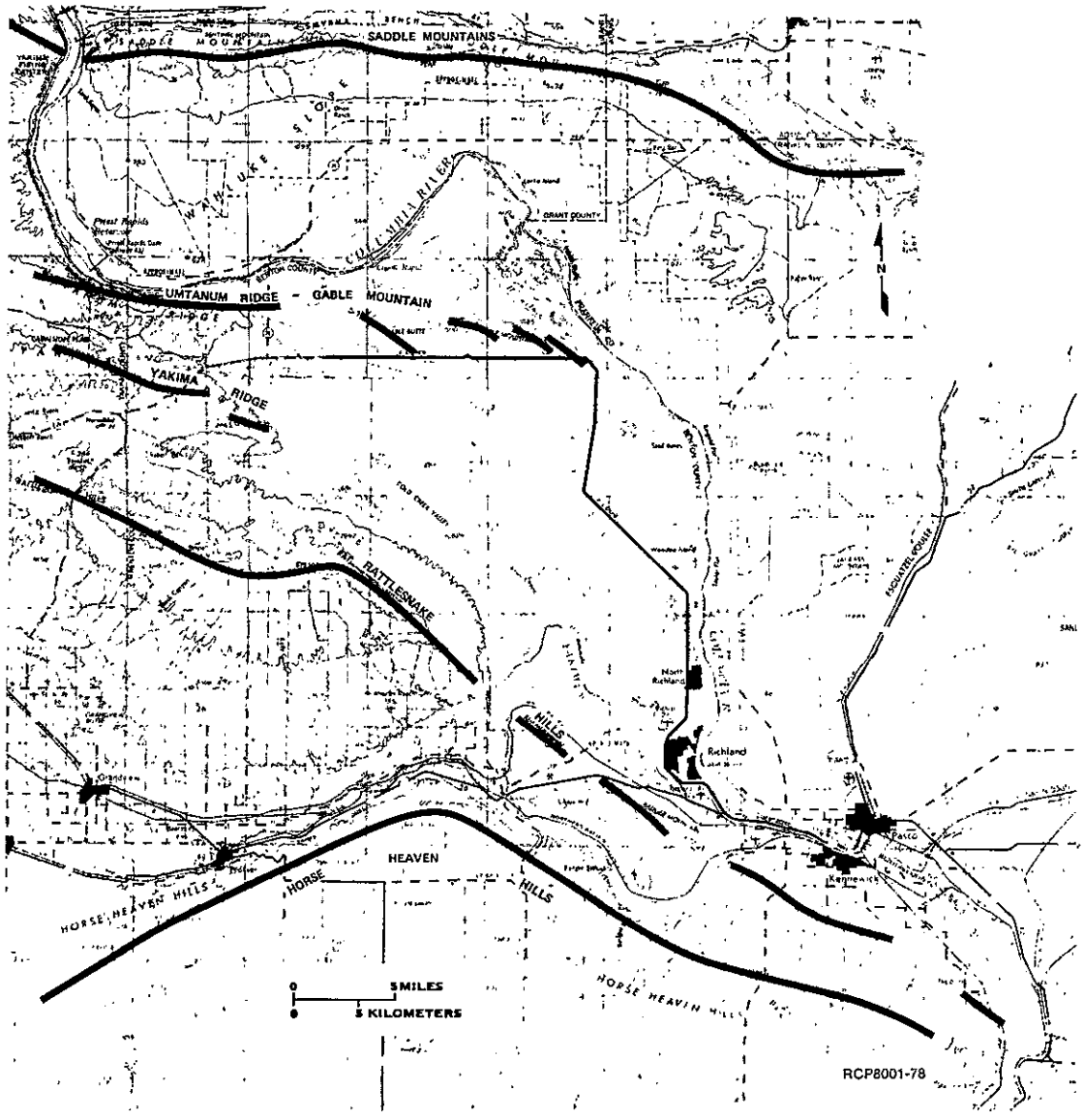

FIGURE III-41. Index Map, Main Yakima Fold Structures in the Pasco Basin.

(c) contour map on the top-of-basalt surface and preliminary structure contour map on the top-of-Wanapum basalt (Plates III-4a and 4b); and, (d) structure cross sections (Plate III-5). The structure contour maps and cross sections represent current interpretations of the geology of the Pasco Basin based on an integration of the results of surface mapping, geophysical surveys, and drilling. The position and attitude of structural features do not match exactly in many places between the top-of-basalt and top-of-Wanapum maps because of structure asymmetry, differences in stratigraphic thickness, and the timing of deformation.

SADDLE MOUNTAINS STRUCTURE

The Saddle Mountains structure marks the northern boundary of the Pasco Basin. It is one of the largest and most prominent anticlinal structures within the Yakima Fold Belt. From its western end, located about 15 miles (25 kilometers) southeast of Ellensburg, Washington, to its eastern end, located about 6 miles (10 kilometers) east of Othello, Washington, it extends nearly 70 miles (110 kilometers) across the western Columbia Plateau. This discussion is confined to the eastern two-thirds of the structure which is within the Pasco Basin study area (Figures III-42 and III-43). Most of the discussion is from Reidel (1978b), from work by Reidel during 1979, and from other cited sources.

The Saddle Mountains structure is a first-order structure with second-order folds and faults on its flanks. The main structure is the Saddle Mountains anticline which is an asymmetric anticlinal ridge with a steep northern flank. The Saddle Mountains structure changes geometry close along strike from a fold in the northwestern part of the Pasco Basin to an open fold in the northeastern part. Maximum structural relief measured on the Wanapum Basalt is about 2,000 feet (600 meters) in the northwestern Pasco Basin, but diminishes to less than 500 feet (150 meters) in the northeastern basin (Plates III-4 and III-5, cross sections A-A', B-B', C-C', and G-G').

Hinge Area

Basalt outcrops in the hinge area of the Saddle Mountains structure have been mapped by Grolier and Bingham (1971), Taylor (1976), WPPSS (1974), Thomas and Others in WPPSS (1977), and most recently by Reidel (1978b). This mapping has revealed that the hinge area can be subdivided into three segments on the basis of fold geometry: (a) a western segment; (b) a central segment; and, (c) an eastern segment (Grolier and Bingham, 1978; Reidel, 1978b; Figure III-42). Two major structural trends (east-west and northwest-southeast) and one minor trend (northeast-southwest) are within the segments.

The Saddle Mountains anticline follows a sinuous east-west trend along the Saddle Mountains structure (Plate III-1) and is principally responsible for topographic relief of the Saddle Mountains (Plate III-5, and cross sections A-A', B-B', C-C', and G-G' on Plate III-5). In the western segment of the Saddle Mountains structure near Sentinel Gap, the Saddle Mountains anticline bifurcates into northern and southern axial traces. Recent mapping by Reidel on the west side of Sentinel Gap

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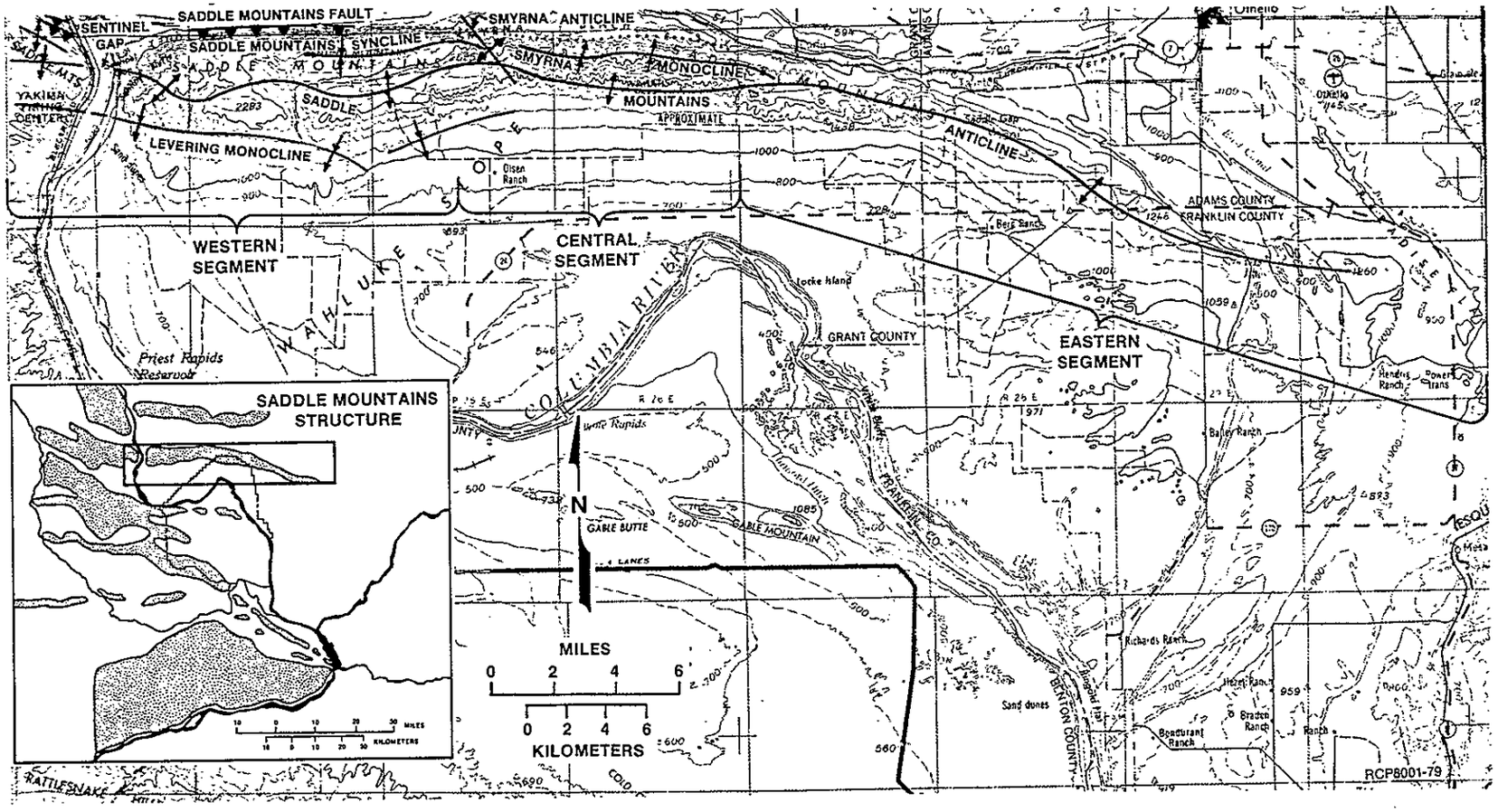

FIGURE III-42. Index Map, Saddle Mountains Structure.

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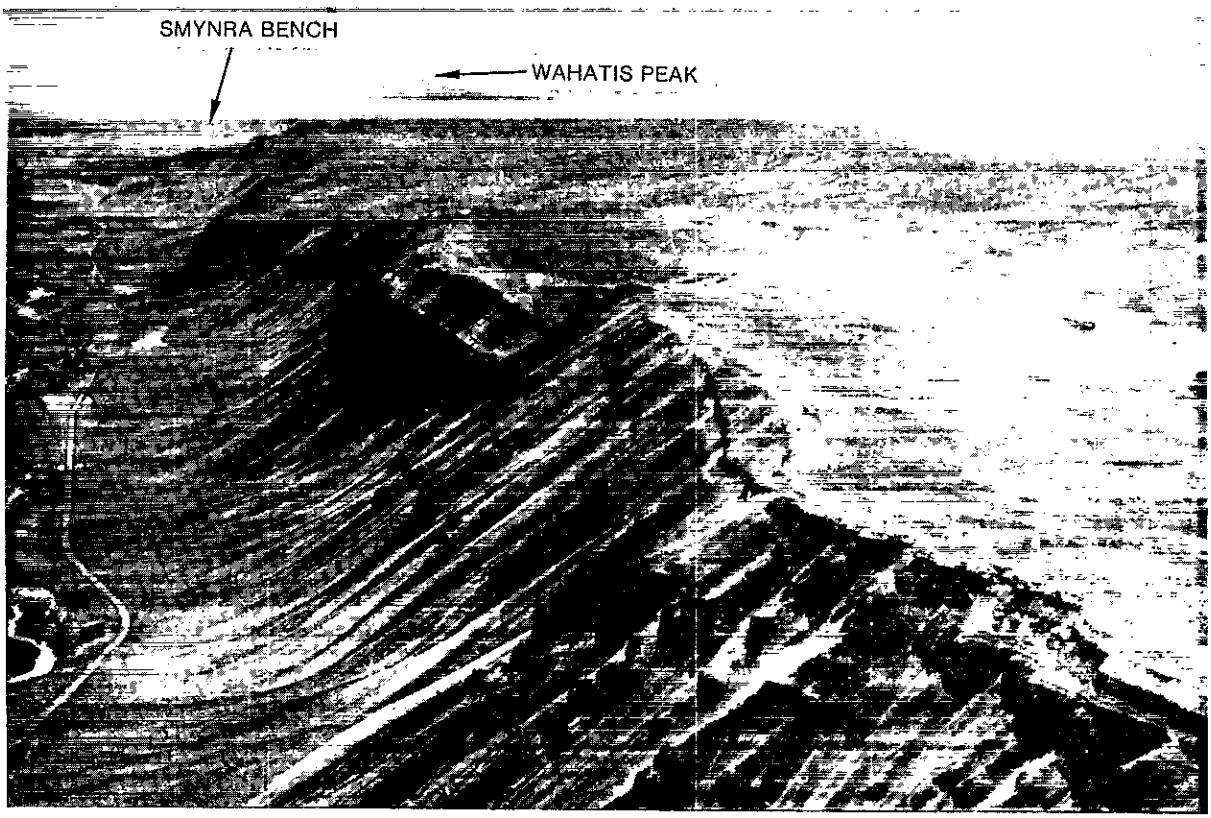

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FIGURE III-43. Saddle Mountains Structure (view toward the east).

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suggests that the Saddle Mountains anticline there might be overridden by a northwest-trending thrust fault (Sec. 32, T15N, R23E) in a manner similar to that observed by Farkas (1972) and by Price in 1979 during work for Rockwell Hanford Operations on Umtanum Ridge (see Structural Analysis of Umtanum Ridge, this chapter).

Between 120 degrees west longitude and the western edge of Smyrna Bench, the Saddle Mountains anticline is an asymmetric fold. The north limb is nearly vertical where exposed and the south limb is less steeply dipping (cross sections A-A' and B-B' of Plate III-5, and Grolier and Bingham, 1978). The south limb is complicated by many parallel-to-subparallel minor folds. The structural low in the Saddle Mountains anticline, the Levering monocline, the convergence of smaller folds, a paleovalley, and a north-south fault, all collectively suggest that this area of the south limb is complex with a long and complicated history.

The boundary between the western segment of the Saddle Mountains structure and the central segment is a complex zone of deformation (Plate III-1, Sec. 2, 3, and 10, T15N, R25E) and marks a change in fold geometry from an open, asymmetrical fold in the western segment to a box fold in the central segment. Near Verified Altitude Bench Mark (VABM) Saddle, the hinge line of the anticline plunges to the southeast. South of Smyrna Bench, the position of the hinge line is south of the topographic crest of the Saddle Mountains. Eastward from Sec. 8, T15N, R25E, the trend of the hinge line is almost east-west, overall, but with local variations.

An abrupt change in the trend of the axial trace and change of fold geometry on the east side of Smyrna Bench mark the boundary between the central and eastern segments of the Saddle Mountains structure. Geometry changes from a tight box fold to the west to a more open eastward-plunging fold to the east. The abrupt change in trend was interpreted as a fault by Glass and Slemmons in WPPSS (1977) based on air photo interpretation, but no offset was found during this study. From the east side of Smyrna Bench, the axial trace of the Saddle Mountains anticline swings northeast and then southeast (S65°E) to the Eagle Lake area where an abrupt east-west directional change occurs and the fold becomes more open and subdued until it is covered by Ringold sediments east of Scooteney Reservoir (Plate III-1). This is the easternmost exposure of the Saddle Mountains anticline.

The Saddle Mountains syncline is located 0.5 to 2 miles (1 to 3 kilometers) north of the Saddle Mountains anticline in the western segment (Sec. 5, T15N, R24E to Sec. 5, T15N, R25E) of the Saddle Mountains structure. Surface geophysical surveys were made across the Saddle Mountains syncline in the southern part of Sec. 3 and 4 to determine if the northwest-trending structures mapped by Reidel (1978b) about 0.5 mile (1 kilometer) north of the projected trace of the Saddle Mountains syncline continue under sedimentary cover toward the syncline. Survey techniques used included gravity, ground magnetic, direct current resistivity, refraction seismic, and Turam.

A modeled geologic cross section based on geophysical survey results is shown in Figure III-44. The axis of the Saddle Mountains syncline was relocated about 400 feet (120 meters) south of its previously mapped location and a west-northwest-trending fault with about 200 feet (60 meters) of vertical displacement is inferred about 1,000 feet (∿305 meters) north of the relocated trace. This fault is interpreted as a continuation of the northwest-trending anticline mapped by Reidel (1978b) near the north-center of Sec. 4, T15N, R24E. Details of the geophysical survey are in Appendix B.

The Smyrna monocline is approximately parallel to the trend of the Saddle Mountains anticline south of Smyrna Bench and forms a northern hinge zone in the central portion of the anticlinal fold. Dips increase along the hinge from 5 to 20 degrees toward the north, south of the hinge, and 60 degrees north to overturned, north of the hinge.

A monocline similar to the Smyrna monocline extends along the north side of the Saddle Mountains from Corfu east approximately to where Washington State Highway 240 crosses the Saddle Mountains (Plate III-1). Dips along the monocline change from 5 to 10 degrees to the north to 20 to 40 degrees to the north. Near Washington State Highway 240, the monocline merges with the Saddle Mountains anticline. This is inferred to be the same monocline on both sides of the landslide block south of Corfu.

North of the Saddle Mountains anticline in the Eagle Lake area (T14N, R29 to 30E) is a series of somewhat en echelon, doubly plunging anticlines and synclines trending from N70°W to N70°E. Most are open folds, but one in the Northeast 1/4, Sec. 12, T14N, R29E is a relatively tight fold with a steeply dipping south limb.

The Saddle Mountains fault has been a topic of considerable discussion (Laval, 1956; Grolier, 1965; Grolier and Bingham, 1971, 1978; Jahns, 1967; Jones and Deacon, 1966; Taylor, 1976; WPPSS, 1977). Laval (1956) interpreted this fault to be a thrust fault based on an exposure near Sentinel Gap, but Grolier and Bingham (1971) interpreted it as a near-vertical fault, noting that "the critical relationships are hidden under talus and sand dunes." WPPSS (1977) emphasized the change in fault geometry along its strike from a high-angle reverse fault in the Smyrna Bench and Sentinel Gap area to a nearly horizontal thrust fault to the west in the Boylston Mountains (see Chapter II).

On the west side of Sentinel Gap, the Saddle Mountains fault is a complex zone with several low-angle fault planes exposed. Neither fault displacements nor attitudes have been measured, but slickensides suggest low-angle, reverse movement. The Sentinel Bluffs sequence is over 900 feet (270 meters) thick on the east side of the river (Taylor, 1976; Long, 1978), but is less than 500 feet (150 meters) thick west of the river, suggesting thinning due to faulting or pinching-out onto a pre-existing structure.

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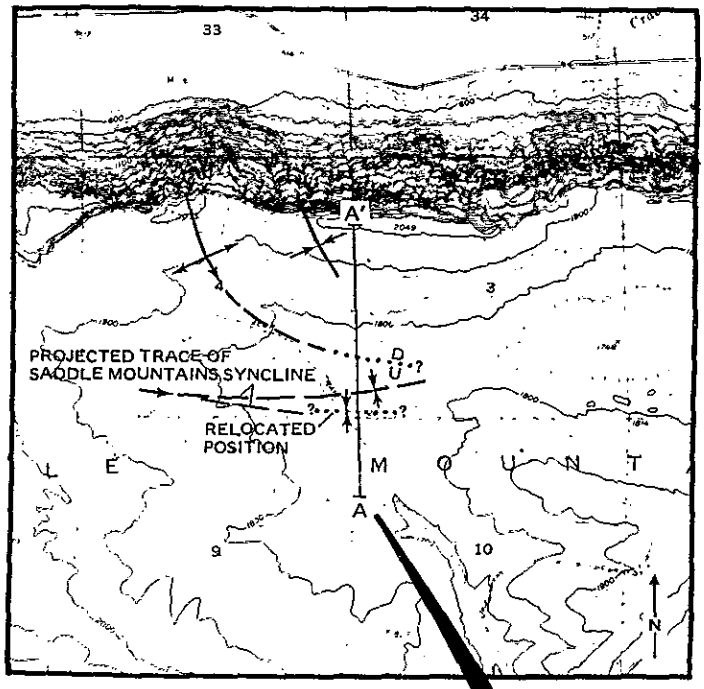
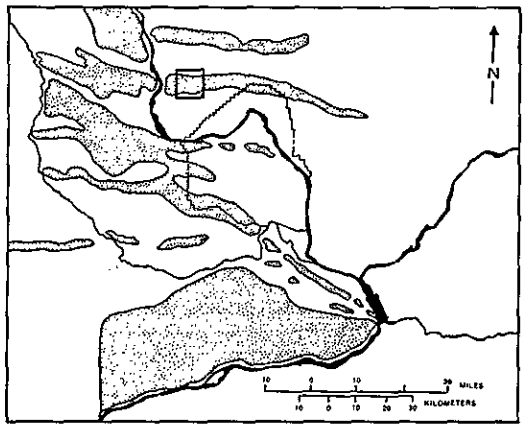


GEOLOGIC FEATURES LOCATION MAP



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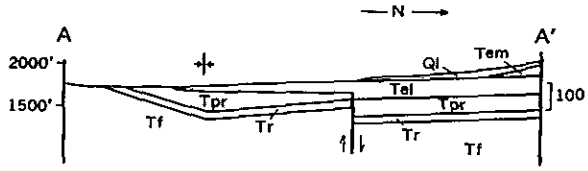

GRAVITY MODELED CROSS SECTION

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FIGURE III-44. Saddle Mountains Syncline Results of High-Resolution Geophysical Survey.

Between Smyrna Bench and Sentinel Gap, the fault could have a maximum stratigraphic displacement of 1,800 feet (600 meters) (Sec. 1, T15N, R24E), but nowhere is the fault plane exposed. The approximate location of the fault zone is shown on Plate III-1. Only one outcrop east of Sentinel Gap (Sec. 33 and 34, T16N, R24E) was found where faulted bedrock might be inferred. The exposures here are poor and relationships are considered tentative at this time. Taylor (1976) interpreted an east-west-trending fault here.

On the east side of Smyrna Bench, Grolier and Bingham (1978) described another exposure of the Saddle Mountains fault (East 1/2, Southwest 1/4, Sec. 1, T15N, R26E). No significant displacement could be found at that location during this field study. This area was discovered to be the westernmost limit of the Huntzinger flow on the north slope of the Saddle Mountains and is interpreted to represent a paleovalley. The overturned Priest Rapids, Huntzinger, and Pomona flows in Sec. 1, T14N, R26E are thought to be related to a possible northwest-trending cross structure. Exposed in a north-south gully are vertical and locally overturned Grande Ronde Basalt and Frenchman Springs, Roza, Priest Rapids, and Elephant Mountain Members (Laval, 1956; Grolier and Bingham, 1971; Taylor, 1976; Reidel, 1978b). A short distance to the south (Southwest 1/4, Southwest 1/4, Sec. 34, T16N, R24E), the Grande Ronde Basalt is folded and sheared from nearly horizontal (to the south) to nearly vertical (in a gully to the north). Individual Grande Ronde Basalt flows could not be mapped through the sheared zone; the two lower flows appear to have been faulted from the vertically standing section. This fault zone is interpreted to be associated with a northwest-southeast fault zone, the Smyrna fault. Evidence for this fault is based on offset in Sec. 3, T15N, R25E, a tectonic shear zone in Grande Ronde Basalt described above, and tectonically brecciated Elephant Mountain Member cropping out along the projection of the fault and shear zones (Southwest 1/4, Southwest 1/4, Southeast 1/4, Sec. 33, T16N, R25E). A major northwest-southeast anticline, the Smyrna anticline, is located near the west end of the Smyrna Bench (Plate III-1, T15N, R25E). Folding along the east-west Saddle Mountains anticline has almost obliterated this structure, but its axis represents the present structural high along the Saddle Mountains anticline. This northwest-southeast structure was recognized primarily on the basis of stratigraphic relationships in the area. Based on flow distribution, an anticlinal ridge several miles (kilometers) wide is inferred to have existed from Frenchman Springs time through Pomona time (10 to 14 million years before present). The anticline apparently reached its greatest topographic relief during Priest Rapids time, when it formed a barrier at least 4 miles (7.5 kilometers) wide. This structure is now bounded on the west by the Smyrna fault.

On the east side of the study area, a third structure is suggested by a change in trend of the Saddle Mountains anticline. Here, the abrupt change in attitude of the beds was interpreted by Glass and Slemmons in WPPSS (1977) as a fault. A northwest-southeast cross structure may cut the Saddle Mountains anticline, but there is no indication of relative displacement. This structure might have resulted from reactivation of an older, buried structure.

Northwest-trending folds of lesser amplitude are between Sentinel Gap and Smyrna Bench (Plate III-1, Sec. 3, 4, and 5, T15N, R24E). These structures are older than the Saddle Mountains fault, but probably are younger than the two northwest-southeast-trending anticlines (Sentinel Mountain and Smyrna). These folds show a relatively long history of deformation. They apparently became active during Priest Rapids time, as indicated by local thickness variations in Priest Rapids flows. Associated synclinal troughs are filled with thick accumulations of Ellensburg sediments and Elephant Mountain basalt which did not overflow the trough. Ellensburg sediments and caliche covering them are deformed, indicating post-Ellensburg deformation along this trend. One syncline has a normal fault (Plate III-3) bounding its west side.

High-resolution geophysical surveys are being conducted along Washington State Highway 24 to determine if structures mapped in the hinge zone of the Saddle Mountains structure continue down the south limb of the structure into and across the Wahluke syncline. Preliminary evaluations indicate there are several complex zones. The nature of these complex zones is being evaluated.

UMTANUM RIDGE-GABLE MOUNTAIN STRUCTURE

The Umtanum Ridge-Gable Mountain structure extends from the east end of Gable Mountain (T13N, R27E) westward and west-northwestward to southwest of Ellensburg, Washington (T16N, R17E), a distance of 70 miles (110 kilometers). This discussion is confined to that portion of the structure between 120 degrees west longitude, the western boundary of the Pasco Basin study area, and the eastern terminus of Gable Mountain (Figure III-45). Only the eastern 25 miles (45 kilometers) of the structure are within the Pasco Basin.

Gable Mountain and Gable Butte are currently interpreted as continuations of the Umtanum Ridge structure because of their similar trends. Gable Mountain and Gable Butte might actually be separate structures, however, or represent a segmentation of a Yakima Fold structure similar to that described in the Saddle Mountains; some reasons are given below.

(a) The hinge area of the Umtanum Ridge structure is relatively narrow and contains some imbricate thrust faults, but is dominated by one anticlinal fold, Umtanum anticline, which plunges approximately 5 degrees east. The hinge area of the Gable Mountain structure, however, is a zone of en echelon, doubly plunging folds, none of which dominate the structure.

(b) The south limb of the Umtanum Ridge structure is interpreted to strike N20°E to N70°E. The northeastward strike is caused by the eastward plunge of the structure. The south flank of the Gable Mountain-Gable Butte structure, however, is interpreted to strike from nearly due east to northwest.

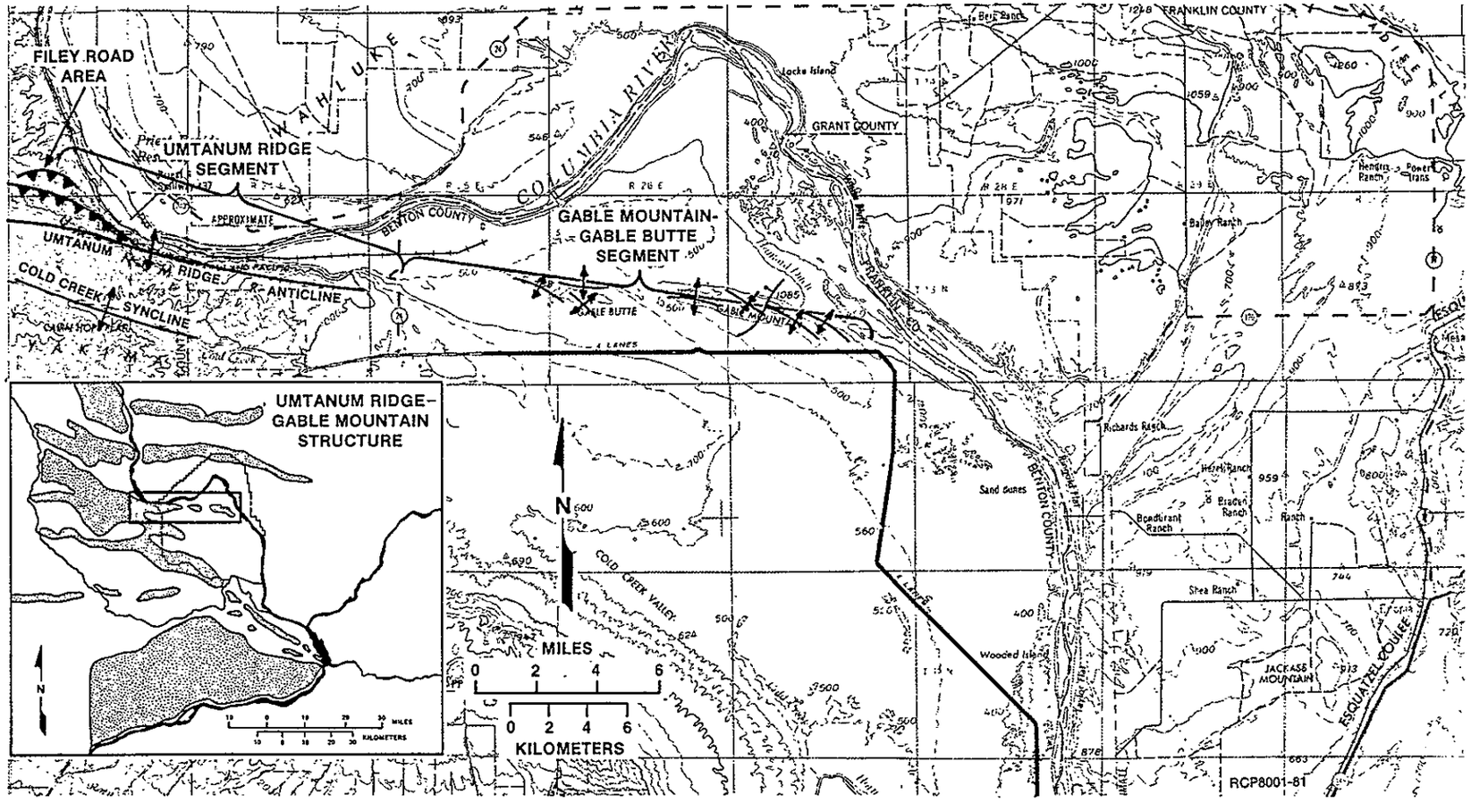

FIGURE III-45. Index Map, Umtanum Ridge-Gable Mountain Structure.

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(c) The south limb of the Umtanum Ridge structure is interpreted as an undeformed dip-slope, except for some minor faulting. The south limb of the Gable Mountain structure is known to contain second-order folds identified on the basis of the numerous wells drilled to the top-of-basalt in the 200 Areas of the Hanford Site on the basis of preliminary results from seismic reflection surveys.

In the following discussion, the Umtanum Ridge-Gable Mountain structure is described in terms of the Umtanum Ridge segment and the Gable Mountain-Gable Butte segment. Within the description of the segments, the structure is described in terms of the southern limb, and the hinge area and northern limb combined.

Umtanum Ridge Segment

The Umtanum Ridge segment is the surficial expression of a complex, asymmetric, non-cylindrical, overturned, plunging anticline (Goff and Myers, 1978) (Figure III-46). The structure trends generally east-west in the vicinity of the Midway Substation, but curves to a west-northwesterly trend at Priest Rapids Dam. Most of the geology of the structure has been described by Goff in his work for Rockwell Hanford Operations, but some work was done by Bond and Others in 1979 (the results of which are included in this report) and the structure was studied by the WPPSS in 1977.

The non-cylindrical character of the fold is indicated by variations in the structural relief and hinge plunge along the structure. Work for Rockwell Hanford Operations in 1979 indicates structural relief (less than 2,900 feet [950 meters]) and structural complexity are probably greatest in the Filey Road area from which the fold plunges 5 degrees to the east. In the vicinity of the Midway Substation, the structure was interpreted by Goff in his work for Rockwell Hanford Operations as a simple asymmetric anticline with a steeply dipping north limb. A more complex cross-sectional geometry is interpreted for the structure at Priest Rapids Dam and within the eastern portion of the Yakima Firing Center boundary (Figures III-47 and III-48; Plate III-5, cross sections A-A').

South Limb of the Umtanum Ridge Segment

The south limb of the Umtanum Ridge segment of the Umtanum Ridge-Gable Mountain structure is a uniform homoclinal dip-slope dipping 5 to 12 degrees south, except for a few unnamed second-order structures, mainly faults (Plate III-1). Some high-angle cross faults trending north-northeast have been identified near the crestal area and extend down into the south limb of the fold. These faults occur in Sec. 11 and 14, T13N, R23E; Sec. 18, T13N, R24E; and Sec. 16, T13N, R24E. Good exposure along this limb of the fold indicates that these faults are of limited extent, each less than about 0.5 mile ($\sim$0.8 kilometer). Some small west-to-northwest-trending faults have been mapped in Sec. 22, 28, and 29, T13N, R24E. These faults are located well down from the hinge zone onto the flank of the structure, nearly in the axis of the Cold Creek syncline.

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FIGURE III-46. Umtanum Ridge-Gable Mountain Structure (view toward the west).

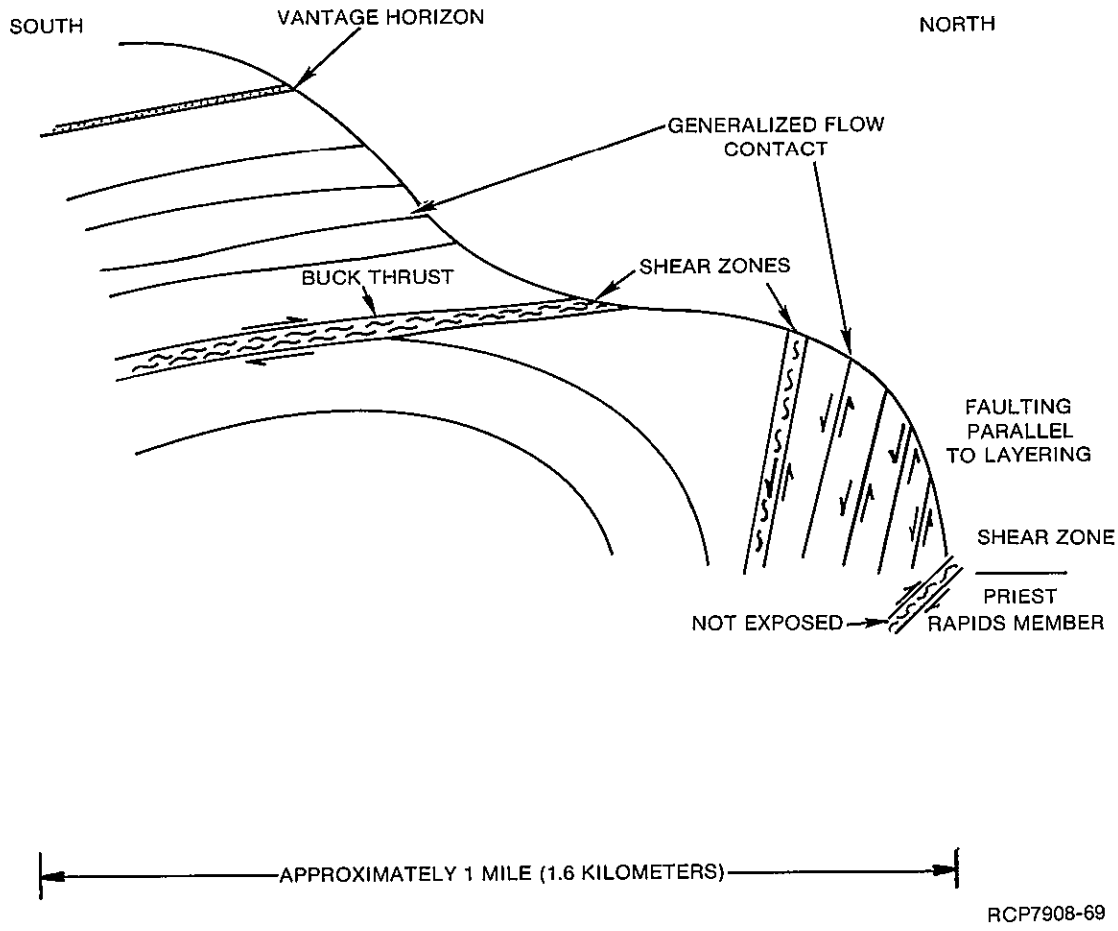

FIGURE III-47. Generalized Cross-Sectional Sketch of the Interpreted Umtanum Ridge Structure of Priest Rapids Dam (view toward the west).

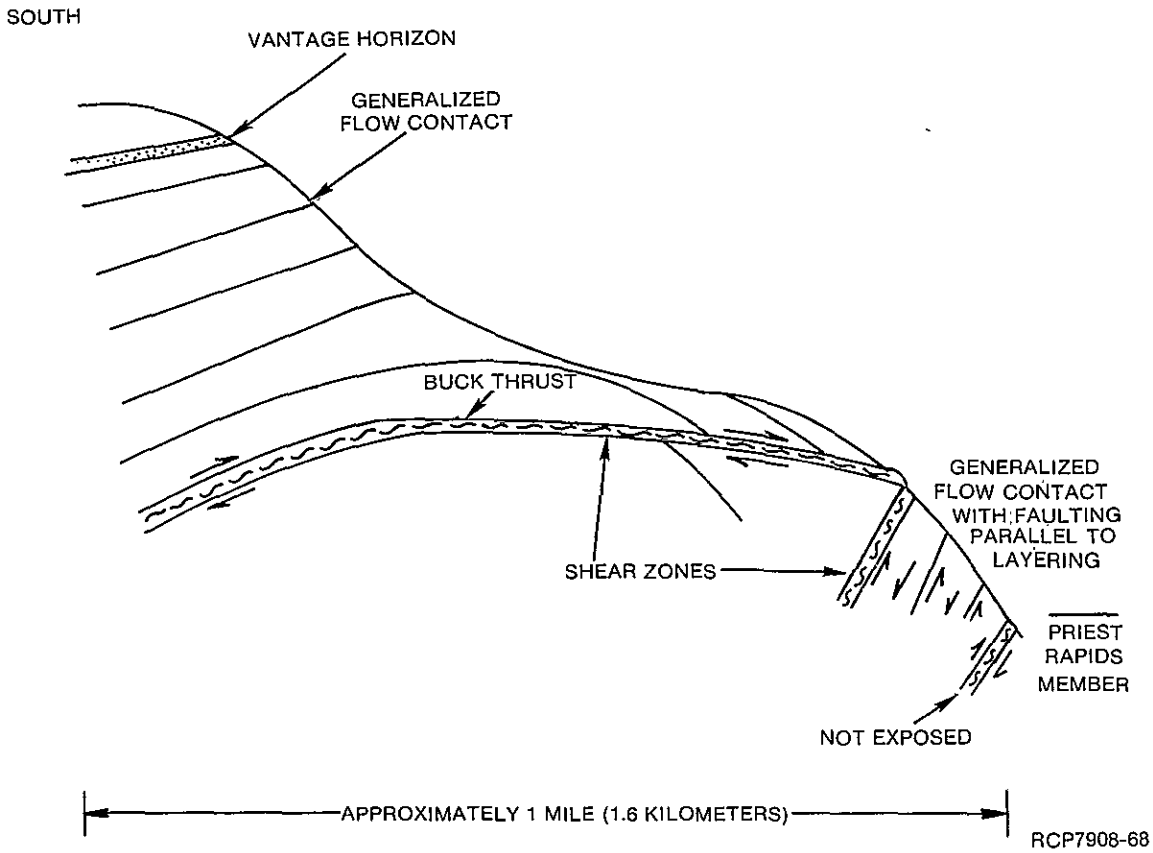

FIGURE III-48. Generalized Structure Cross Section of the Interpreted Umtanum Ridge Structure at the Eastern Boundary of the Yakima Firing Center (view toward the west).

In the Southwest 1/4 of T13N, R25E, the Umtanum Ridge segment of the Umtanum Ridge-Gable Mountain structure is interpreted to turn southeasterly (Plate III-4) from its overall easterly trend to the west of this area. This southeasterly trend of the structure is similar to the en echelon, second-order folds along the Gable Mountain-Gable Butte segment of the Umtanum Ridge-Gable Mountain structure. Individually, these en echelon folds also have a southeasterly trend. The southeasterly trend along the Umtanum Ridge structure might be associated with an inferred structure between the eastern end of Umtanum Ridge and the western end of Gable Butte. This structure is inferred on the basis of a ground-water barrier identified in the upper Priest Rapids units in the vicinity of T13N, R25E (Newcomb and Others, 1972).

The structure mapped in Sec. 14, T13N, R24E is inferred on the basis of a subtle lineament observed by Goff on aerial photographs. This structure coincides with the Juniper Springs landslide, and a northeasterly trending aeromagnetic anomaly identified in this area by Weston Geophysical Laboratories in WPPSS (1977). The nature of the aeromagnetic anomaly associated with the Juniper Springs structure is not known; however, about 5 miles (∿ 8 kilometers) west of the Juniper Springs structure in Sec. 24, T13N, R24E a valley-filling segment of the Wahluke and Huntzinger flows is exposed on the south flank of Umtanum Ridge. This valley-filling exposure is currently interpreted as the eroded remnant of a flow that originally extended southwest into the northeast corner of T12N and across the Yakima Ridge structure (see Stratigraphy in this chapter).

Hinge Area and North Limb-Umtanum Ridge Structure

The actual fold axis of the first-order Umtanum Ridge structure has not yet been completely defined because the hinge area, the regions of greatest curvature of layering, has not been delineated along the entire length of the structure. For this reason, the hinge area and the shorter, poorly exposed north limb of the structure are discussed together. Where the hinge area can be delineated, its width is relatively narrow in relation to the width of the straight southern limb of the fold. The structure may, therefore, be described as "kink-like" in a purely descriptive sense. Dip of layering within the shorter, planar, northern limb varies from approximately 35 degrees north to overturned and dipping 35 degrees to the south (Plates III-1 and III-5, cross section A-A').

Recent detailed mapping of the distribution of lithologic units within the Grande Ronde Basalt in the Priest Rapids Dam vicinity by E. H. Price has revealed a large-scale thrust zone within the hinge of the fold (Figures III-47 and III-48). The thrust, which was first described by Farkas (1972), is indicated by a discordance in the flow layering and stratigraphic sequence on the north side of the structure relative to a concordance in the flow layering and stratigraphic sequence on the south side of the structure. The thrust zone consists of a 30- to 60-foot (10- to 20-meter) thick tectonic breccia traceable along Umtanum Ridge from the Yakima Firing Center boundary to just east of Prist Rapids Dam.

Detailed geologic mapping in the Filey Road area west of Priest Rapids Dam by R. D. Bentley indicates the structure in that area is more complex than that in the Priest Rapids Dam area. The structure in the Filey Road area is interpreted as three imbricate thrust slices involving Grande Ronde and Wanapum Basalt. In this part of the Umtanum structure, the rocks are folded, overturned, and thrust over relatively undeformed Mabton equivalent (?) sediments of the Ellensburg Formation. The sediments are, in turn, overlain by relatively undeformed Pomona Member and post-Mabton/Ellensburg units not involved in the thrusting. An example of one of the thrust faults within the Filey Road area is shown in Figure III-49. Additional information on the hinge zone of the Umtanum structure is given in the section in this report on Structural Analysis of Eastern Umtanum Ridge.

The Gable Mountain-Gable Butte Segment of the Umtanum Ridge-Gable Mountain Structure

Gable Mountain and Gable Butte are topographically isolated, anticlinal ridges of basalt and interbedded sediments which are the only extensive bedrock outcrops in the central Pasco Basin (Plate III-1). Portions of Gable Mountain and Gable Butte have been mapped by Newcomb and Others (1972), Bingham and Others (1970), WPPSS (1974), and Brooks (1974). The surface expression of Gable Mountain and Gable Butte is a series of westerly trending, doubly plunging, en echelon anticlines and synclines. These structures are interpreted as second-order folds within the closure of an asymmetric first-order fold, consistent with the interpretation of Fecht (1978). These folds are flanked by the Wahluke syncline and Cold Creek syncline to the north and south, respectively. Although geometry of the first-order fold is somewhat obscured by the second-order folds, it has been estimated from surface exposures, geophysical surveys, and well data. The southern flank of the first-order fold has a gentle southerly dip (about 2 degrees); the northern flank has a steeper northerly dip (approximately 11 degrees).

Second-order folds on Gable Mountain and Gable Butte trend west to northwest, with the exception of a northeasterly trending syncline on Gable Butte. Generally, second-order fold axes are parallel and form a westerly trending, en echelon pattern across Gable Mountain and Gable Butte. The axial trends of individual second-order folds are generally curvilinear. The termini of the hinge lines in both anticlinal and synclinal folds are either doubly plunging or are subdued by surrounding folds having higher amplitudes and greater wavelengths. The second-order folds tend to be asymmetric in profile, with the two larger, second-order folds on Gable Mountain having opposite directions of asymmetry. Angles subtended by the two flanks and the fold closure of the second-order folds range from open to gentle, and angular to rounded, depending on the amplitude and wavelength of a given fold.

Two faults have been identified on Gable Mountain (Bingham and Others, 1970; Newcomb and Others, 1972; Fecht, 1978). The first fault is near the west end of Gable Mountain (Plate III-1, Sec. 23, T13N, R26E). It trends north and dips 30 degrees to the east (Bingham and Others, 1970). Stratigraphic relationships and dip of the fault planes indicate it to be a reverse fault with about 75 feet (25 meters) of

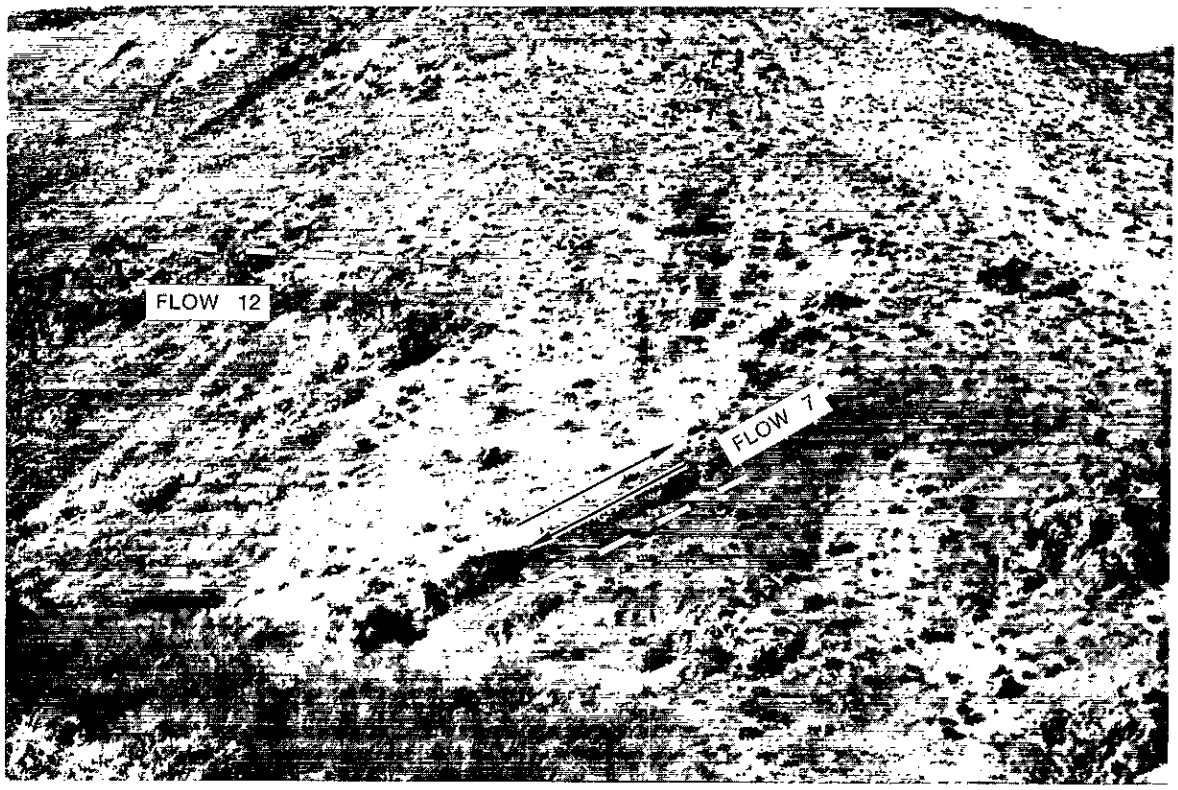

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FIGURE III-49. Thrust Fault near Filey Road. Flows were numbered stratigraphically downward from the Vantage Member horizon.

offset. The second fault is in the central portion of Gable Mountain along a northeasterly trending escarpment (Plate III-1, Sec. 19, T13N, R27E). The fault was exposed after an extensive trenching program. It has a sinuous northeasterly to easterly trend and terminates on the west end of the eastern Gable Mountain anticline. Bingham and Others (1970) estimated the dip of the fault to be from 10 to 34 degrees to the south, and that movement along the fault was low-angle reverse with undetermined offset. Trenches dug across this fault revealed undeformed sediments overlying the fault. The sediments have been radiocarbon dated at greater than 40,000 years before present (Bingham and Others, 1970).

The buried south limb of the Gable Mountain-Gable Butte structure is known to contain second-order folds in the area north of the 200 East Area of the Hanford Site (Fecht, 1978). This interpretation is supported by preliminary geophysical survey results from that area. The south limb of the structure also contains an approximately 1-mile (0.6-kilometer) wide buried channel beginning in Sec. 4, T12N, R27E and trending N55°W to Sec. 7, T13N, R26E. This channel is eroded at least 125 feet (40 meters) into the top-of-the-basalt bedrock Plate III-4 and might have been partially controlled by an inferred northwesterly trending fracture zone between Gable Mountain and Gable Butte. In addition, core hole DB-10 penetrated a reverse fault on the south limb of the Gable Mountain-Gable Butte structure. This fault is described in a subsequent section of this chapter.

Geophysical surveys are being conducted at three locations along the Gable Mountain-Gable Butte structure to identify and trace second-order structures in the buried hinge zone, to locate structures that cross-cut the Gable Mountain-Gable Butte structure, and to map second-order structures on the south limb of the first-order structure. These surveys have not been completed.

YAKIMA RIDGE STRUCTURE

The Yakima Ridge structure is a group of topographic ridges representing the surficial expressions of plunging anticlines, monoclines, and related faults. This structure extends west-northwest from T12N, R24E to T13N, R18E near Yakima, Washington, a distance of approximately 37 miles (60 kilometers). This discussion is confined to the part that lies east of 120 degrees west longitude. Only the easternmost one-third of the structure is within the Pasco Basin study area.

The Yakima Ridge structure within the Pasco Basin has been studied by Goff for Rockwell Hanford Operations, Bond and Others (1978), and Kienle in WPPSS (1977). The dominant fold within the Yakima Ridge structure is the Cairn Hope Peak anticline (Plate III-5, cross section A-A'). The shorter and steeper north limb of this anticline dips 30 to 40 degrees north and its wider southern limb dips 10 to 15 degrees south. Grande Ronde Basalt is exposed within the structure core. The Cairn Hope Peak anticline trends N70-N75°W and plunges gently southeastward. The southern limb of the Cairn Hope Peak anticline contains two monoclines.

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The northernmost of the two monoclines, the Cairn Hope Peak monocline, trends N60°W and is interpreted by Bond and Others (1978) to merge into the Silver Dollar Fault of Goff and Myers (1978) (see Figure III-50). The southern unamed monocline trends N70°E.

The Silver Dollar fault offsets Frenchman Springs Member against Umatilla and Pomona Members across a fault breccia zone 165 to 230 feet (50 to 70 meters) wide (Goff and Myers, 1978). The mapped length of the fault is about 3 miles (5 kilometers). Because exposures of the fault zone are poor, the inclination of the fault surface is not readily determinable. The Silver Dollar fault was interpreted by Goff and Myers (1978) and Goff for Rockwell Hanford Operations as a high-angle, reverse fault, but by Bond and Others (1978) as possibly a normal fault.

In T12N, R24E, Goff mapped several small, en echelon anticlines and synclines that form the eastern part of Yakima Ridge. These are open, doubly plunging, slightly asymmetrical, second-order folds; collectively, they form the first-order Yakima Ridge structure in that area. The easternmost surface exposure of the Yakima Ridge structure, as mapped by Bond and Others (1978), is represented by two anticlines and a syncline which plunge eastward into the Pasco Basin. A nearly vertical fault in T12N, R24E was mapped by Bond and Others (1978) as truncating the west end of the southernmost second-order anticline. A third fault was proposed by Kienle (in WPPSS, 1977) and by Bond and Others (1978) to account for a linear escarpment and apparent structural displacement on the extreme eastern and southern ends of Yakima Ridge (T12N, R25E). The existence and nature of such a fault have not been confirmed because of the limited exposure in that area.

The top-of-basalt contour map (Plate III-4a) shows an elongate structural high east of Yakima Ridge in Sec. 22, 23, and 24, T12N, R25E. This buried structural high plunges east-southeast into the central Pasco Basin and has aeromagnetic anomalies and linears associated with it (Plates III-6a and 6b). The buried structural high is interpreted as an eastward continuation of the Yakima Ridge structure. Current interpretations are that the Yakima Ridge structure either plunges abruptly eastward at the east end of Yakima Ridge or, more likely, is faulted along a northwest-trending fault that passes through the area of closely spaced top-of-basalt contours in Sec. 20 and 21, T12N, R25E (Plate III-4a). Such a fault (Figure III-51) might be associated with a northwestward continuation of the Rattlesnake Mountain fault (or associated faults) through the northeastern corner of Snively Basin; it would probably be a "scissor" fault with decreasing throw to the northwest. A reflection seismic survey was made from the east end of Yakima Ridge east for about 2 miles (3 kilometers) across the projected trace of the postulated fault; the data are being evaluated.

The Yakima Ridge structure is separated from the Umtanum Ridge structure by the Cold Creek syncline which plunges 3 to 5 degrees east-southeast into the central Pasco Basin. The axis of the Cold Creek syncline approximately coincides with the course of Cold Creek. Dips on

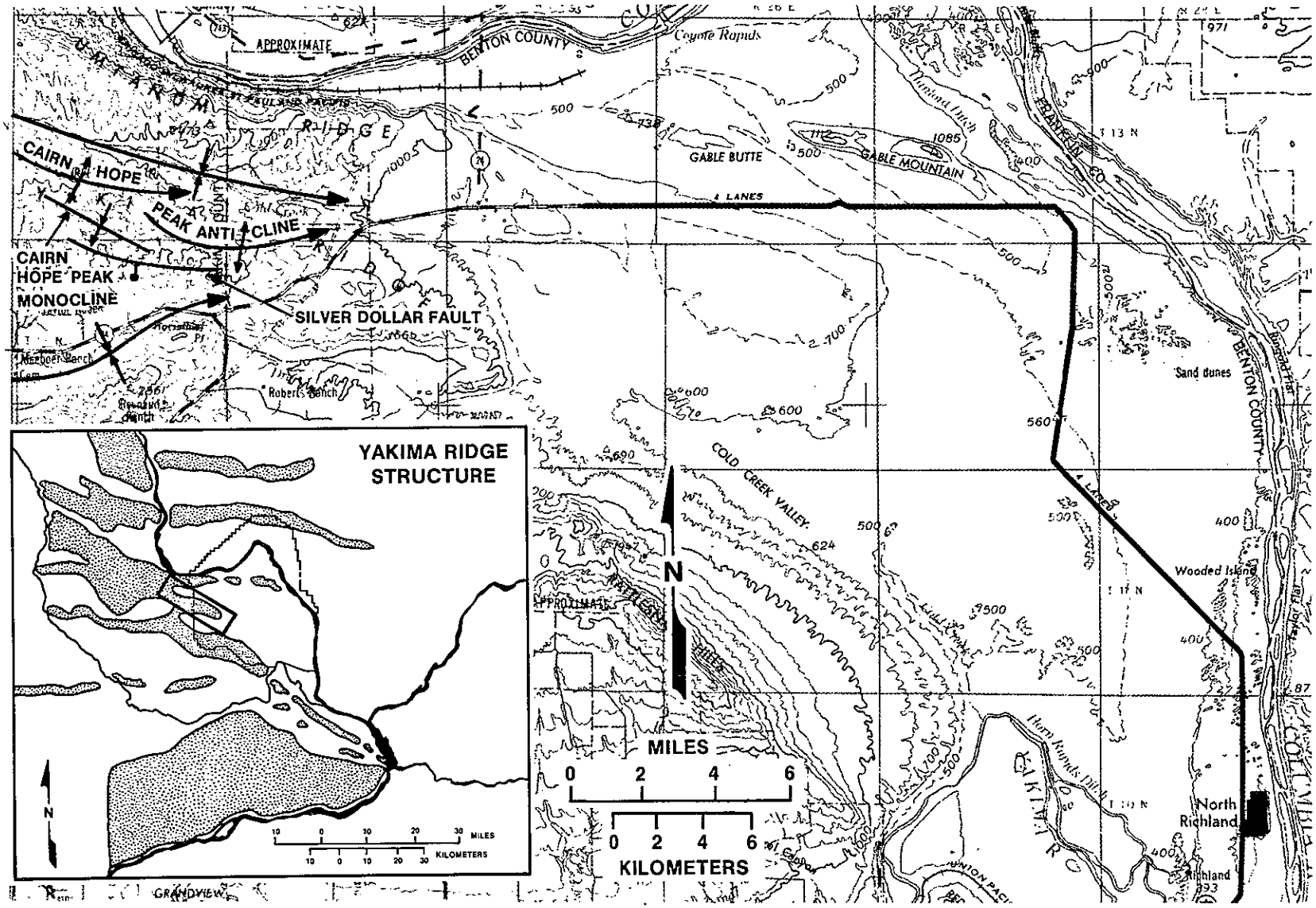

FIGURE III-50. Index Map, Yakima Ridge Structure.

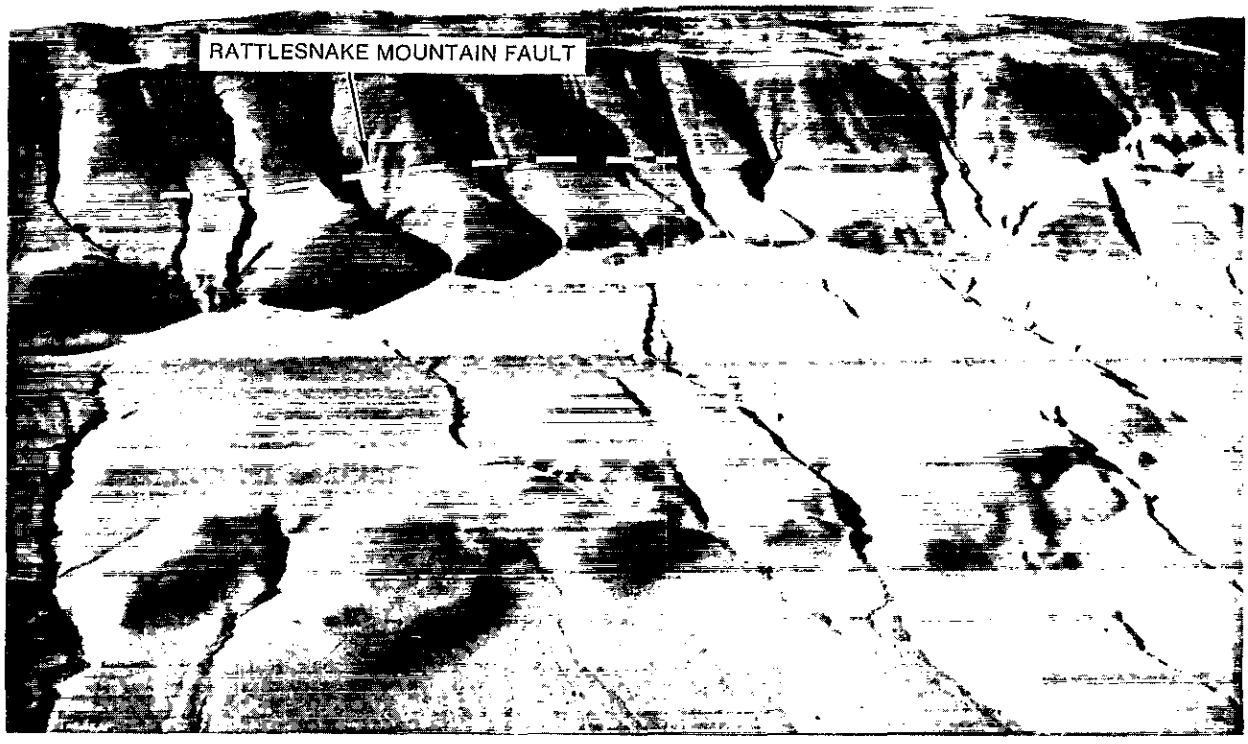

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FIGURE III-51. Location of the Rattlesnake Mountain Fault along the North Flank of Rattlesnake Mountain (view toward the south).

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the limbs of the Cold Creek syncline are less than 10 degrees south on the north limb and less than about 40 degrees north on the south limb. The Cold Creek syncline plunges into the Pasco Basin subsurface culminating in a deep depression centered about Sec. 9, T12N, R25E (Plate III-4a).

RATTLESNAKE HILLS STRUCTURE

The Rattlesnake Hills structure extends across the Columbia Plateau from Wallula Gap (T7N, R31E) northwestward toward Yakima, Washington where it merges with Ahtanum Ridge (WPPSS, 1977). Ahtanum Ridge is discussed in Chapter II. This discussion is confined to that portion of the Rattlesnake Hills structure lying between 120 degrees east longitude and the eastern boundary of the Pasco Basin study area (Figure III-52).

The aligned anticlines between Rattlesnake Mountain and Wallula Gap are considered part of the Rattlesnake Hills structure and are referred to as the Rattlesnake Mountain-Wallula segment. The western portion of the structure is referred to as the Rattlesnake Hills segment. The Rattlesnake Hills segment is curvilinear with an east-west trend. The Rattlesnake Mountain-Wallula segment is curvilinear with a southeastern trend.

The information presented in this section comes primarily from reconnaissance surface mapping by J. N. Gardner for Rockwell Hanford Operations during 1977 and from detailed surface mapping by Bond and Others (1978) and Jones and Landon (1978). Information was also obtained from an aeromagnetic survey and from boreholes.

Rattlesnake Hills Segment

The Rattlesnake Hills segment consists of two main folds, the Rattlesnake Hills anticline and the Rattlesnake Hilsl north anticline. The Rattlesnake Hills north anticline is 15 miles (25 kilometers) long, beginning in Sec. 32, T12N, R20E and extending east to Sec. 23, T12N, R23E (Plate III-1). The Rattlesnake Hills north anticline is separated from the Yakima Ridge structure by a broad, first-order, asymmetric syncline (Plate III-5, cross section A-A'), the longer, gently dipping northern limb of the syncline is the southern limb of the Yakima Ridge structure. The Rattlesnake Hills north anticline is a northeasterly trending, asymmetric anticline that plunges gently into the Pasco Basin; dips range from 15 to 45 degrees north on the north limb and 5 to 23 degrees south on the south limb. A small, second-order anticline north of Horsethief Point is doubly plunging, asymmetric, and en echelon to the trend of the Rattlesnake Hills north anticline. Faulting parallel to the fold hinge has been recognized by Bond and Others (1978), which they interpret to have both normal and reverse movements. One low-amplitude, short, nearly symmetrical anticline trending N20°E occurs in Sec. 28, T12N, R23E. This anticline is entirely within the southern limb of, and trends obliquely to, the Rattlesnake Hills north anticline.

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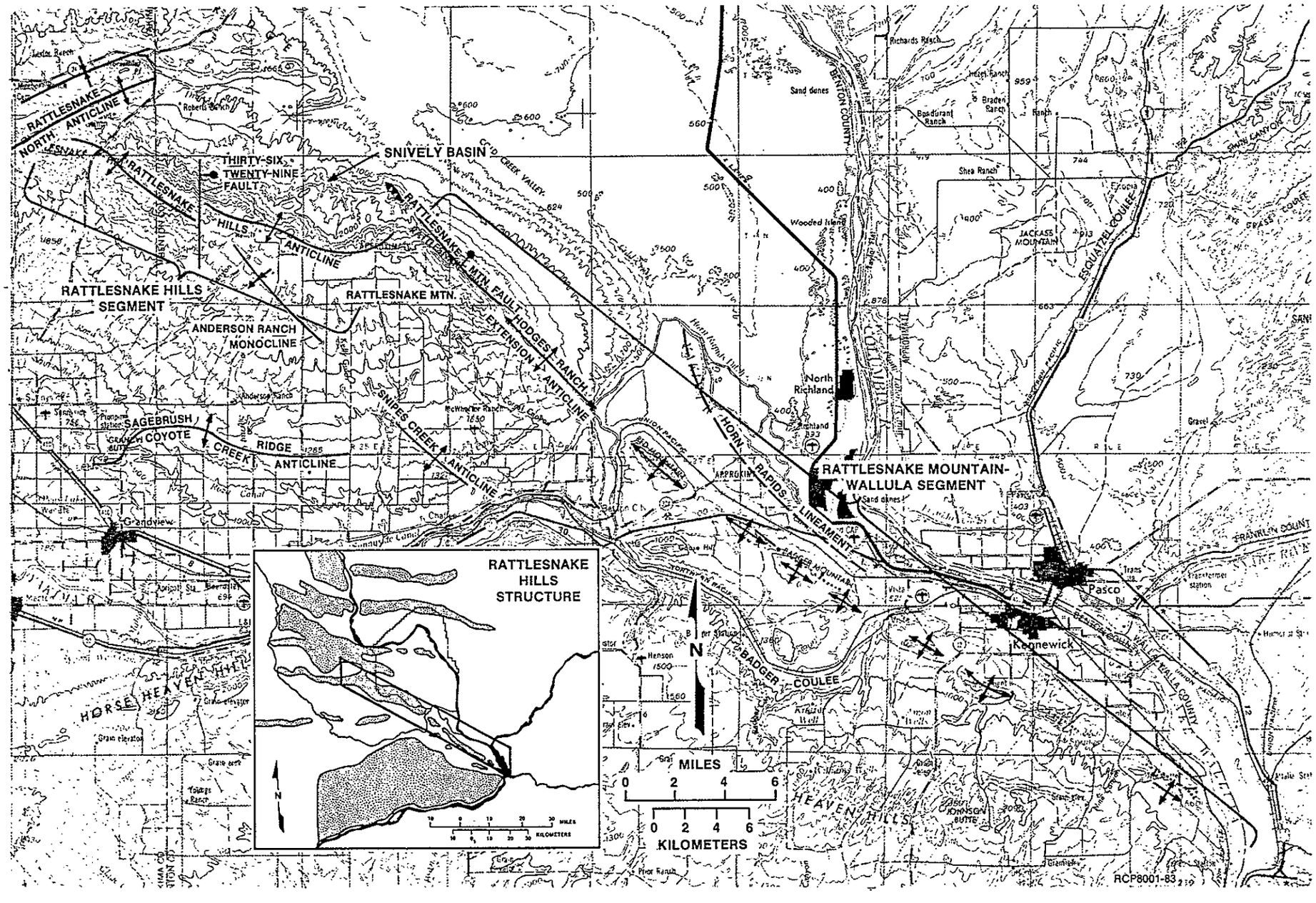

FIGURE III-52. Index Map, Rattlesnake Hills Structure.

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The Rattlesnake Hills anticline trends approximately N70°W, except for its easternmost 3 miles (2.9 kilometers) which trend nearly due east (Plate III-1). The anticline is asymmetrical, its north limb dips 12 to 15 degrees north, and the south limb dips 3 to 16 degrees south (Bond and Others, 1978). Both limbs contain secondary structures. The anticline has two culminations and one (possibly two) depressions. One culmination is at Sec. 6, T11N, R23E and a second is at Sec. 8, T11N, R24E where the anticline is crossed by the Thirty-Six Twenty-Nine fault, which is a vertical fault about 2.5 miles (4 kilometers) in length trending north-south between Sec. 5 and 17 of T11N, R24E. The western side of the fault is up relative to the east. Bond and Others (1978) interpret the fault as a "scissor" fault and relate the 2.5 miles (4 kilometers) apparent offset of the Rattlesnake Hills anticline across the fault as "due to differential flexuring on either side of the fault." Many additional, second-order folds are associated with the hinge area of the Rattlesnake Hills structure west of the Thirty-Six Twenty-Nine fault (see Bond and Others, 1978 for a more complete description of these structures).

East of the Thirty-Six Twenty-Nine fault is the Snively Basin complex and the Anderson Ranch monocline. Snively Basin is a structurally complex area at the junction of the Rattlesnake Hills segment and the Rattlesnake Mountain-Wallula segment (Plate III-1). Overall, Snively Basin appears to be a down-dropped block and landslide complex. However, the lateral continuity of basalt units and structures from this complex into the surrounding area indicates slump movement might not be as pronounced as topography suggests (Brown, 1970; Bond and Others, 1978; Kienle in WPPSS, 1977). Similar conclusions were reached by Jones and Price during work for Rockwell Hanford Operations in 1979 as shown on Plate III-1. The basalt layers in the Snively Basin complex are gently folded into a series of broad, open anticlines and synclines. The northernmost anticline, with its north limb dipping up to 85 degrees, is more asymmetric and has a shorter wavelength than the other anticline. In the Benson Springs area of Snively Basin, a thrust fault is proposed by Jones and Price (this study) (Plate III-1) to explain the superposition of gently south-dipping basalt over steeply north-dipping layers of the same flows. This fault is aligned with a projection of the Rattlesnake Mountain fault mapped by Bond and Others (1978) 1 mile (0.6 kilometer) to the southeast. Aeromagnetic linears in the Snively Basin complex (Plate III-6d) generally are parallel to trends of structure shown by surface mapping.

The Anderson Ranch monocline is a broad flexure in the generally homoclinal south limb of the Rattlesnake Hills anticline. The Anderson Ranch monocline trends northwest and can be traced about 4.5 miles (7 kilometers) from Sec. 16 to Sec. 36, T11N, R24E. The Snipes Creek anticline appears to be a southeastward continuation of the Anderson Ranch monocline. The Snipes Creek aeromagnetic linear (Plate III-6d) coincides with the Snipes Creek anticline.

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The hinge area of the Rattlesnake Hills structure west of Rattlesnake Mountain is similar to the hinge area of the Saddle Mountains, in that each consists of a complex system of sinuous, easterly trending folds, has a north-south fault, and has a dominant fold forming the hinge. The two structures differ, in that the Saddle Mountains structure has a curvilinear trend; whereas the trend of the Rattlesnake Hills structure shifts abruptly at the west end of Rattlesnake Mountain.

Rattlesnake Mountain-Wallula Segment

The Rattlesnake Mountain-Wallula segment of the Rattlesnake Hills structure is a series of doubly plunging, locally faulted anticlines with a curvilinear trend ranging from N50°-N65°W. Individual anticlines are not everywhere parallel to this trend; some app-ar to be en echelon. Mapping of this structural segment was by Jones and Landon (1978) and Bond and Others (1978).

Rattlesnake Mountain is a linear topographic ridge trending N50°W. Bond and Others (1978) interpret Rattlesnake Mountain as an uplifted fault block bounded by a steeply dipping, possibly reverse, fault along its steep northeastern slope (Plate III-1). Structural displacement by the fault is about 1,300 feet (400 meters) and is confined to a zone about 330 feet (100 meters) wide (Bond and Others, 1978). The fault dies out to the southeast into the Hodges Ranch extension anticline. The Hodges Ranch extension anticline is asymmetric with its shorter limb dipping 15 to 18 degrees northeast and its southwest limb dipping 6 to 8 degrees southwest.

The prominent aeromagnetic anomalies associated with Rattlesnake Mountain (Plates III-6a and 6b) are related mainly to topography and truncated fronts of normal polarity flows (Frenchman Springs and Elephant Mountain Members) and reversed polarity flows (Priest Rapids and Pomona Members) exposed in the steep north scarp of Rattlesnake Mountain. The anomalies are also related to the Rattlesnake Mountain fault (Plate III-1) which coincides with the Rattlesnake Mountain aeromagentic linear (Plate III-6d). In addition, the Rattlesnake Mountain aeromagnetic linear extends southeast across the Yakima River past Red Mountain beyond the mapped extent of the Rattlesnake Mountain fault and is probably related to faulting along much of the Rattlesnake Mountain-Wallula segment of the Rattlesnake Hills structure, such as that along the north side of Badger Mountain (Plate III-1).

North of the Rattlesnake Mountain fault, basalt flows dip 45 degrees to the northeast (Plate III-5, cross section G-G'). This is interpreted by Bond and Others (1978) as drag along the fault. Within 2 miles (3 kilometers) to the north, the dips flatten to 3 to 7 degrees and this low dip angle continues beneath the Iowa Flats area farther to the northeast. The structure at Iowa Flats is interpreted as an arcuate homocline with dip directions radiating to the northeast and east away from the Rattlesnake Mountain and Hodges Ranch extension anticline. Exposures in gulleys and ravines of Iowa Flats indicate no significant faults or folds within the homocline. The Iowa Flats area is similar to the Rattlesnake Mountain backslope area where comparatively good exposures also indicate an arcuate homoclinal limb which is undeformed except for the Anderson Ranch-Snipes Creek features and the Sagebrush Ridge-Coyote

Creek structure (Bond and Others, 1978). Except for some minor folding discussed below, the homoclinal limb underlying the Iowa Flats area is interpreted as maintaining the 3- to 7-degree dip to the northeast into the Wye Barricade (Hanford Site) depression (Plate III-4). Three structures, two known and one postulated, are considered as probably deforming the Iowa Flats homocline in the subsurface. One is an extension of the Horn Rapids lineament to the north or northwest; the second is an extension to the east of the Yakima Ridge subsurface high in the basalt near the mouth of Dry Creek (Plate III-4a); and, the third is an inferred flexure or fault paralleling Cold Creek. To better evaluate these possibilities, high-resolution geophysical surveys are being conducted on the north limb of the Rattlesnake Mountain structure in the Iowa Flats area, and the Pasco Basin aeromagnetic survey was repositioned to cover this area. Several small aeromagnetic linears have been identified (Plate III-6d) which may represent bedrock structures in the Iowa Flats area. Evaluation of these linears is not complete.

The series of aligned, slightly en echelon, doubly plunging anticlines between Rattlesnake Mountain and Wallula Gap have been extensively studied (WPPSS, 1974; Farooqui in WPPSS, 1977). The Butte (Sec. 2 and 3, T7N, R30E) is an anomalous structure along this trend apparently caused by faulting, not folding, along the north dip-slope of the Horse Heaven Hills anticline. The fault juxtaposes the steeply dipping Umatilla Member against the flat-lying Ice Harbor Member; offset appears to be as much as 165 feet (50 meters).

Outcrops of massive breccia have been found in two places (South 1/2, Sec. 8, T7N, R31E and Southwest 1/4, Sec. 8, T8N, R29E) along the Rattlesnake Hills-Wallula segment. These breccias are tectonic, but whether they result from faulting, folding, or a combination of the two is uncertain (Jones and Landon, 1978). Northwest of the east end of Badger Coulee is a series of three doubly plunging, faulted anticlines (Badger Mountain anticline of Bond and Others, 1978). Badger Mountain fault is interpreted to cut across the north limb of these anticlines. Offset appears to be greatest at the eastern end (340 feet [60 meters]) and decreases to the northwest. Northeast of the Rattlesnake Mountain-Wallula segment is a series of northwesterly aligned basalt knolls. The knolls have been identified as the Horn Rapids lineament by Bingham and Others (1970). Bond and Others (1978) interpreted them to be open, plunging folds, possibly of the same origin as those in the Rattlesnake Mountain-Wallula segment.

HORSE HEAVEN HILLS STRUCTURE

The Horse Heaven Hills structure extends N70°W from Van Sycle Canyon, located about 2 miles (3 kilometers) east of Wallula Gap to about 3 miles (5 kilometers) west of Benton City, and then S60°W to the boundary of the Pasco Basin study area; from there, the structure continues a general westerly trend to the Cascade Range. The Horse Heaven Hills structure is a first-order structure with two structural trends within the Pasco Basin map area; the eastern portion trends N60°W and the western portion trends S65°W. From 1976 to 1978, Gardner, Jones, and

Fecht mapped in the Wallula Gap area from the eastern map boundary to approximately 1 mile (2 kilometers) west of Wallula Gap. Jones and Landon (1978) mapped from Wallula Gap northwest to the eastern end of Badger Coulee. The remainder of the Horse Heaven Hills in the Pasco Basin study area was mapped by Bond and Others (1978). Wanapum and Saddle Mountains Basalt flows are exposed along the Horse Heaven Hills structure, but outcrops of Grande Ronde Basalt are in the Wallula Gap-Van Sycle Canyon area and in the Horse Heaven Hills along the southeastern-southwestern boundary of the Pasco Basin study area (Plate III-1).

The Wallula Gap fault cuts the north flank of the Horse Heaven Hills structure at Wallula Gap with a maximum offset of about 1,000 feet (330 meters) (Gardner, 1977). The Hanford formation lies undisturbed across the fault trace. The fault strikes N65°W and extends to the east from the eastern boundary of the Pasco Basin study area to approximately 1.5 miles (2 kilometers) west of Wallula Gap--where it appears to merge into the north flank of the Horse Heaven Hills structure. The north side of the fault is down-thrown, but the fault apparently changes along strike from normal to reverse from east to west, respectively. Last movement, indicated by slickensides, appears to have been strike-slip. At one place, just east of the map area, the fault zone is about 1,000 feet (330 meters) wide and is a breccia of Grande Ronde Basalt and Frenchman Springs Member.

The Northwest-Trending Segment

The northwest trend of the Horse Hills structure within the Pasco Basin study area (Figure III-53) has several second-order folds: Jump-Off-Joe anticline (Jones and Landon, 1978); Badger Canyon monocline, Gander Hill anticline, Goose Hill anticline (Bond and Others, 1978); and Horse Heaven Hills anticline south and off the map area (Bond and Others, 1978). The Horse Heaven Hills anticline is a broad, open, asymmetrical anticline slighly south of the Pasco Basin study area. Badger Canyon monocline forms its northern hinge line.

West of Wallula Gap (9.6 miles [16 kilometers]) is Jump-Off-Joe anticline, a doubly plunging, asymmetrical anticline with Umatilla Member exposed in the core and Pomona and Elephant Mountain Members exposed on the dip-slope. The north limb dips up to 50 degrees north. The southern limb merges with the Horse Heaven Hills anticline south of the Pasco Basin study area. Previous reports (Jones and Deacon, 1966; Bingham and Others, 1970; Farooqui in WPPSS, 1977) suggest a fault along the north flank of Jump-Off-Joe anticline, but no conclusive evidence of such a fault was found by Jones and Landon (1978) and none is shown on Plate III-1.

The Badger Canyon monocline extends N60°W from northwest of Jump-Off-Joe anticline to just north of Webber Canyon (Bond and Others, 1978). The monocline has a south limb dipping 1 to 2 degrees northeast. Three nearby vertical faults, the Badger Coulee fault, the Badger Canyon fault, and the Webber Canyon fault, cut the north limb of the Badger Canyon monocline (Bond and Others, 1978). Maximum offset for the three faults is estimated at 240 feet (80 meters), with the down-thrown side

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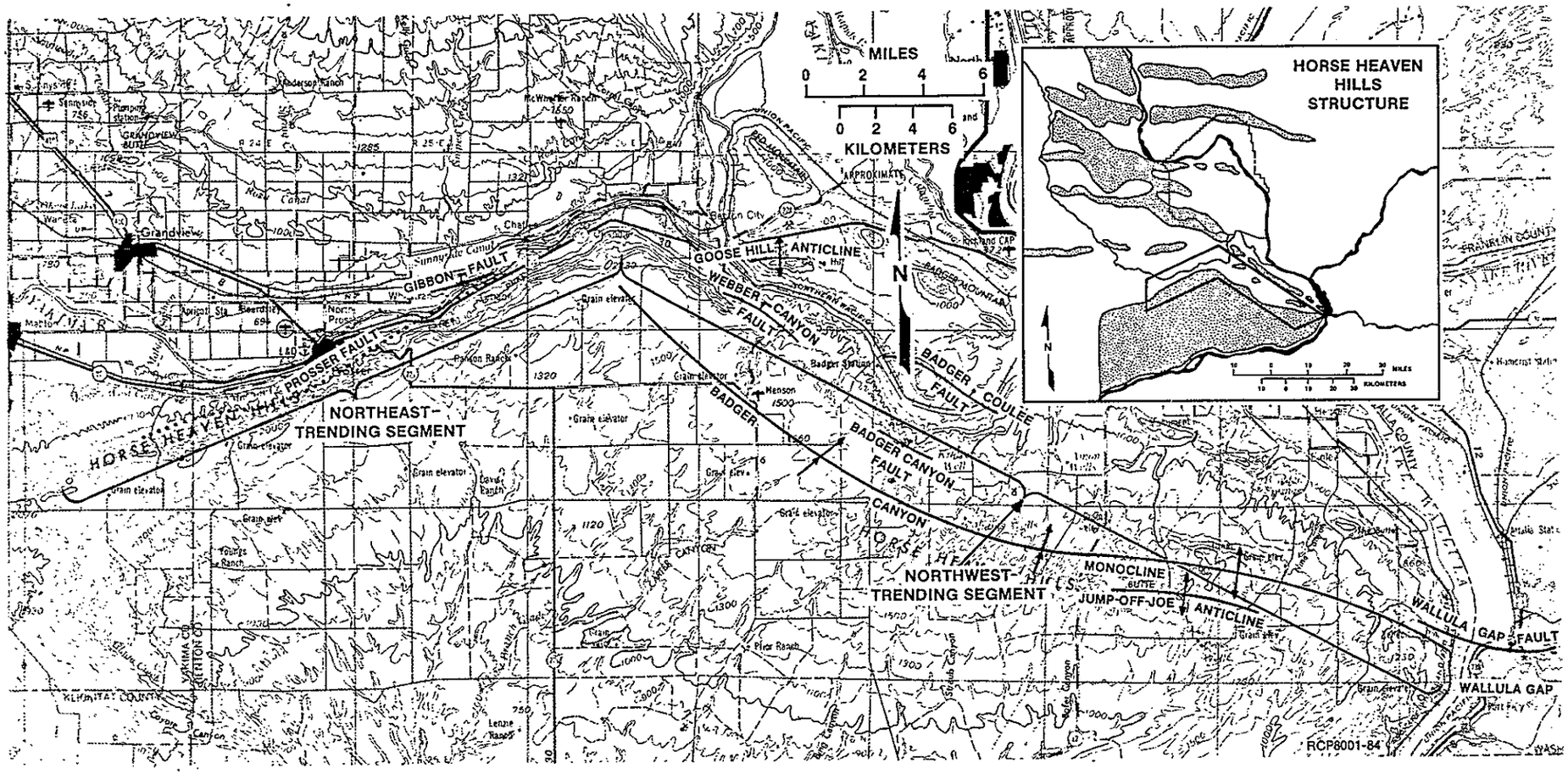

FIGURE III-53. Index Map, Horse Heaven Hills Structure.

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to the northeast. North of Badger Coulee is an isolated hill, informally named Gander Hill (Bond and Others, 1978) and is interpreted as an erosional remnant of an open fold on the north flank of the Badger Canyon monocline. Gander Hill is bounded on the north by the Badger Coulee fault. The south flank dips 3 to 7 degrees southeast and has been partly eroded. The Goose Hill anticline is northwest of Gander Hill along the same trend, and is a nearly symmetrical, east-west, elongate structure. Its axis is curvilinear and has an amplitude of about 450 feet (150 meters), and is doubly plunging, with its south limb dipping from 5 to 20 degrees southwest and the north limb dipping from 8 to 12 degrees northeast.

The Northeast-Trending Segment

The northeast-trending segment of the Horse Heaven Hills structure within the Pasco Basin study area (Figure III-53) includes the Gibbon fault, Prosser fault, and several associated subparallel structures (Bond and Others, 1978). These structures are partially obscured by landslide debris, colluvium, and loess (Plate III-1).

The Gibbon fault strikes east-northeast in the Northeast 1/4, Sec. 26, T9N, R25E. It offsets two units of the Ellensburg Formation, the Levey interbed to the northwest, and the stratigraphically lower Selah interbed to the southeast. The fault is interpreted to be nearly vertical, downthrown to the northwest, and to have an offset of approximately 210 feet (70 meters).

The Prosser fault is proposed by Bond and Others (1978) to account for the "breaks of steepening in slope" and the topographic relief along the northeast-southwest segment of the Horse Heaven Hills. They concluded however, that the existence of the fault does not preclude that a large part of the structural relief could be due to folding. Several minor structures are along the northeast-trending segment. An asymmetrical anticline in Sec. 20, T9N, R26E has north limb dips up to 30 degrees northwest and south limb dips of approximately 10 degrees southeast. The ridge crest of the Horse Heaven Hills is a conspicuous line of undulating hills which might be structurally controlled (Bond and Others, 1978).

The Intersection of the Northeast and Northwest Structural Trends

The geologic mapping in the Pasco Basin and of the Yakima Fold Belt on the west consistently shows two structural trends: one that is east-west to northwest-southeast; and, one that is less pronounced that trends northeast. At the intersection of the northwest and northeast trends (Figure III-54) in the Horse Heaven Hills is an extremely complex zone of faulting and folding. This area is important, since evidence exists here that leads to the conclusion that the Horse Heaven Hills structure is either one structure with a bend or two structures with two different trends. In spite of the detailed mapping by Bond and Others (1978), no direct evidence is shown that supports either hypothesis.

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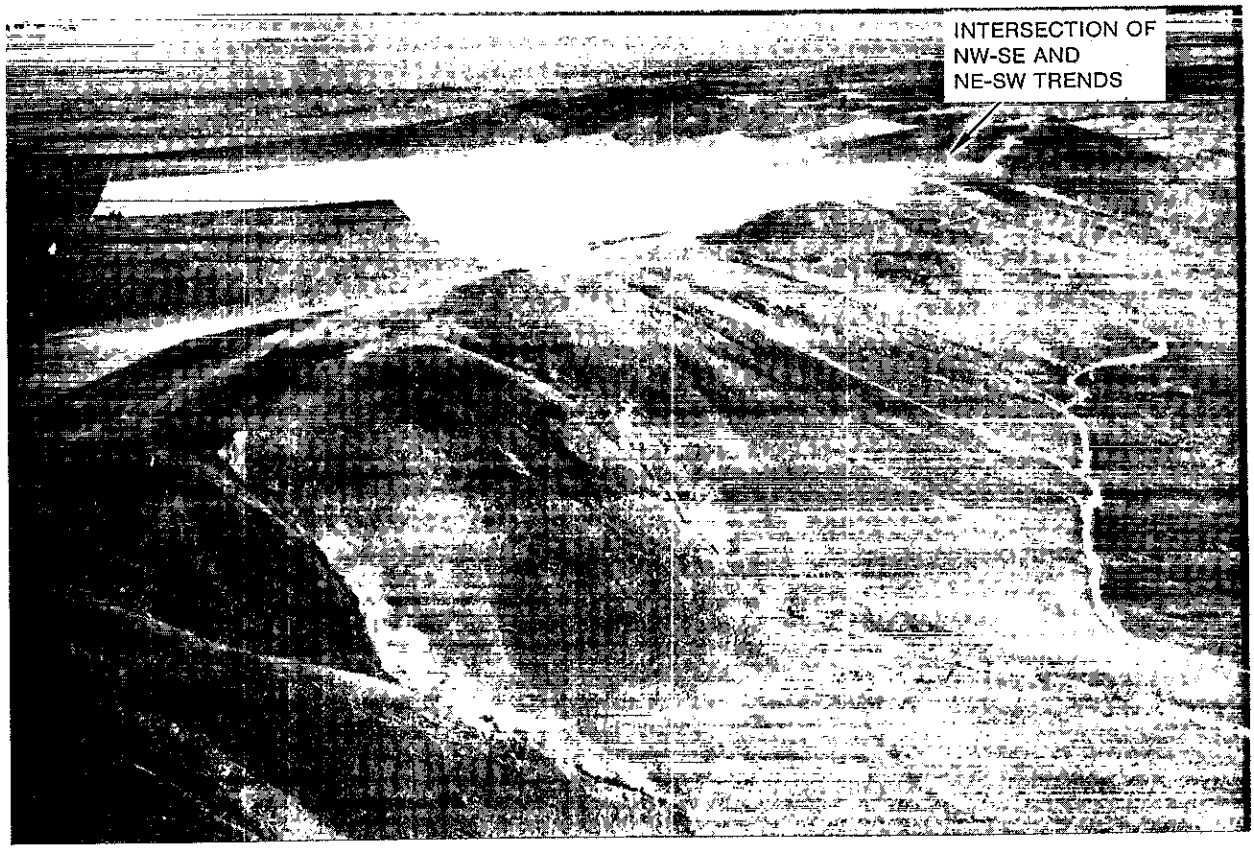

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FIGURE III-54. Horse Heaven Hills Structure (view of northeast-trending segments and northwest-trending segments).

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Prominent aeromagnetic linears are associated with the northwest structural trend and the northeast structural trend of the Horse Heaven Hills structure (Plates III-6a and 6d). These aeromagnetic linears are related to both topography and structures; e.g., the Prosser fault.

EASTERN PASCO BASIN STRUCTURE

The eastern Pasco Basin (Figure III-55) is a southwest-dipping homocline partially covered with younger sediments. The homocline is relatively undeformed, except for some subtle folds mapped in bedrock exposures (Plate III-1) and identified using top-of-basalt elevations (Plate III-4a) in local wells. Ice Harbor Member vents and dikes also occur along a linear system in this part of the Pasco Basin study area. The homocline forms the eastern structural boundary of the Pasco Basin. The apparent lack of deformation and gentle, 1-degree, southwest dip cause the homocline to contrast sharply with the more highly deformed areas in the central and western Pasco Basin.

Surface mapping in the eastern Pasco Basin revealed several low-amplitude folds with wavelengths of approximately 1 mile (1.6 kilometers) or less (Plate III-1). Reidel (this study) mapped N65°W-trending folds northwest of Mesa. Swanson and Helz (1979) mapped an anticline with a N15°W trend. Southwest of Eltopia, Washington, a series of 3 or 4 parallel folds trending north-northwest was mapped west of Ice Harbor Dam by Swanson and Others (1977), Swanson and Helz (1979), and Bond and Others during 1979 for Rockwell Hanford Operations (Plate III-1). In the central part of the eastern Pasco Basin, a broad, low-amplitude anticline trending north-northwest has been delineated from top-of-basalt elevations in local wells (Plate III-4a). This high is interpreted as a structural anticline that probably represents a continuation of the anticline mapped by Swanson and Helz (1979) southwest of Eltopia. An alternative interpretation suggested by D. A. Swanson during a review of this report is that the high might be a constructional high built by small eruptions along the Ice Harbor vent system. A series of fanning, low-amplitude crests and troughs mapped near Eltopia by Walters and Grolier (1960) were not observed during field mapping by Bond and Others during 1979 for Rockwell Hanford Operations (Plate III-1).

No large faults have been identified in the eastern Pasco Basin. A graben filled by the Basin City basalt flows reported by Swanson and Others (1975) has been interpreted by Reidel (this report) (Plate III-1) as an erosional channel in the Elephant Mountain Member filled by Basin City flows.

A northwest-trending linear system of Ice Harbor dikes and vents exists in the eastern Pasco Basin (Plate III-1). This vent system has been mapped by Swanson and Others (1975) from south of the Snake River to north of Basin City, Washington. The orientation of dikes mapped in the field corresponds spatially with anomalies from an aeromagnetic survey by Weston Geophysical Research in WPPSS (1977) and from survey results reported by Swanson and Others (1979c). Swanson and Others (1979c) interpret these anomalies as caused by the Ice Harbor dikes system, but they were alternatively interpreted as related to tilted

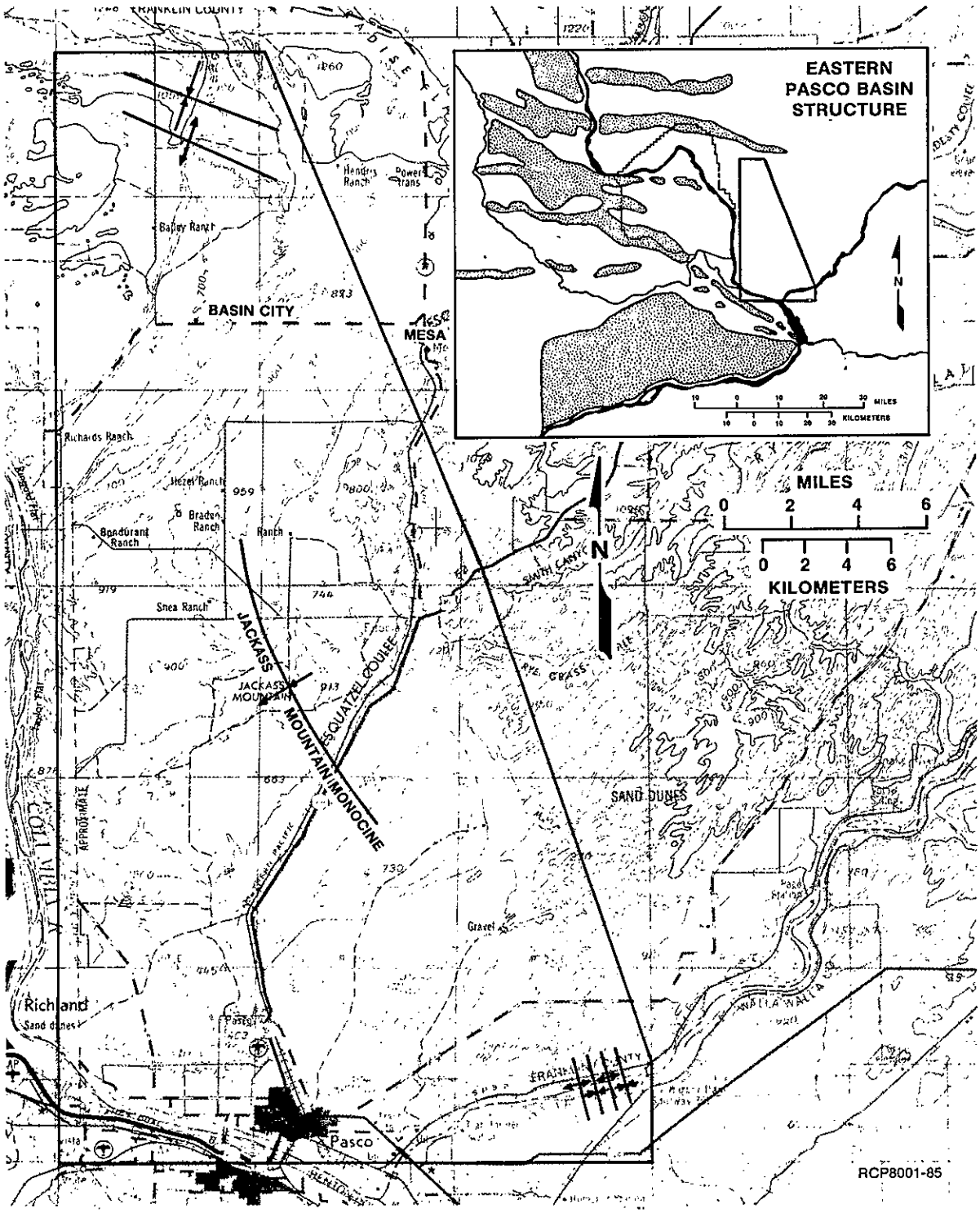


FIGURE III-55. Index Map, Eastern Pasco Basin Structure.

flow edges by Weston Geophysical Research in WPPSS (1977). The same linear aeromagnetic anomalies were detected by the aeromagnetic survey flown for Rockwell Hanford Operations by Quigson Prospects, Inc. (Appendix C; Plate III-6d). The linears (Plate III-6d) trend N25°W and have horizontal vector gradients up to 64 gammas per mile (40 gammas per kilometer). The short wavelength and high gradients associated with these anomalies are indicative of narrow, linear sources and are consistent with the interpretation by Swanson and Others (1979c), who also state that the source of these anomalies is correlated to the feeder dikes for the Ice Harbor flows. These Ice Harbor aeromagnetic linears terminate to the northwest against the Ringold Coulee magnetic high and its associated linear (Plate III-6d). The Ringold Coulee anomaly is a group of broad highs along a northwest-southeast linear trend. These patterns tend to be much broader than the Ice Harbor anomalies and thus suggest a deeper source. The source of this anomaly might be deeper parts of the Ice Harbor dike system, although the discontinuous nature of the highs and the different orientation and asymmetrical signature suggest that a deep, broad upwarping of the basalt is more plausible.

STRUCTURE OF THE CENTRAL PASCO BASIN

Most of the central Pasco Basin is covered by sediment, and bedrock structures are not exposed. Interpretations are based mainly on two maps: the top-of-basalt contour map (Plate III-4a); and, the top-of-Wanapum Basalt structure contour map (Plate III-4b). The contour maps were prepared using depths of key horizons in boreholes, projections of structures from nearby bedrock exposures, and available results from standard geophysical surveys (gravity, aeromagnetic, reflection seismic, and magnetotelluric). The contours on the top-of-basalt map (Plate III-4a) are, in essence, contours on an erosional unconformity across much of the Pasco Basin. Therefore, the top-of-basalt map is not a true structure contour map. However, assuming erosion has removed little of the buried basalt across large areas, the top-of-basalt contours generally approximate structural contours. An important exception is in the southeastern Pasco Basin where deposition of the Ice Harbor Member in a synclinal position effectively reduced the structural relief on the top-of-basalt relative to the top-of-Wanapum basalt.

An aeromagnetic survey (Appendix C) and reflection seismic survey (Appendix D) were recently completed in the Pasco Basin. These surveys were designed to locate and trace second-order structures on the limbs of buried folds and to trace synclinal axes. Many aeromagnetic highs and linears correlate well with known structures on the top-of-basalt and top-of-Wanapum Basalt maps, but some aeromagnetic linears were identified which do not correlate with any known bedrock structures. Both types of aeromagnetic anomalies are discussed in this section.

The reflection seismic surveys identified velocity anomalies at several locations along their survey lines. Some of these anomalies are probably related to fine bedrock structure; whereas others are related to erosional channels in the top-of-basalt and abrupt lateral lithology changes in the sediments overlying basalt. This work is in progress and no interpretations are included in this report. Examples of how this analysis is being performed are given in Appendix D.

Magnetotelluric surveys in the Pasco Basin are described in Appendix E. This survey revealed five geoelectric layers beneath the Pasco Basin. If it is assumed that thick and thin zones in the three deepest geoelectric layers and highs and lows on the top of these three layers correspond to thickness variation and structural configurations, respectively, of actual deep rock units, then the following preliminary interpretation can be made regarding the deep structure of the Pasco Basin.

(a) The dominant structural trends beneath the volcanic rocks (Columbia River Basalt Group rocks and older, deeper rocks) underlying the Pasco Basin are northeasterly. This contrasts sharply with the northwesterly trend in the Yakima Fold Belt.

(b) The northeasterly trending zone of thinning and the northeasterly trending high in the deep units are nearly coincident in space.

(c) Results from the magnetotelluric survey are consistent with previous gravity surveys by Deju and Richard (1975), refraction survey by Hill (1972), and seismic studies by Eaton in Smith (1978), which indicate a thin crust beneath the Pasco Basin, generally along a northeast trend.

Maps showing elevation and thickness of the geoelectric layer are given in Appendix E.

The Pasco Basin is elongate northwest-southeast and is somewhat arcuate in form. Main structural trends are easterly in the northwestern part and southeasterly in the southeastern part (Plate III-4a). The Saddle Mountains structure is convex to the north and forms the northern boundary of the basin. The southern boundary is formed by the Rattlesnake Hills structure which is convex to the south. The geometry of the central basin reflects these two structures. In the northwestern part of the basin, the Wahluke syncline, the Umtanum Ridge-Gable Mountain structure, the Cold Creek syncline, the Yakima Ridge structure, and the Benson Ranch syncline trend subparallel to the Saddle Mountains structure. The north Pasco Basin structure and portions of the Pasco syncline reflect the Rattlesnake Hills structures. Structural relief decreases eastward from the western basin margin and many folds terminate within the central Pasco Basin. The southeastern part is structurally less deformed by first-order folds than the northwestern part of the basin. The Wahluke and Cold Creek synclines are the two major synclines in the northwestern Pasco Basin. They subdivide the northwestern Pasco Basin into two sub-basins (Plate III-4a). The southeastern Pasco Basin is currently interpreted as a simple basin without sub-basins. The Wahluke syncline lies between the Saddle Mountains structure and the Umtanum Ridge-Gable Mountain structure. The trough line of the Wahluke syncline is much nearer the Umtanum Ridge-Gable Mountain structure than the Saddle Mountains structures; consequently, its cross section is asymmetric with a steep southern limb (Plate III-5, cross section E-E'). The top-of-basalt is approximately 200 feet (61 meters) below mean sea level in the lowest part of the Wahluke syncline. This depression, named the Coyote Rapids depression, forms the northern subbasin of the northwestern

part of the Pasco Basin. The Wahluke syncline plunges into the Coyote Rapids depression from the east and west (Plate III-4a). The Cold Creek syncline is geometrically similar to the Wahluke syncline. The Cold Creek syncline is situated between the Umtanum Ridge-Gable Mountain structure and the Yakima Ridge structure. The Cold Creek syncline is asymmetrical with a steeper southern limb (Plate III-5, cross section G-G') and a trough line near the Yakima Ridge structure (Routson and Fecht, 1979). The Cold Creek syncline plunges east into the Wye Barricade (Hanford Site) depression where the top-of-basalt is about 150 feet (50 meters) below mean sea level. A minor depression, the Cold Creek Valley depression, occurs along the Cold Creek syncline south of the Yakima Barricade (Hanford Site). These two depressions form the southern sub-basin in the northwestern part of the Pasco Basin. The Cold Creek syncline is traced south of the 200 East Area (Hanford Site) as a broad aeromagnetic low. The general trend of the aeromagnetic low is northwest-southeast, except that it might trend northeast between the Cold Creek Valley and the Wye Barricade depressions. Borehole data are insufficient in that area to test this possibility. The Cold Creek syncline is interpreted to die out in the Wye Barricade depression. The Benson Ranch syncline is a subtle syncline situated between the Yakima Ridge and the Rattlesnake Hills structures. From borehole data, the Benson Ranch syncline appears midway between the two bounding structures. The syncline gently plunges from Dry Creek Valley toward the central basin on the east. The Benson Ranch syncline is probably down-dropped to the east along the same northwest-trending fault that is postulated to offset the Yakima Ridge structure (see previous discussion of Yakima Ridge structure). The Benson Ranch aeromagnetic anomalies and linears (Plate III-6a) indicate the Benson Ranch syncline and Yakima Ridge anticline continue southwest into the central Pasco Basin, but probably die out toward the Wye Barricade depression.

The Pasco syncline is a broad, low-amplitude depression in the southeastern part of the Pasco Basin. It lies between the Jackass Mountain structure and the Rattlesnake Hills structure and has sinuous trend and no well-defined trough near the Wye Barricade depression. North of the easterly trending segment of the Pasco syncline is a series of small domes aligned parallel to the syncline (Plate III-4a). These domes are low relief, areally small features, with short arcuate trends. Several structures converge and lose definition in the Wye Barricade depression, which is currently interpreted as a relatively broad, flat depression. These structures include: (a) the Wahluke syncline; (b) the Umtanum Ridge-Gable Mountain structure; (c) the Cold Creek syncline; (d) the Yakima Ridge structure; (e) the Benson Ranch syncline; and, (e) the Pasco syncline. This relationship is also shown by aeromagnetic survey results. The 56320 gamma contour line (Plate III-6a) includes a set of aeromagnetic lows which correspond to the broad synclinal low including the Wye Barricade depression shown by the contour on the top-of-basalt (Plate III-4a). The low trends approximately east-west beneath the Columbia River across the northern tip of Wooded Island.

Several aeromagnetic anomalies have been identified in the central Pasco Basin. These anomalies are described below and shown on Plates III-6a through 6d. Evaluation of the structural significance of these anomalies is under way. The 200 East Area anomaly is an elliptical aeromagnetic high with its major axis oriented approximately east-west. It is limited on the north and south by moderate horizontal gradients of 13 gammas per mile (20 gammas per kilometer). It terminates to the east along the north-south-trending May Junction linear. Abundant well data for this area reveal a broad high on the upper surface of the basalt. The 200 East Area anomaly is enigmatic, because its total field expression dominates the Gable Mountain anomaly, yet the top-of-basalt beneath the 200 East Area anomaly is approximately 700 feet (213 meters) lower in elevation than the Gable Mountain areas. Therefore, Gable Mountain should be expected to exert a stronger influence on the total field than it apparently does. A possible explanation of this peculiar situation is that the 200 East Area anomaly is an expression of a strong dipole field which destructively interferes with the Gable Mountain anomaly to subdue its effect. The May Junction linear is a unique anomaly in two respects. First, its trend is north-south and, secondly, its horizontal vector gradients are as high as 67 gammas per mile (40 gammas per kilometer), the largest in the immediate area. Contours on the top-of-basalt (Plate III-4a) indicate a relatively steep slope striking north-south and dipping to the east (Fecht, 1978). It is debatable, however, whether this slope, by itself, is sufficient to account for the high horizontal gradients. The Gable Mountain linear trends for approximately 13 miles (22 kilometers) from western Gable Mountain to the Wooded Island anomaly. Horizontal vector gradients consistently average 41 gammas per mile (25 gammas per kilometer) along the entire length of this linear. The Gable Mountain linear marks the approximate boundary between the May Junction-Wooded Island lows and the generally higher intensities to the northeast. The Gable Mountain linear may indicate a continuation of the Gable Mountain structure farther southeast than currently mapped (Plate III-4a). The Hanford linear, which parallels the northwestern end of the Gable Mountain linear, has characteristics similar to the Gable Mountain linear. The Wooded Island anomaly is a large, closed, lobate low that trends approximately northwest-southeast. The lowest magnetic intensities of the central Pasco Basin are related to this anomaly. This low intensity might be related to thickening reversely polarized flows such as the Pomona Member, or it could represent a pronounced structural depression. Top-of-basalt contour maps (Plate III-4a) do not, however, indicate a deepening of the basalt, nor is there evidence for subcrops of the Pomona Member. One possibility is that the magnetic susceptibilities and/or natural remanent magnetization intensities of the rocks in this area are well below average relative to the surrounding rocks. The 300 Area linear is a northeast-southwest-striking feature on the total field map. This anomaly is expressed as a comparatively uniform horizontal gradient from Red Mountain to Baxter Canyon. The total field increases to the southeast, perpendicular to the linear from 56330 to 56510 gamma contour lines.

TECTONIC FRACTURES AND POSSIBLE TECTONIC FRACTURES PENETRATED BY CORE HOLES

This section is a discussion of those fractures penetrated by Pasco Basin core holes which are interpreted to have formed in response to tectonics, either directly or indirectly. (Non-tectonic fracture and cooling fractures were described previously.) All basalt core recovered from Pasco Basin core holes is fractured to same degree. Cooling fractures are abundant in basalt core. Figure III-56 is an example of relatively undeformed core.

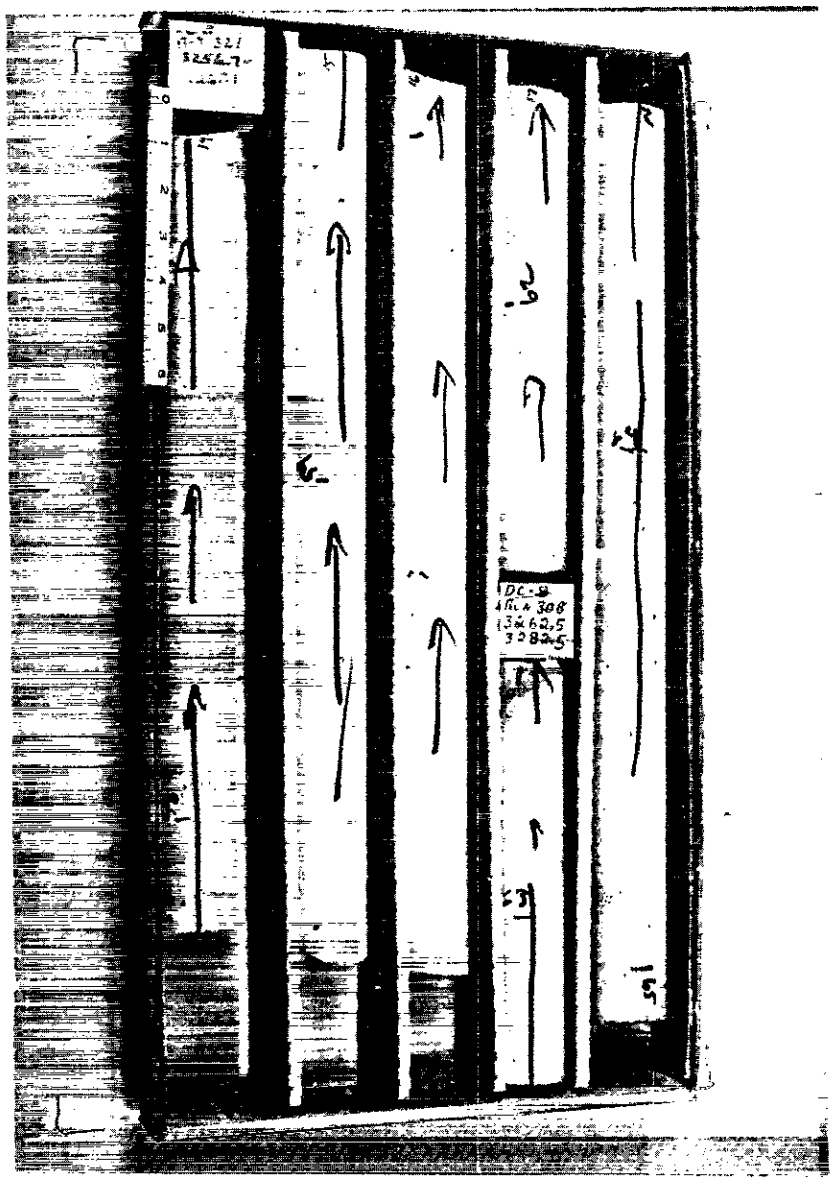
Core hole DB-10 was drilled on a structure thought to be a sharply folded anticline (Figure III-57). Core from DB-10 revealed 2 fault zones: 1 at about 400 feet (130 meters) drilled depth; and, the other at about 575 feet (192 meters) drilled depth. These 2 fault zones are oriented 40 to 45 degrees to the core axis and are characterized by slickensides and by tectonic breccia in a gouge matrix (Figure III-58). Basalt units were identified above, below, and between the two faults in DB-10 and compared with the unfaulted stratigraphic section penetrated by nearby boreholes. This revealed that the stratigraphic section is repeated across the 2 faults in DB-10, which indicates that the 2 DB-10 faults are reverse faults with about 160 feet (55 meters) of combined throw. The DB-10 core was not drilled as oriented core; therefore, the strike of the reverse faults is unknown. Thus, the top-of-basalt high where DB-10 was drilled might be caused by faulting in addition to sharp folding. Figure III-59 is an interpretation of the relations seen in DB-10.

Core hole DC-8 penetrated shears of limited extent with surfaces having apparent slickensides in a low K_2O flow below the Umtanum flows in the Schwana sequence, Grande Ronde Basalt (Figure III-60). The shears occur in a thin flow and might have formed during the late stage of flow emplacement or they might be tectonic; the latter interpretation is preferred.

Core hole DC-4 penetrated 13 feet (4 meters) of Vantage Member sandstone and shows offsets of up to 4 inches (10 centimeters) in the central part of the sandstone interbed (Figure III-61). The offsets are interpreted as high-angle, normal faults with a slight amount of folding. The offsets are not in the upper portion of the interbed and are considered to be a syngenetic response to loading during deposition or due to compaction loading by the overlying basalt flow. The offsets might also be tectonic.

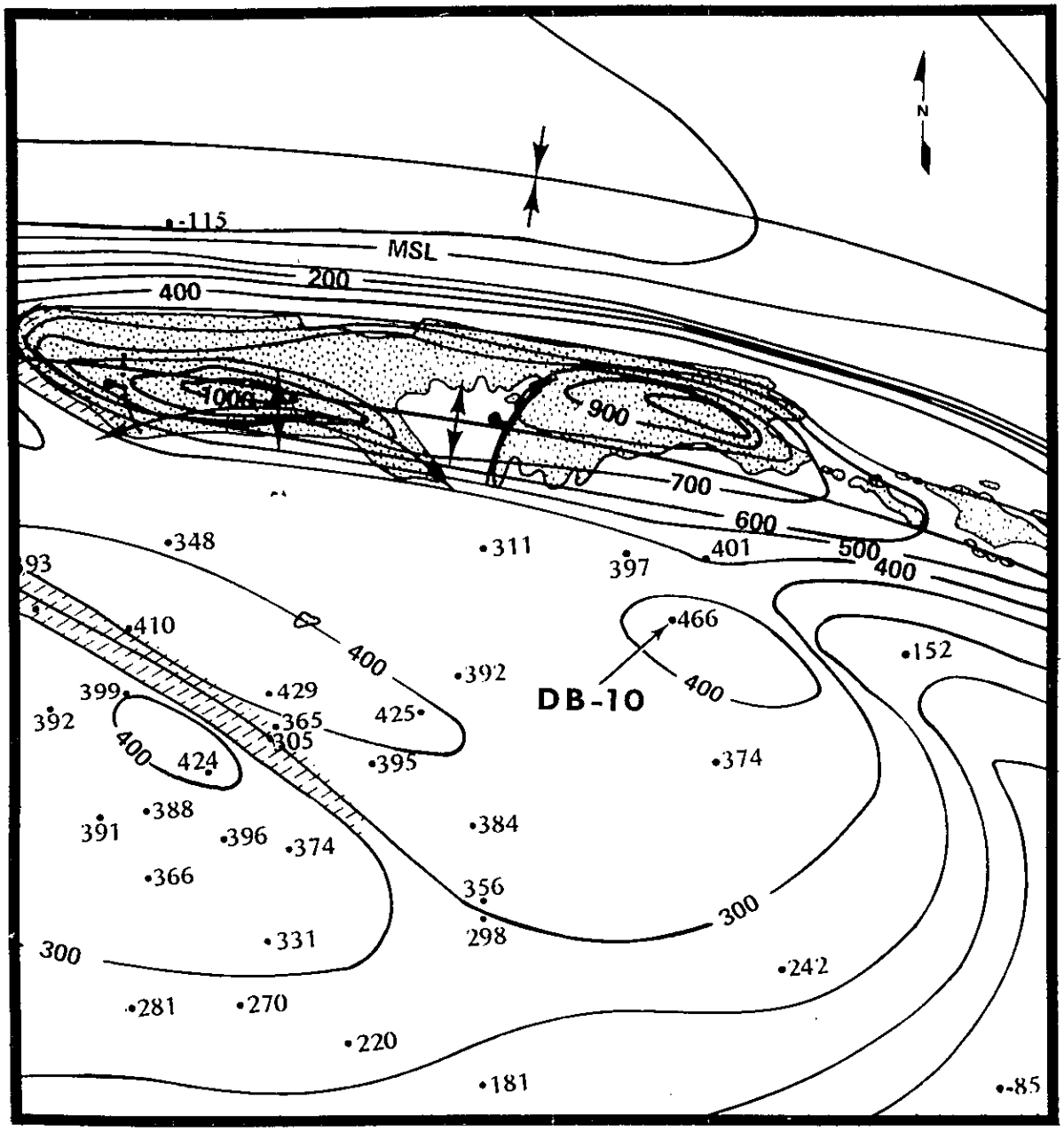
The most widespread and least understood fractures observed in core are the subhorizontal, closely spaced fractures that form small discs perpendicular to the core axis known informally as "poker chips" (Figure III-62). They have undulating, doubly curved, saddle-shaped surfaces that are almost always free of mineralization. They are thus different from normal cooling joints, which invariably contain some secondary mineralization or alteration, and occur at various angles to the core axis. Poker-chip fracturing is limited almost exclusively to flows of the Grande Ronde Basalt and is more common in some boreholes

9 2 1 2 1 9 4 1 7 0 4



780688-18 cn

FIGURE III-56. Core from Core Hole DC-8 (3,256.7 to 3,265.1 feet [992.6 to 995.2 meters]) Showing Relatively Unfractured Grande Ronde Core.



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0 ½ 1 MILE

0 ½ 1 KILOMETER

FIGURE III-57. Location of Core Hole DB-10.
Contours are elevations of the top of basalt.

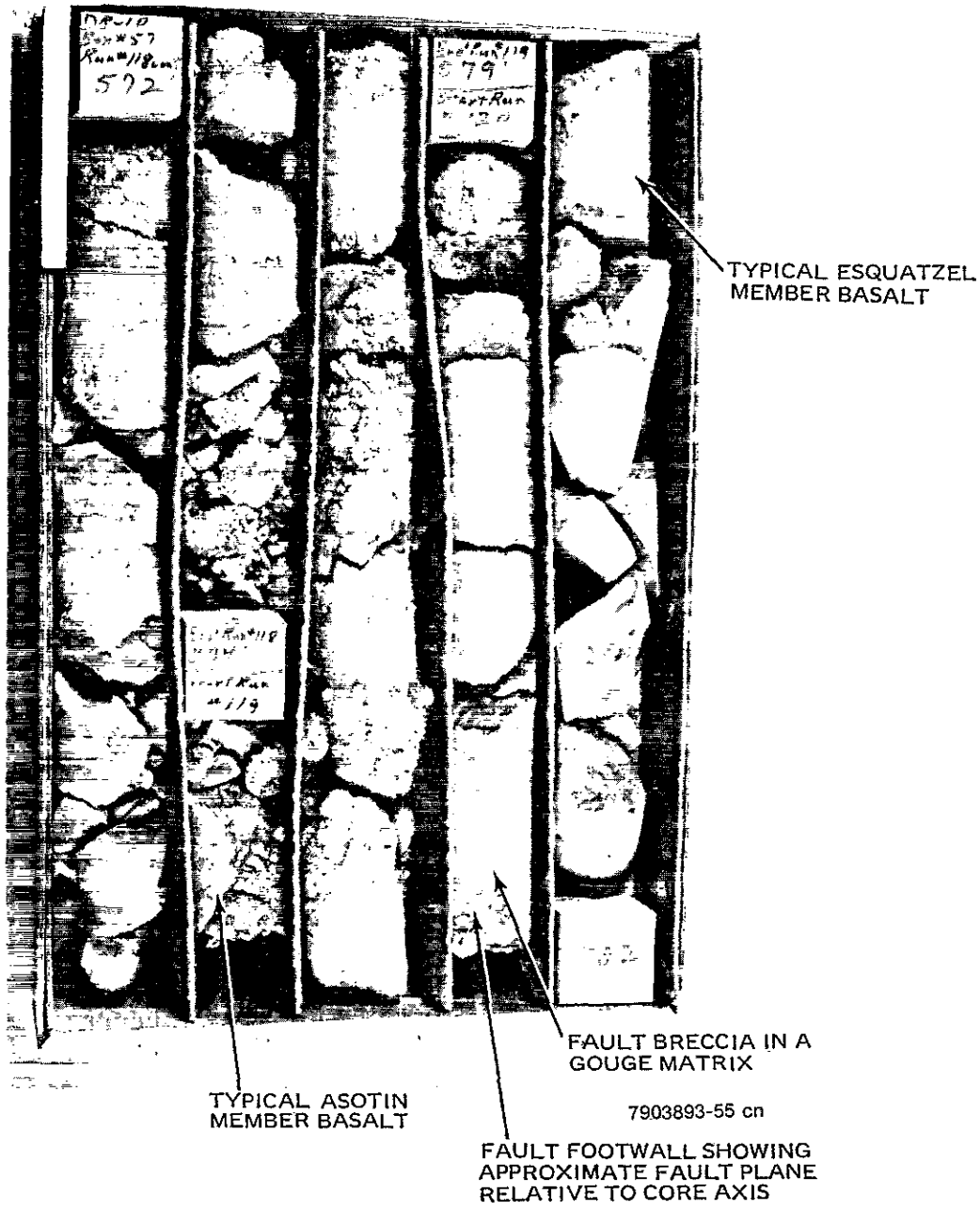


FIGURE III-58. Core from Core Hole DC-10 (572 to 582 feet [174.3 to 177.4 meters]) Showing Fault Gauge and Fault Plane at 580 Feet Drilled Depth.

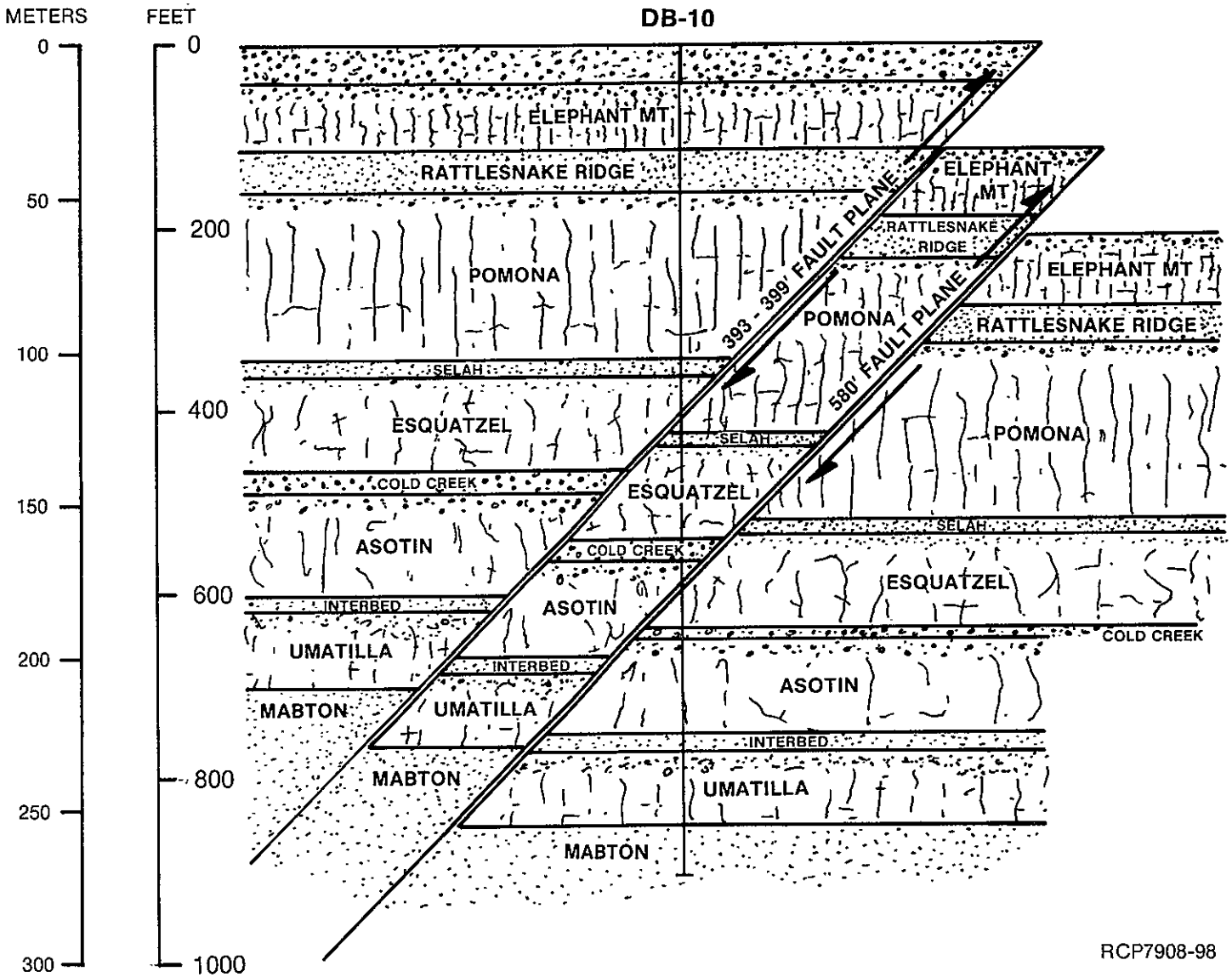


FIGURE III-59. Interpretation of Repeated Section by Reverse Faults, Core Hole DB-10.

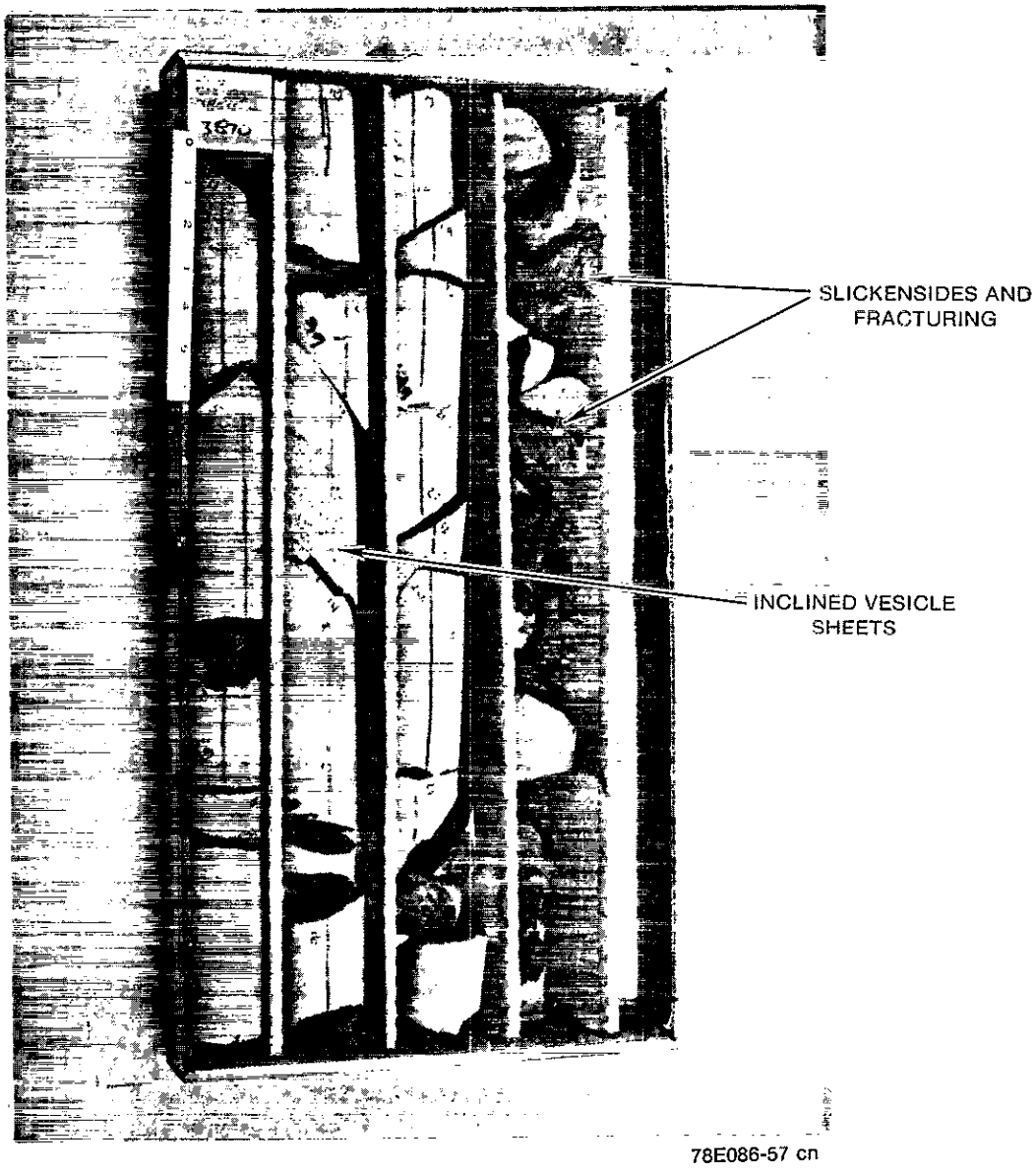
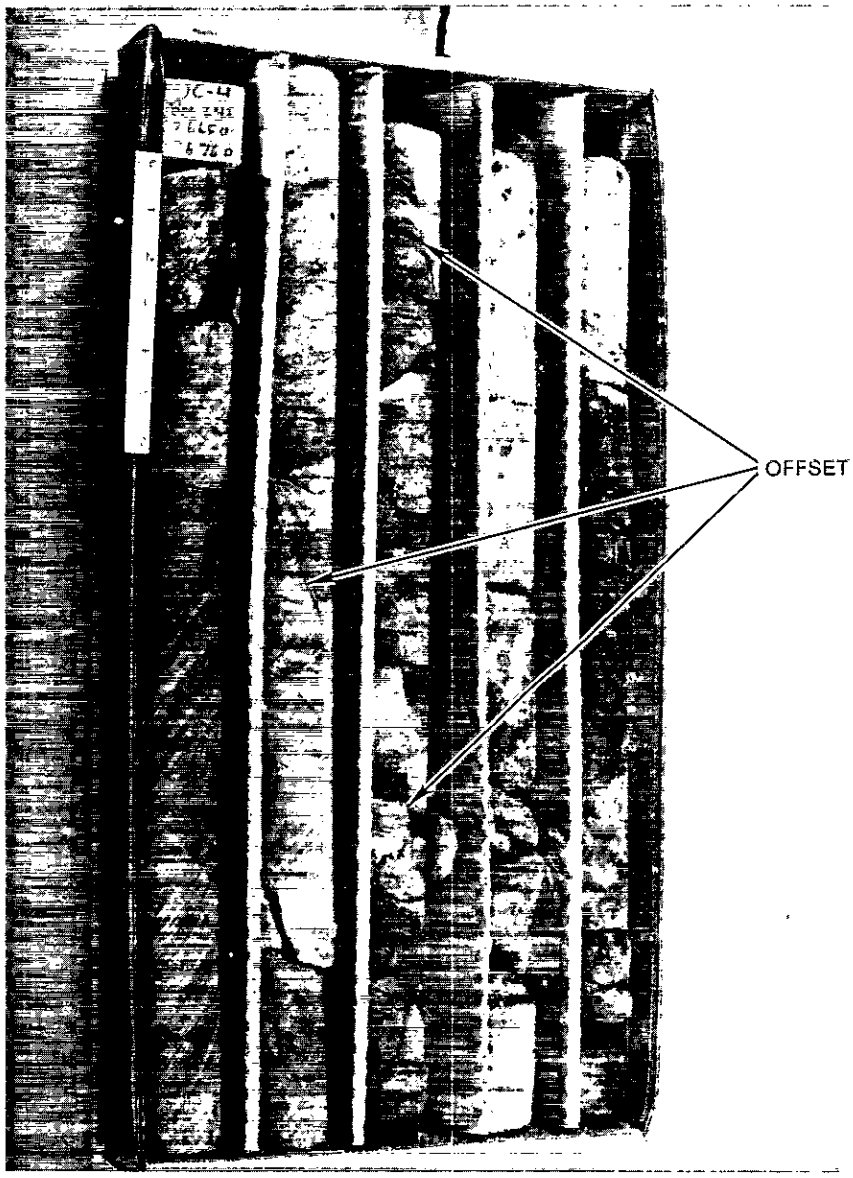
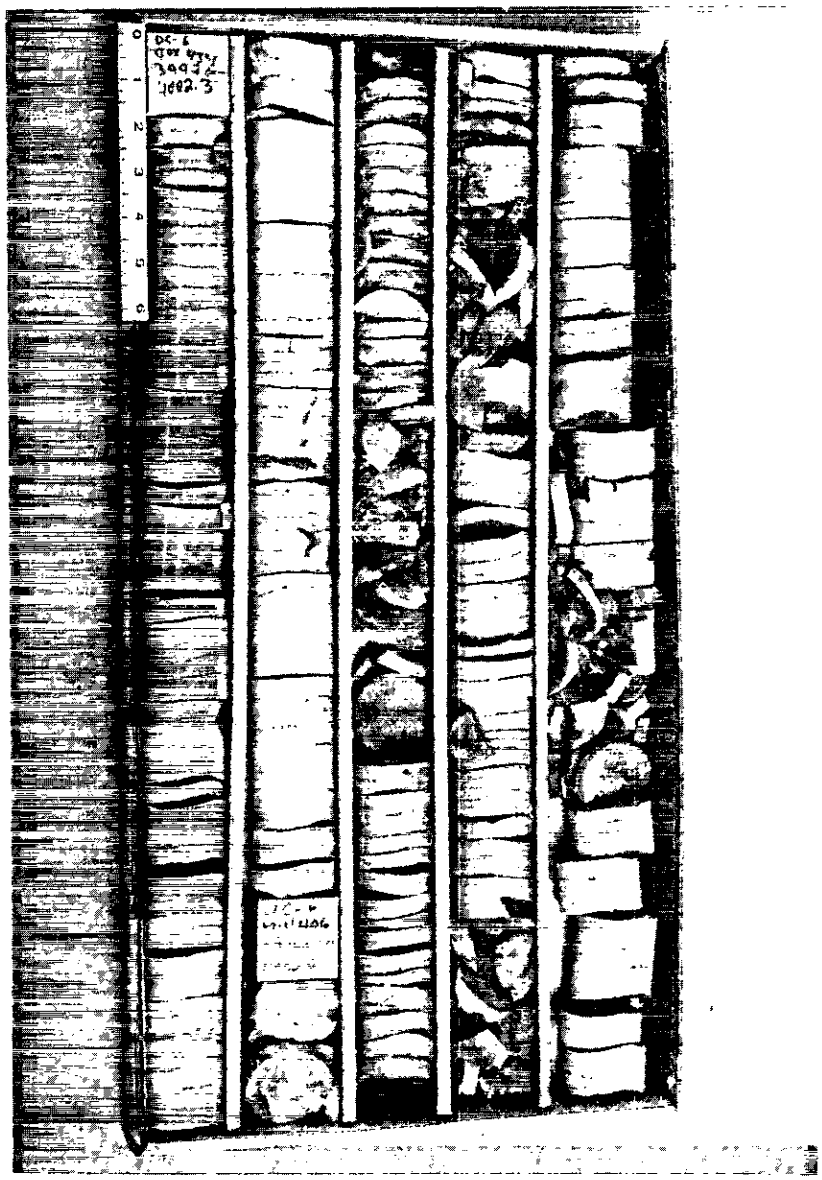


FIGURE III-60. Core from Core Hole DC-8 (3,864 to 3,870 feet [1,177.7 to 1,179.5 meters]) Showing Slickensides, Fracturing, and Inclined Vesicle Sheets.



7812808-37 cn

FIGURE III-61. Core from Core Hole DC-4 (2,665 to 2,676 feet [812.3 to 815.6 meters]) Showing High-Angle Offset of Clay Layers in the Vantage Member.



7908737-109

FIGURE III-62. Core from Core Hole DC-6 (3,992 to 4,002.3 feet [1,216.9 to 1,219.9 meters]) Showing Closely Spaced Discing. Note that shattered discs are mechanical fractures caused during extraction from core barrel.

than others (note the intervals of discing [poker chips] on Figure III-38. Lithostatic stress release is currently considered the most probable cause of poker-chip fractures. Other possible causes include tectonic stress release or the actual drilling process. In addition, some poker-chip fracturing might be related to a primary anisotropy, such as microlite alignment or alignment of microvesicles created during flow emplacement and cooling. Study of poker-chip fractures is under way.

STRUCTURAL ANALYSIS OF UMTANUM RIDGE

In the fall of 1978, Rockwell Hanford Operations began an analysis of Yakima Fold structures in the Pasco Basin. The objective was to map deformational patterns at a scale of 1:6,000 or larger and emphasize the style of deformation, kinematic models, and the location and character of probable intraflow and interflow tectonic structures on the limbs of the folds.

Eastern Umtanum Ridge (Figure III-63) was selected as the first Yakima Fold structure to receive a detailed structural analysis because: (a) it is the most prominent Yakima Fold structure in the west-central Pasco Basin; (b) the internal structure within the ridge is well exposed in the deep gulleys along the north flank of the ridge; (c) it had been mapped at 1:24,000 (Goff, in his work for Rockwell Hanford Operations); and, (d) subsurface information was available in the Priest Rapids Dam area (Mackin, 1955). In addition, portions of Umtanum Ridge have been mapped at 1:62,500 and studied by the Washington Public Power Supply System, Inc. (1974).

Detailed mapping of the Saddle Mountains structure by Reidel (1978a) and reconnaissance mapping of the Hanson Creek structure by E. H. Price (this report) suggested that the Umtanum Ridge structure might be typical of the style of deformation within less exposed Yakima Fold structures.

Planning and organizing Umtanum Ridge work began in early 1979. At that time, it was known that R. D. Bentley of Central Washington University had already mapped in detail portions of Umtanum Ridge in the Filey Road area west of Priest Rapids Dam (Figure III-63). The mapping was of the type and scale to be of use for part of our structural analysis of Umtanum Ridge, but Bentley's report, structure contour maps, and cross sections had not yet been prepared. Rockwell Hanford Operations contracted with R. D. Bentley to finalize his geologic map of the Filey Road area and prepare an accompanying text, maps, and cross sections. E. H. Price worked with Bentley during the early spring of 1979, when he completed his field work in the Filey Road area.

In June 1978, W. Saur of Washington State University began an analysis of jointing and faulting along part of eastern Umtanum Ridge under a Northwest College and University Association for Science student fellowship as part of the structural studies being conducted by Rockwell Hanford Operations. This research is presently incomplete.

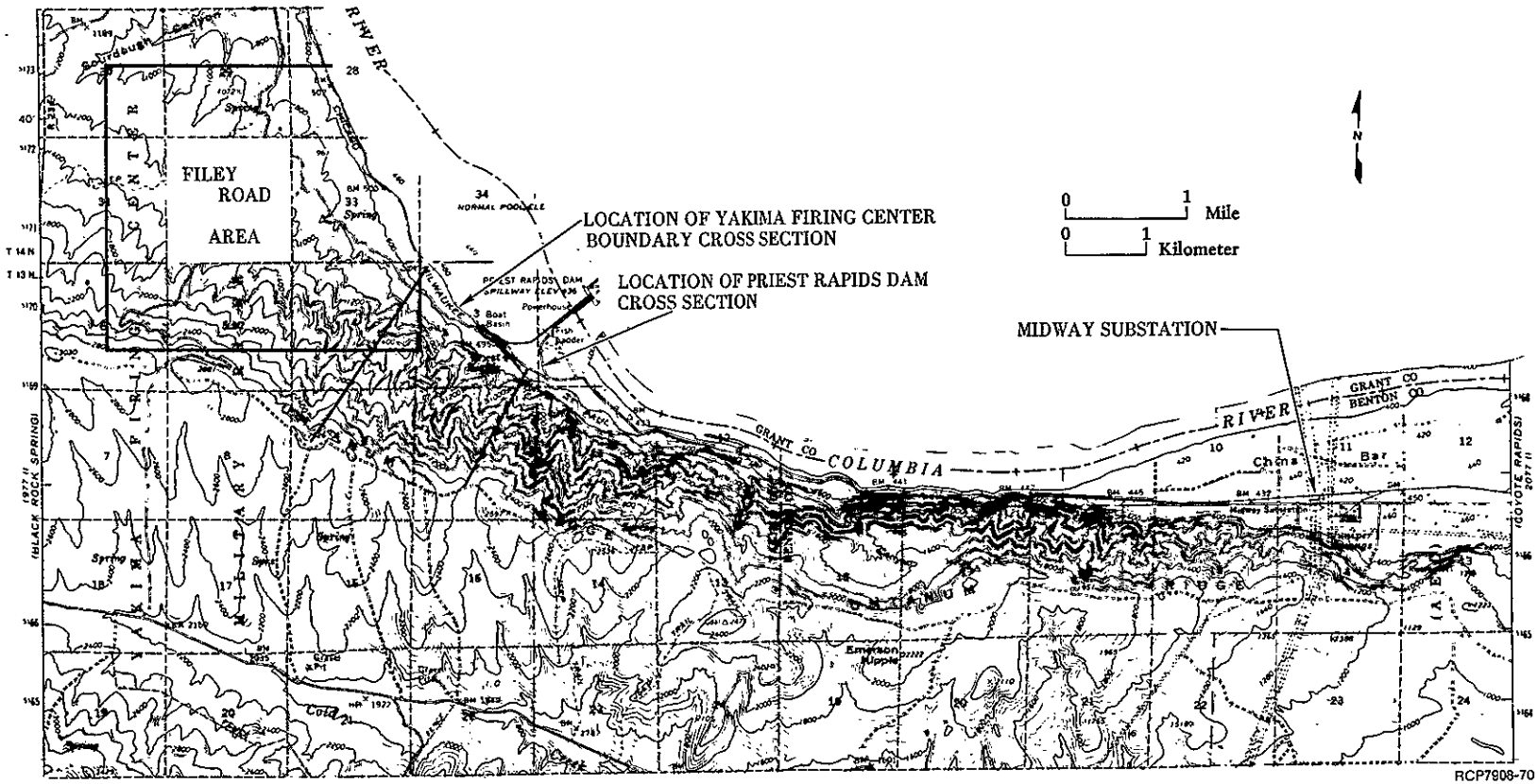


FIGURE III-63. Index Map, Eastern Umtanum Ridge Structural Analysis Study Area.

The field work and the preliminary maps and structure cross sections prepared by Bentley and discussions with Saur formed the basis for the beginning of detailed mapping and structural analysis performed along Umtanum Ridge east of the Filey Road area. The results of this work to date are presented in this section.

Structural Geometry

The Umtanum Ridge structure is an asymmetric, non-cylindrical, overturned, plunging anticline whose crestal surface bifurcates into several subsidiary, en echelon folds along the major fold trend (Goff and Myers, 1970; Goff, in work for Rockwell Hanford Operations). (A description of the structural geometry of Umtanum Ridge has been given previously in this chapter.)

Systematic tectonic master joint sets described by Goff (in work for Rockwell Hanford Operations) appear to have a geometric relationship to the large structure. These tectonic joints are distinguished at the outcrop by their very planar nature and cross-cutting relations with recognized primary features such as cooling joints and flow layering. These joints are superimposed upon primary jointing and also upon one another. Geometric relationships of the master joint sets to a simple fold model are generalized in Figure III-64. These relationships include: a joint set striking sub-parallel to the general fold hinge (Set 1); a joint set striking orthogonal to the general fold hinge (Set 2); a conjugate set of shear joints which forms an acute angle sub-parallel to the general fold hinge direction (Set 3); and, a conjugate joint set of shear fractures which forms an acute angle perpendicular to the general fold hinge (Set 4).

For purposes of discussion, the Umtanum Ridge structure is divided into four structural blocks and each block is described below.

Block 1. The major thrust zone, shown schematically in Figures III-65 and III-66, has tentatively been named the Buck thrust. The stratigraphic section above the thrust consists of the planar, relatively longer, southern limb of the fold which contains part of the Grande Ronde and all of the Wanapum Basalts in stratigraphic succession. This section is referred to as Block 1.

Block 2. Block 2 is beneath the Buck thrust (Figures III-65 and III-66) and consists of folded Grande Ronde Basalt flows. Within Block 2, the radius of curvature of flow layering is the least among all constructed cross-sectional blocks and represents the fold hinge. Another discordance of layering is at the intersection of vertical to overturned layering of the Umtanum Ridge structure with north-dipping layering of Block 2. This discordance is interpreted to be a shear zone (shear zone A of Figures III-65 and III-66) and is designated as the northern boundary of Block 2.

Block 3. The existence of a reverse fault at the base of Umtanum Ridge (shear zone B of Figures III-65 and III-66) was originally postulated by Mackin (1955) and supported by Goff and Myers (1978) and Goff in his work for Rockwell Hanford Operations. Such a fault is required to

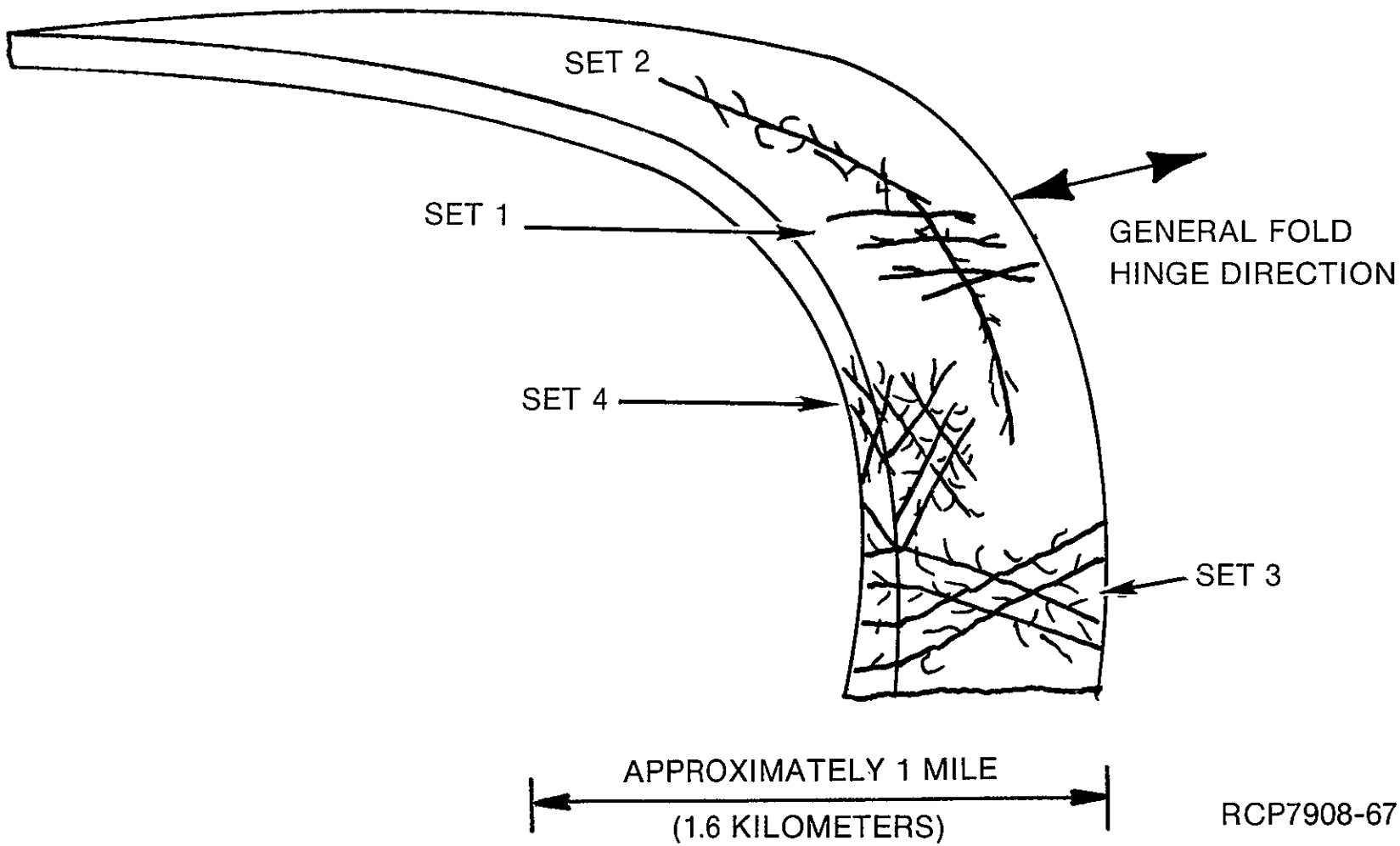


FIGURE III-64. Schematic Diagram of Systematic Master Joint Sets Recognized within the Umtanum Ridge Structure. Joint sets are superimposed upon one another in various parts of the fold.

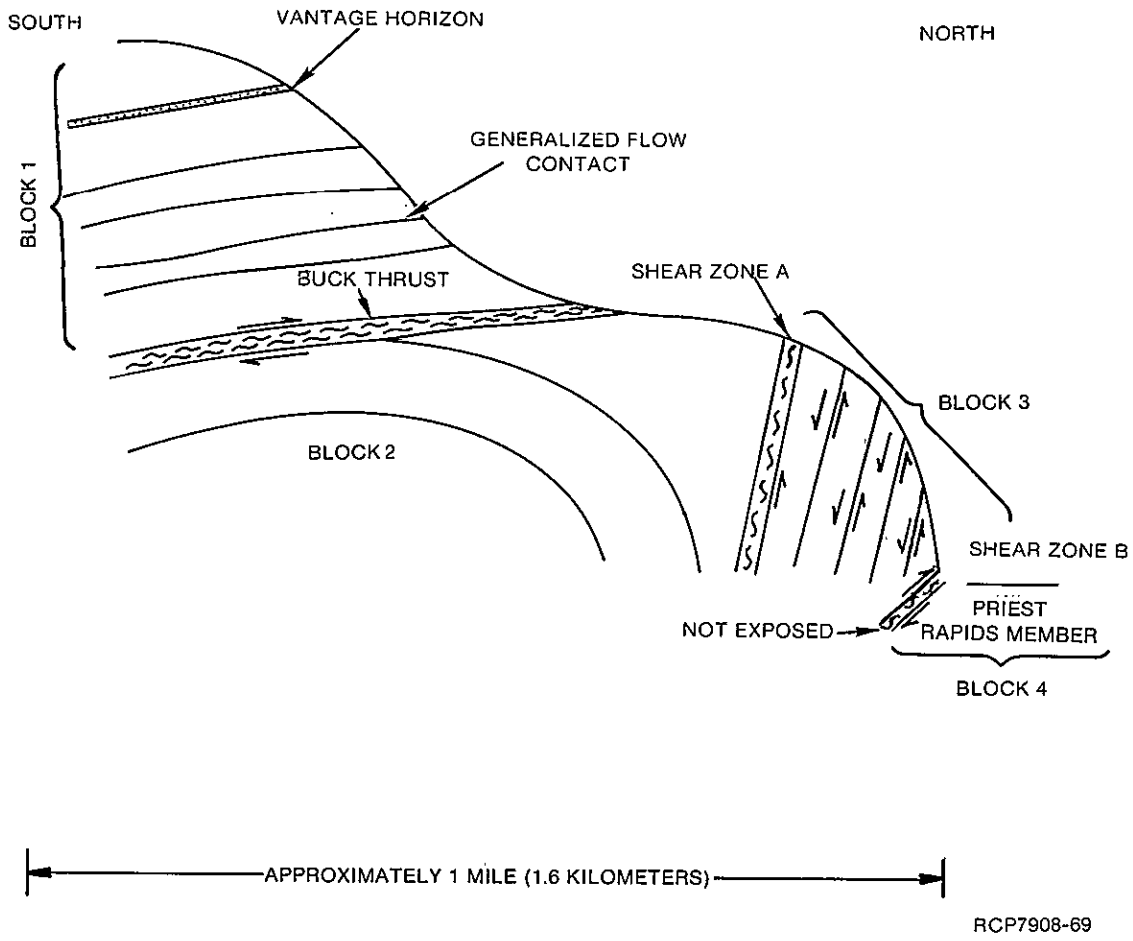


FIGURE III-65. Generalized Interpreted Structure Cross Section of the Umtanum Structure at Priest Rapids Dam (view toward the west).

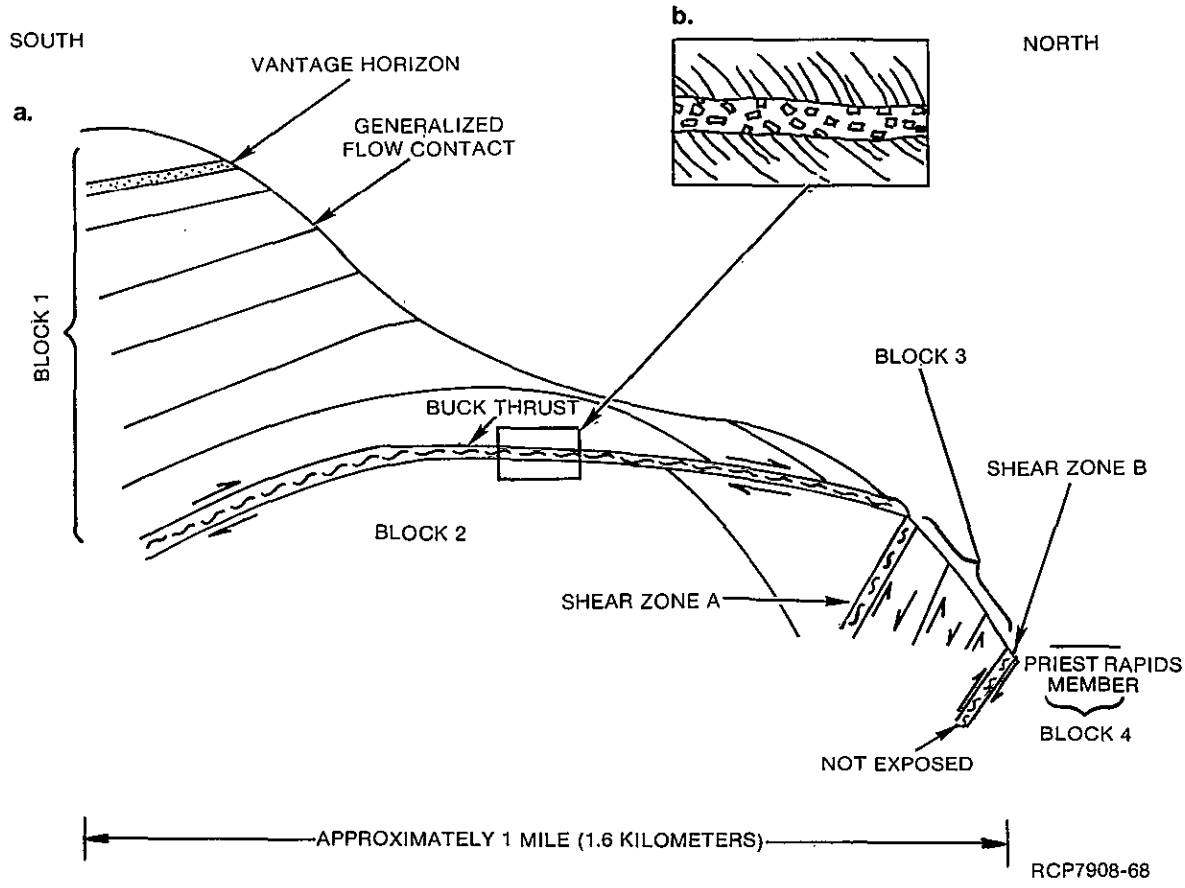


FIGURE III-66. Generalized Interpreted Structure Cross Section of the Umtanum Structure at the Eastern Boundary of the Yakima Firing Center (view toward the west).

account for the abutment of horizontal Priest Rapids Member against the overturned Sentinel Bluffs sequence at Priest Rapids Dam. This fault defines the northern boundary of Block 3. Layering within Block 3 is very planar and vertical to overturn; it is thus interpreted to represent the shorter, north limb of the anticlinal fold.

Block 4. Block 4 consists of the flat-laying flows of Priest Rapids Member to the north of shear zone B of Figures III-65 and III-66.

Mesoscopic Tectonic Deformational Features

Tectonic deformational features observed with interflow and intraflow zones include master joints, tension fractures, and fault breccia with its associated gouge, steps, and slickensides on discrete slip planes.

Master joints are recognized as a concentration of closely spaced, parallel, planar fractures (Long, 1978).

Tectonic breccia is used as a general term expressing fracturing and brecciation due to tectonism. An example of a fractured colonnade is shown in Figure III-67. In the Umtanum Ridge structure, this would include tension fracturing as described below plus master jointing. Within the hinge area of the fold near Priest Rapids Dam, the fracturing is sufficently penetrative on a large scale and of such consistent orientation that it may be described as fracture cleavage. Further research may prove it to be related geometrically to the fold.

Physical characteristics of sheared basalt within fault breccias have been described in detail by Goff in his work for Rockwell Hanford Operations. In his work, he described anastomosing breccia zones within highly sheared rock and more planar breccia or shear zones. Where breccia zones can be recognized as planar features, sigmoidal curviplanar tension fractures are commonly geometrically associated with the breccia zones and are superimposed upon other previous jointing (Figure III-68). These relationships are diagrammatically sketched in Figure III-69. En echelon sets of sigmoidal tension fractures, some with calcite filling, commonly have little breccia development as shown schematically in Figure III-69a. This feature is interpreted to represent an early stage of strain in development of a fault breccia zone. The width of tension fracture zones varies from a few inches to several feet (centimeters to meters). There is no observed relationship between spacing of fractures and width of the fracture zone. There is, however, a direct relationship between closeness of fracture spacing and increased number of fractures with proximity to the inflection point of sigmoidal arcs. In Figure III-69a. the zone of greater number of shear fractures probably represents a plane of incipient shear failure or faulting. Where shear movement is interpreted to have taken place, small fracture blocks are observed to have been rotated in a manner consistent with relative movements suggested by fractures (Figure III-69b). Further documentation and quantification of these relationships is presently under way.

9 2 1 2 1 9 4 1 7 1 3

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FIGURE III-67. Tectonic Breccia in a Fractured Colonnade of a Grande Ronde Basalt Flow, Umtanum Ridge.

9 2 1 2 1 9 4 1 7 1 9

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FIGURE III-68. Sigmoidal Tension Fractures Associated with Incipient Breccia Zone Development.

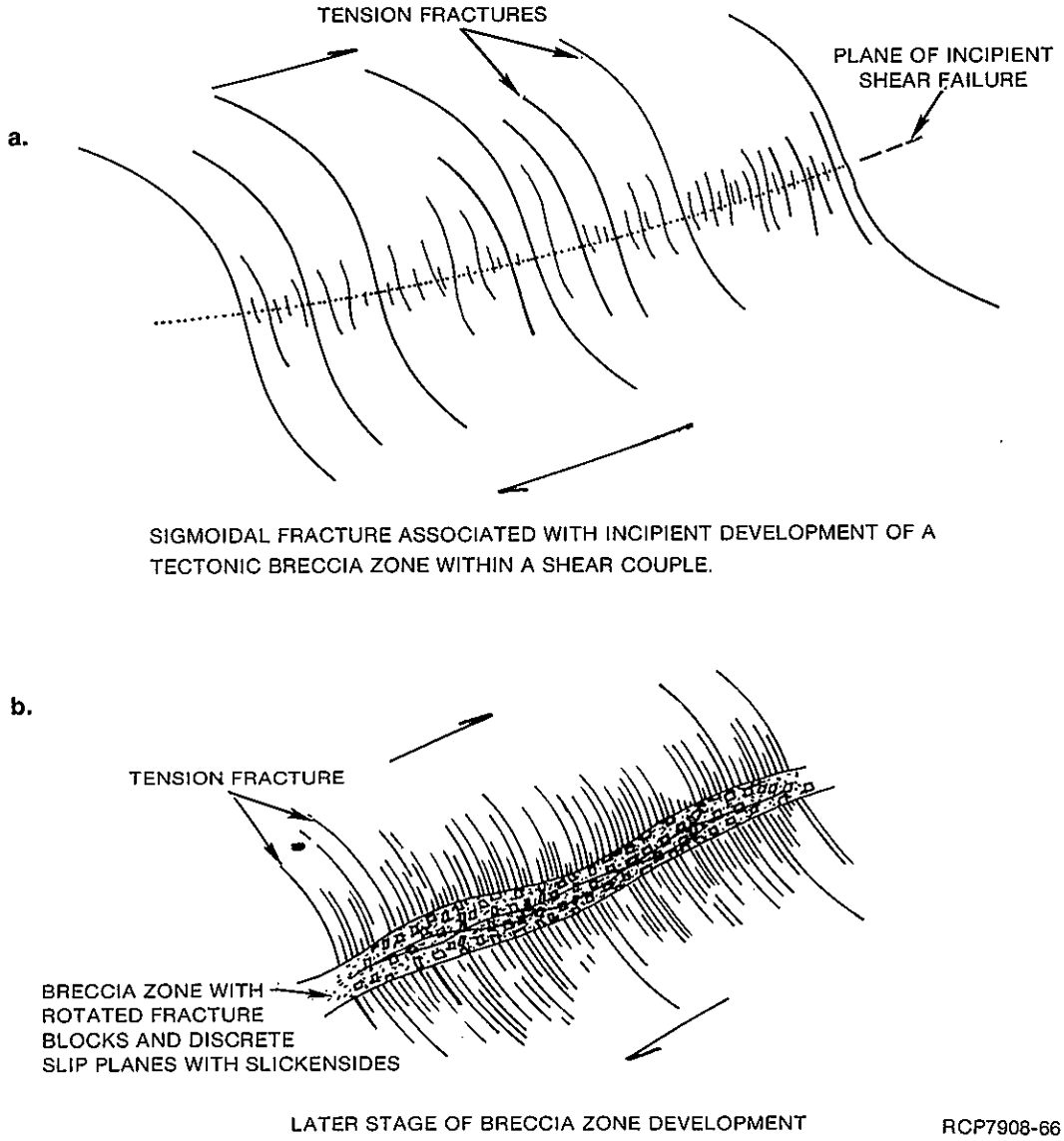

FIGURE III-69. Inferred Fault Breccia Zones and Tension Fracture Relationships. Note: Length of observed tension fractures can range from 1 inch to 50 feet (2.54 centimeters to 15.25 meters).

Discrete surfaces of slip locally are developed within some breccia zones. The surfaces usually are made up of intersecting slip "planes" which define three-dimensional triaxial lensoids (after Myers, 1968) within the breccia. Slickenside striae on the lensoid surfaces are parallel to the long axis of lensoids. Where fault plane surfaces have been parted, slickensided surfaces are undulatory, with undulation axes parallel to the slickenside lineation direction (Figure III-70).

Using a classical interpretation, movement directions determined from slickenside steps developed on the Umtanum Ridge slip surfaces would indicate opposing movement directions on a single surface. However, closer observation of the steps indicates two step varieties are present; one produced by the intersection of fractures with slip planes, and another produced by the accumulation of the fine-grained gouge on the slip surfaces. The latter is more common and the steps appear to oppose the direction of movement suggested by tension fractures.

Recent laboratory experimentation and field documentation by Gay (1970), Norris and Barron (1969), and Hobbs and Others (1976) show that slickenside steps can give the "wrong" sense of relative movement if the material composing the step is fine-grained gouge (the interested reader is referred to diagrams in these publications.) Asymmetry of the step in profile is produced by accreting crushed material onto the riser of a step. The facing directions of accretionary steps in fine-grained gouge from Umtanum Ridge always show the same orientation with respect to movement directions of any one tension fracture pattern. These relationships suggest that study of attitudes of tension fractures and accretionary steps may be a useful tool in recognizing and tracing major faults and in determining relative movement directions along faults. Care should be taken, therefore, in determining relative movement directions of faults in basalt from slickenside steps alone.

Distribution of Strain within the Umtanum Ridge Structure

Rock units within the Umtanum structure exhibit varying degrees of strain associated with varying amounts of flexure of the layering. Flows depicted in Blocks 1 and 4 of Figures III-65 and III-66 are only slightly folded and have undergone very little internal strain. Within 30 feet (10 meters) of the Buck thrust, the relative frequency of the curviplanar tension fractures which appear to be genetically related to the thrust increases.

Flows within Block 2 include part of the exposed hinge area of the anticlinal structure and are variably fractured into a tectonic breccia in regions of greatest curvature or near faults. Locally, within Block 2, zones of anastomosing tectonic breccia are so well developed that visual distinction between colonnade and entablature is often difficult. However, even in zones of extensive brecciation, the flow top and flow contacts generally have retained their coherency with respect to being identifiable flow features.

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FIGURE III-70. Slickensides Plunging Steeply Eastward in Vertical Layering.

The dominant strain displayed within Block 3 is extensive fault brecciation and secondary fracturing. Fault breccias generally are much thicker than in Block 2, have extensive slickensided and undulatory slip planes, and generally are vertical to south-dipping parallel to the layering. Fault zones commonly are developed at contacts between layers, but also occur within layering. Accretionary steps on gouge slip surfaces and slickenside lineations that plunge steeply east on the same slip surfaces indicate dip-slip movement, with the north side up along individual shears of Block 3. This extensively sheared block may be thinned tectonically with respect to its original stratigraphic thickness.

Numerous, small-displacement faults striking northeast or northwest occur within Blocks 2 and 3 and commonly cross the boundary between the two blocks. They are defined as discrete slip planes with slickensides dipping steeply toward the north or moderately toward the south, but oblique to layering. Such faults readily can be traced across individual outcrops, but are difficult to trace laterally for more than a few feet (meters).

9 2 1 2 1 9 4 1 7 2 3

Deformational Mechanisms

The three blocks of the Umtanum structure have had three different strain histories and thus have different mechanisms of deformation. Faulting parallel to layering within Block 3 (the short limb of the fold) is suggestive of flexural slip between or parallel to layering as the dominant deformational mechanism (Goff, in his work for Rockwell Hanford Operations). The brecciation of intraflow features without destruction of flow contacts within Block 2 suggests brittle behavior, but with a component of ductile bending as part of the mechanism for their origin. The longer, south limb of the fold (Block 1) and the area north of the fold (Block 4) are relatively undeformed. Numerous, small-displacement faults that cross block boundaries are interpreted to be related to a very late stage of the structural development or perhaps to later gravity adjustments.

Kinematic Model

Fracture patterns and lithologic offsets in the southern limb of the Umtanum fold (Figure III-66) indicate the south limb has been thrust generally toward the north, over the core of the fold (Farkas, 1972). The thrust zone itself is curviplanar, suggesting it is either folded or that it initially developed with a curviplanar geometry. The thrust transects folded layering, as shown in Figure III-66, implying that a large part of thrusting was post-folding and that it could have formed only in a compressional environment. The actual amount of crustal shortening is as yet undetermined, but it could be several times as great as that due to folding alone.

The reverse, "kink-like" geometry of the fold profile suggests that the mechanical anistropy of basalt layering resulted in buckling. Buckling that forms asymmetric kinks takes place only with a component

of flexural slip parallel to the flows of one limb and a component of internal strain due to the bending of each layer in the hinge zones. These relationships are shown in Figure III-71.

Slickenside lineations of Block 3 which plunge steeply eastward are shown diagrammatically in Figure III-72. The lineation directions indicate that shearing during folding was not simply a bending of flow layering perpendicular to the fold hinge direction, but that a component of right lateral shear between Blocks 1 and 4 was also involved. This right lateral shear implies, therefore, that bulk movement direction and local principal compressive stress directions were not exactly perpendicular to the fold hinge, but had a northwesterly component in this part of the fold. In this interpretation, Block 1 has moved to the west relative to Block 4. The various orientations of master joints (Sets 1 and 2) and shear fractures (Sets 3 and 4) suggest variations in the local stress regime within flow layering during progressive growth of the fold.

Depending upon the degree of anisotropy and rheological properties of the layering, shortening due to kinking reaches a maximum when the kink angle (angle α on Figure III-71) is approximately 60 to 80 degrees (Ramsay, 1967). The folds "lock up" and cannot develop further because of the high magnitude of shear strains required to thin the layering in the shorter limb. Further compression disrupts the continuity of layering by breaking (thrusting) in the mechanically weakest regions; i.e., the hinges. One of more faults typically develop.

From similarities in style of deformation between a theoretical kink and the Umtanum structure, it seems reasonable to suggest a developmental model for the Umtanum structure that involved "kink-like" buckling of layering under compression oblique to the fold hinge. When shortening reached its maximum, "lock-up" of folding occurred. Shortening then continued by overthrusting along at least three major shear zones which form the boundaries between the four blocks.

Features Projected into Unexposed Regions

Analysis of deformational mechanisms and the inferred kinematic model may allow projections of observed features into unexposed or poorly exposed parts of the Umtanum structure and into other Pasco Basin structures. These projections, however, are valid only for the above-interpreted deformation mechanisms and kinematic model, and for single-phase deformation which does not involve superposition of two or more structures.

Tectonic master jointing is recognized throughout the exposed part of the fold and should be present where the fold is unexposed. Aside from master jointing, the kink model predicts that the long, straight limbs of asymmetric folds should be relatively undeformed. Shorter, more steeply inclined layers should be highly sheared parallel or sub-parallel to flow layering. Hinge areas of folds whose layering is flexed beyond a small degree of curvature (exact amount undetermined) should be highly fractured and brecciated. In folds in which angle α

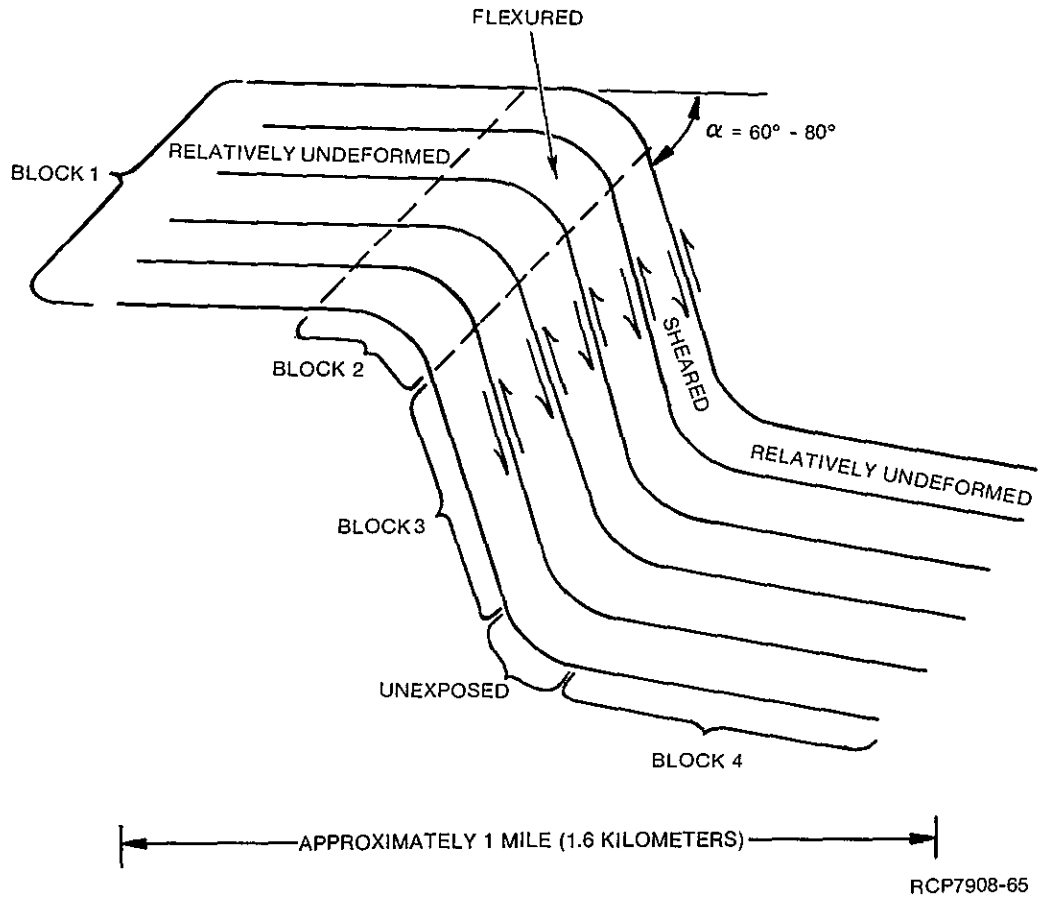

FIGURE III-71. Reverse Kink Geometry Model of the Umtanum Ridge Structure.

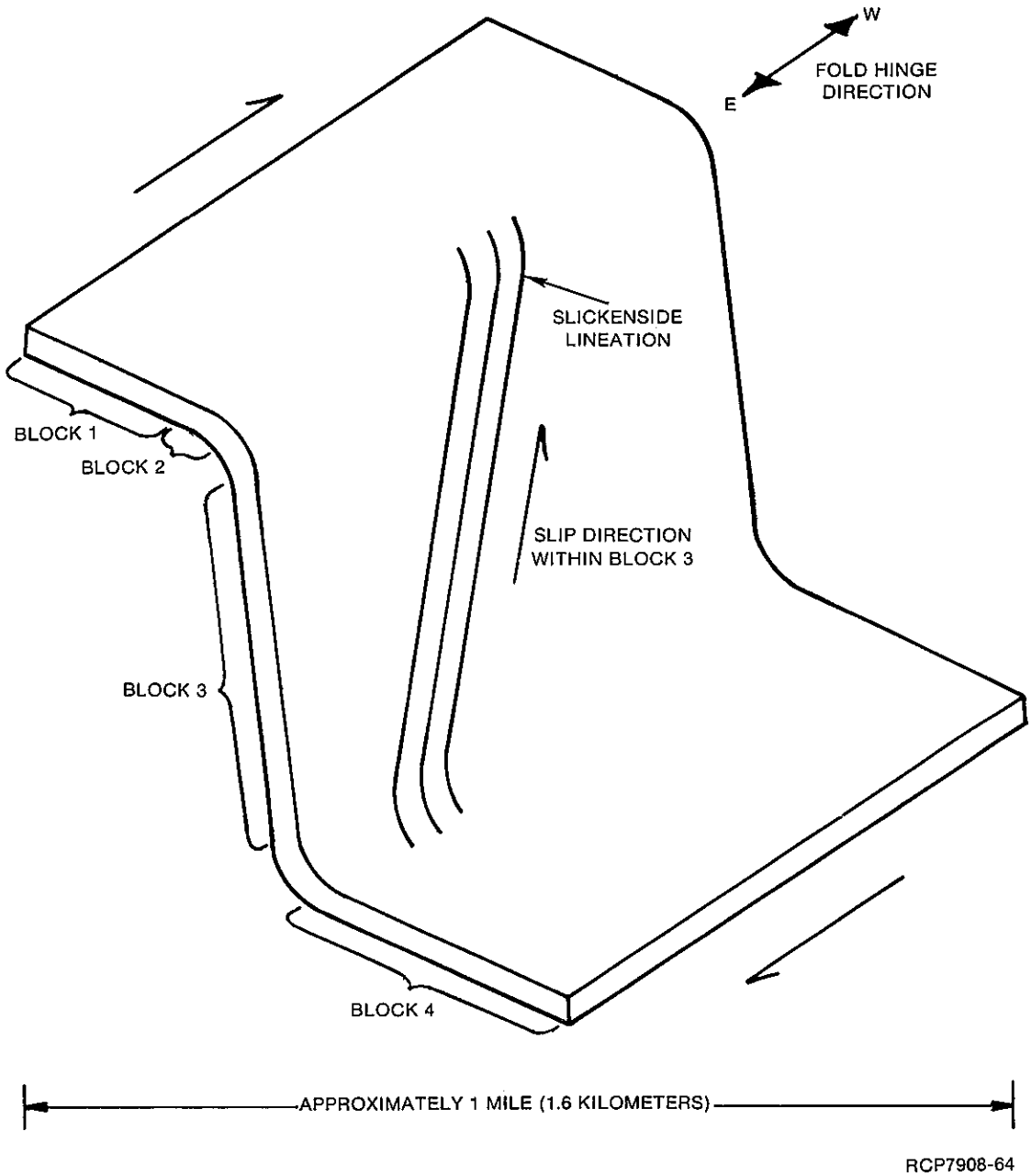

FIGURE III-72. Schematic Diagram Showing Relationship of Slickenside Lineations in Block 2 with Interpreted Relative Movement Directions of Blocks 1 and 4.

(Figure III-71) exceeds 60 degrees, major thrust faulting should be found. The model implies that for folds in which the southern limb dips approximately 10 degrees (as is common in the Pasco Basin), thrusting might be found in the structure if the northern limb dips 50 degrees or more.

The Buck thrust is parallel to flow layering of the longer, straight south limb, but movement along the thrust will have had to cease toward the hinge of the syncline paralleling Cold Creek (Plate III-1) because this structure is itself a separate fold.

Age of Deformation in the Umtanum Structure

The distribution of flows around and across the Umtanum anticline was interpreted by Goff and Myers (1978) to indicate that the phase of initial growth of the structure occurred before extrusion of the Umatilla Member and continued until after eruption of the Elephant Mountain Member. In the Filey Road area, Bentley during work for Rockwell Hanford Operations has found evidence indicating that most of this deformation involved Grande Ronde and Wanapum Basalts and that considerable erosion had taken place before emplacement of the relatively undeformed Pomona Member. These relationships, as interpreted in the Filey Road area, are shown in Figure III-73. No Quaternary-age tectonic deformation has been found in association with the Umtanum structure (Goff and Myers, 1978).

GEOMORPHOLOGY

The geomorphology of the Pasco Basin is discussed in relationships to regional geomorphology and to land systems or areas of recurring patterns of land forms within the basin. The Pasco Basin lies within the Yakima Folds and Central Plains sections of the Columbia Basin subprovince of the Columbia Plateau physiographic province (Freeman and Others, 1945) (Figure III-74). Within the basin, three major land systems are designated. These are: (a) ridge terrain, which includes ridge summits and upper ridge slopes; (b) lower slope terrain, which includes middle and lower ridge slopes; and, (c) basin and valley terrain, which includes fluvial plains and alluvial drainage channels (Figure III-75).

The Pasco Basin climate is influenced by the high Cascade Range to the west and prevailing direction of storm faults from the Pacific Ocean eastward over these high mountains. The orographic effect is dramatic, in that the region has relatively mild temperatures and is dry. There are occasional periods of high winds. Summers are generally hot and dry; most of the moisture comes during winters, which are relatively mild.

RIDGE TERRAIN

Ridge terrain consists of prominent anticlinal basalt ridges known as the Yakima Folds and is located in the Yakima Folds section of the Columbia Basin subprovince. Orientation of the folds is generally east-west, although there are also north-northwest- and northeast-trending

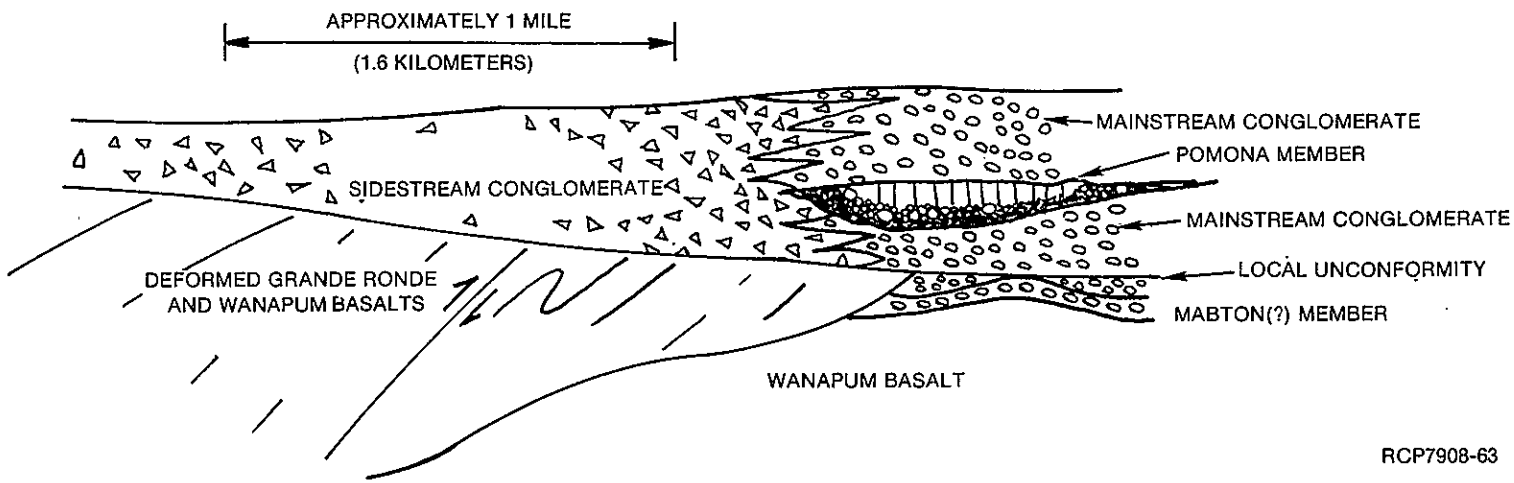

FIGURE III-73. Diagrammatic Cross Section of Part of the Filey Road Area. Sketch shows relationships of the Pomona Member and Ellensburg Formation conglomerates.

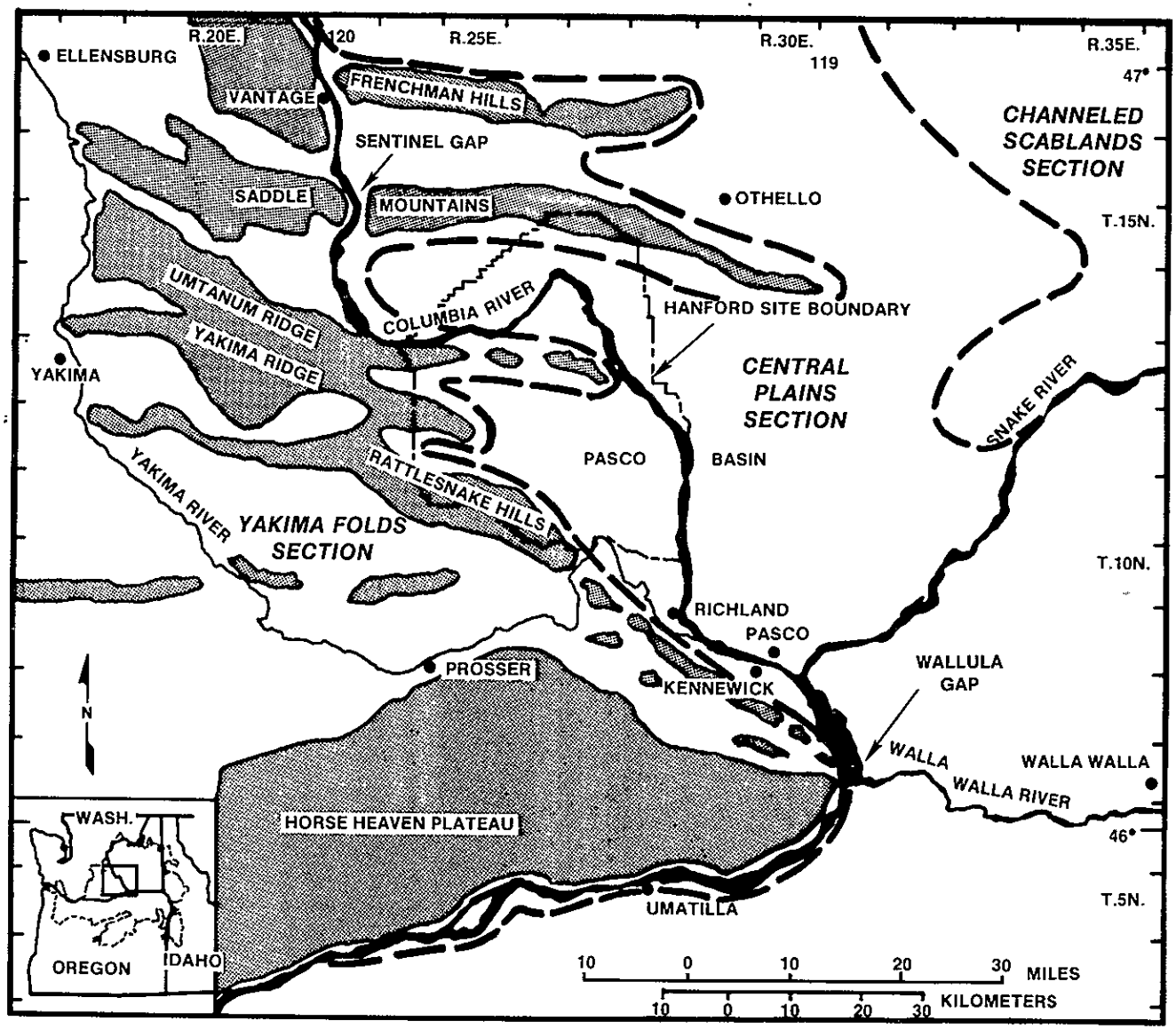

FIGURE III-74. Physiographic Provinces, Pasco Basin.

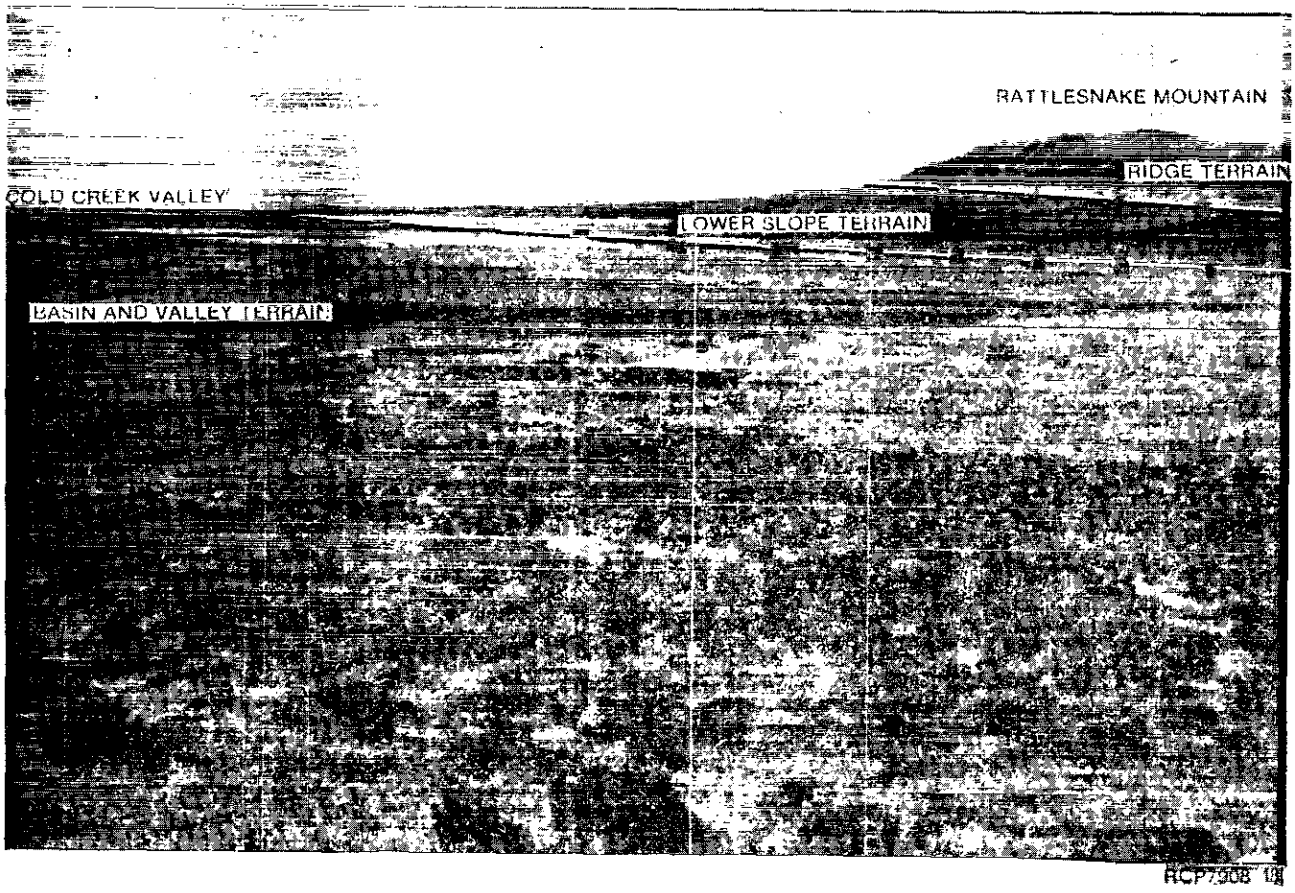

FIGURE III-75. Major Land Systems within the Pasco Basin.

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segments. These ridges are asymmetrical, with generally steeper northern flanks. Undulating topography and escarpments in the ridge terrain are often associated with second-order folds and minor faults which are common within the closure of major folds. The ridges are of tectonic origin, formed by endogenic forces.

Aggradation of the ridge terrain is minimal and consists predominantly of a thin veneer of loess which typically mantles the gentle, southern dipping slopes of ridges and the ridge summits.

Ridge terrain, with relatively high relief, is readily susceptible to denudation by various natural processes including weathering, erosion, and mass wasting. Due to the moderate, dry climate, weathering is a minor denudational agent in ridge terrain. Erosion and mass wasting are the most active processes.

Erosion of ridge terrain is principally by fluvial processes which have formed an extensive network of rills and gullies which form parallel and dendritic drainage patterns. Erosional escarpments are common along steeply dipping flanks and deeply incised gullies of the ridge terrain. Only minor alluvium occupies the rills and gullies. Extensive erosion has occurred at Sentinel Gap in the Saddle Mountains and Wallula Gap in the Horse Heaven Hills. In these areas, the Columbia River has cut water gaps, narrow gorges bounded by high basalt cliffs, through the resistant basalt ridges. During Pleistocene flooding, erosion of the water gaps was more intense, steepening slopes and enlarging the gaps at an increased rate.

Mass wasting of the ridge terrain is mainly by rockfall, debris flow, and block slump. Within the ridge terrain, escarpments and cliffs are the predominant landforms in areas of mass wasting. Some mass-wasted debris accumulates in the ridge terrain, but most accumulates in the lower slope terrain. During portions of the Pleistocene, frost action was more intense and mass wasting was accelerated.

LOWER SLOPE TERRAIN

The lower slope terrain predominantly consists of middle and lower slopes of anticlinal basaltic ridges of the Yakima Folds section, but also includes minor portions of the bounding Central Plains section. Landscape in this terrain is a product of both aggradational and degradational processes.

Aggradation of lower slope terrain results primarily from denudation of ridge terrain, although catastrophic flood deposits blanket portions of this terrain. Alluvial fans reach from the mouths of gullies in lower slope terrain and extend into basin and valley terrain. The interfluves in lower slope terrain are characterized by talus below cliffs and steep slopes or bedrock outcrop with a veneer of loess on gentle backslopes. Mass-waste debris commonly accumulates in this terrain and includes basaltic talus, hummocky mounds of basaltic debris, and slump blocks of basalt.

Catastrophic flooding of the Pasco Basin during the Pleistocene has aggraded portions of lower slope terrain with sediments of the Hanford formation. The most common facies of the Hanford formation in this terrain is the Touchet Beds, which occur along the lower slopes of the basaltic ridges bounding the basin. Bars composed of the Pasco Gravels facies are found in the lower slope terrain and are especially common in the southwestern Pasco Basin along the series of doubly plunging anticlines extending southeastward from Rattlesnake Mountain. Ice-rafted erratics and bergmounds, isolated mounds of diamicton deposited by grounded, debris-laden, ice bergs, commonly are found on the surface of Hanford formation sediments.

Degradation of lower slope terrain is mainly by fluvial processes and mass wasting. Erosion by fluvial action has incised gullies which are commonly deeper than those of the ridge terrain and are partially filled with basalt and interbed debris. Drainage patterns are dendritic and parallel, and are controlled predominantly by the geometry of the ridge slopes. Denudation by mass wasting is similar to that of ridge terrain, but not as extensive.

BASIN AND VALLEY TERRAIN

Basin and valley terrain consists of the low, sediment-filled portion of the Pasco Basin in the Central Plains section and synclinal valleys of the Yakima Folds section. The Pasco Basin is a structural and topographic basin formed contemporaneously with the Yakima Folds. In this terrain, the Columbia, Snake, and Yakima Rivers, late Pleistocene catastrophic floods, and short-lived ephemeral streams have aggraded sediments which increase in thickness toward the center of the basin. Also, eolian processes have aggraded an extensive network of sand dunes. Denudation by fluvial, eolian, and mass-wasting processes in this terrain are relatively minor, although the rate of eolian denudation is increasing locally because of farming and industry.

The landscape of the basin and valley terrain up to about 1,100 feet (335 meters) in elevation is dominated by effects of late Pleistocene catastrophic floods. Aggradational landforms resulting from this flooding include sheet deposits, flood bars, current ripples, and bergmounds.

Sheet deposits are common both in Touchet Beds and Pasco Gravels and form broad plains of thick, sedimentary sequences in extensive portions of the Pasco Basin. Surfaces of these plains locally are modified by abandoned flood channels, present-day river channels and flood plains, flood bars, current ripples, and bergmounds.

Another common landform related to late Pleistocene catastrophic flood events in the basin and valley terrain is subfluvially deposited bars. Two major types of flood bars associated with main channel deposits occur in the Pasco Basin. Based on the nomenclature of Baker (1973), these are: (a) expansion bars in which flood gravels occur as a result of decelerating flow of an expanding reach downstream from a

channel constriction; and, (b) pendant bars in which flood gravels occur immediately downstream from bedrock projections. Large expansion bars occur on Wahluke Slope south and east of the Sentinel Gap constriction and south of constrictions flanking Gable Butte. Prominent pendant bars occur at many places, including: (a) south of the hill west of Scooteney Reservoir in the northeastern Pasco Basin; (b) southeast of Gable Mountain and Gable Butte in the basin interior; and, (c) along a series of doubly plunging anticlines of the Rattlesnake Hills in the southern portion of the basin.

Giant current ripple marks often are associated with expansion bars and sheet deposits of the Pasco Gravels. Well-developed current ripples consisting of patterns of alternating parallel ridges and swales have been recognized by examination of aerial photographs of the Wahluke bar, in channels both north and south of Gable Butte, and north of the horn of the Columbia River (Baker, 1973; Lillie and Others, 1978). Poorly developed current ripples forming a chaotic series of closely spaced mounds have been recognized northeast of Gable Butte and south of the horn of the Columbia River.

Bergmounds commonly overlie Touchet Beds and bedrock on the western and southern margins of the Pasco Basin (Bretz, 1930; Fecht and Tallman, 1978). Bergmounds commonly occur in clusters of mounds with ice-rafted erratics scattered between the mounds.

Floodwater sculptured the landscape throughout the basin and valley, forming an extensive network of abandoned flood channels and coulees, terraces, and scabland. Abandoned floodwater channels and coulees were the main channels of late Pleistocene floods. Abandoned flood channels are shallow with gently sloping banks; coulees are deeply incised and steepsided. Abandoned floodwater channels are common through the Pasco Basin, but are best defined in an area of anastomosing channel ways in the vicinity of Gable Mountain and Gable Butte (Fecht, 1978). Floodwater coulees are confined to the eastern portion of the basin and valley terrain. Floodwaters flowing across eastern Washington eroded deep channels into the basalt and Ringold sediments to form a series of generally northeasterly trending coulees. Major coulees along the eastern margin of the Pasco Basin are shown in Figure III-76.

In the northwestern portion of the Pasco Basin, floodwater terraces occur above the present Columbia River channel. These terraces flank and parallel the present channel southeast of Sentinel Gap and north of the Columbia River east of Priest Rapids Dam. The terraces represent a series of dissected floodwater channel remnants that were produced by erosion during late stages of catastrophic flooding as waters receded from the basin.

Floodwaters entering the northeastern portion of the Pasco Basin from the Quincy Basin scoured structurally deformed basalts on the southeast end of the Saddle Mountains. The resulting landscape is the scablands of the Othello Channels (Bretz, 1923) and other areas of minor

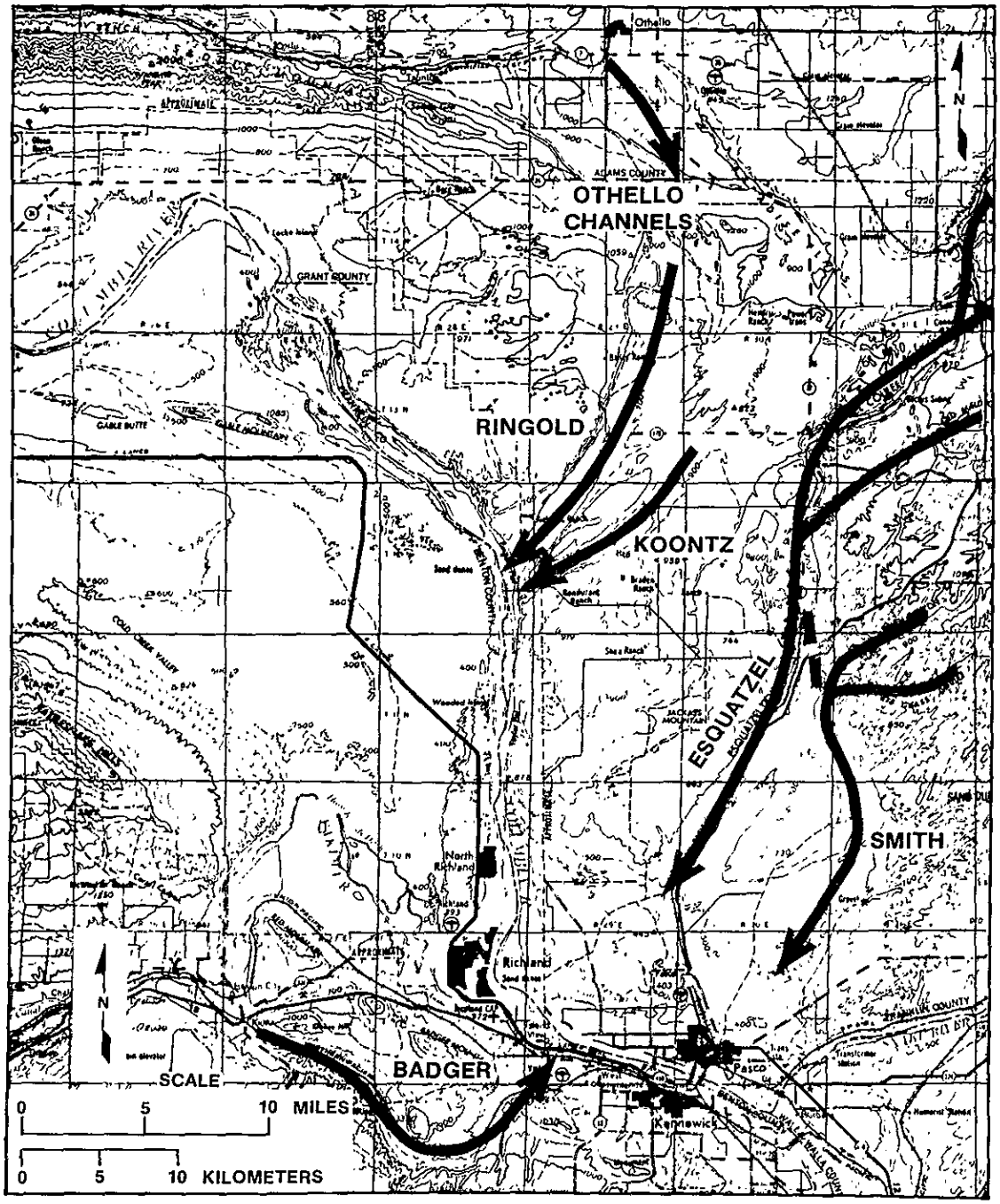


FIGURE III-76. Major Coulees in the Pasco Basin. All except Badger Canyon were eroded by Pleistocene floodwaters (see text for discussion of Badger Canyon).

scabland south to Esquatzel Coulee. Scablands also occur near Chandler, Washington where floodwaters inundated the Yakima Valley. Most other areas of the basin and valley terrain are aggraded sequences of subfluvially deposited sediments.

A remnant Pliocene plain of Ringold sediments which crop out above extensive catastrophic flood deposits occurs in the northeastern portion of the Pasco Basin. The western margin of the plain is limited by the abrupt slope of the White Bluffs along the Columbia River. The plain, which is largely depositional, consists of relatively undeformed sediments, locally deeply incised by catastrophic floodwaters. Incision of the plain by fluvial processes generally follows northeasterly trends of the floodwater channels. However, a series of erosional gullies in the White Bluffs between Ringold and Taylor Flats have northwesterly trends (Figure III-76).

The basin and valley terrain is principally an accumulation area of sediment deposition. Minor, local denudation by fluvial erosion and mass wasting has occurred. Fluvial erosion was most extensive during late Pleistocene flooding, but Holocene erosion has also occurred along the rivers draining the Pasco Basin. Mass wasting in the form of landslides occurs along the White Bluffs.

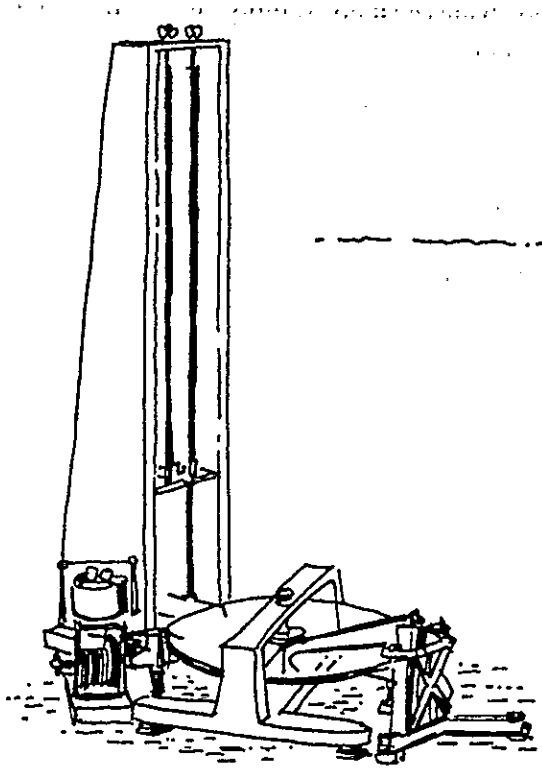
The Pasco Basin is drained by the Yakima, Snake and Columbia Rivers, each of which has maintained approximately the same course since at least late Pleistocene time. Degradation of the river channels has primarily been incision into their present channels. However, portions of the rivers have undercut their banks, resulting in steep, abrupt river banks (e.g., White Bluffs). Portions of the floodplains of the Yakima and Columbia Rivers have been eroded by moderately extensive lateral planation. Construction of dams during the past few decades has moderated fluvial erosion by these rivers.

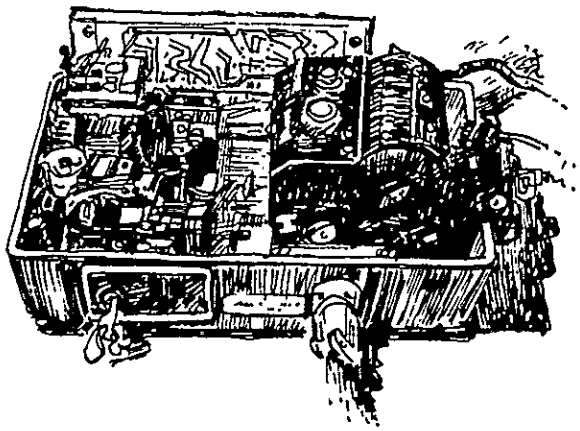
Badger Canyon in the southern portion of the Pasco Basin is a coulee, but was not eroded by late Pleistocene flooding (Figure III-76). Badger Canyon is an abandoned Yakima River channel, filled at least in part by flood sediments. These sediments partially filled the coulee and are apparently responsible for diverting the Yakima River to its present course.

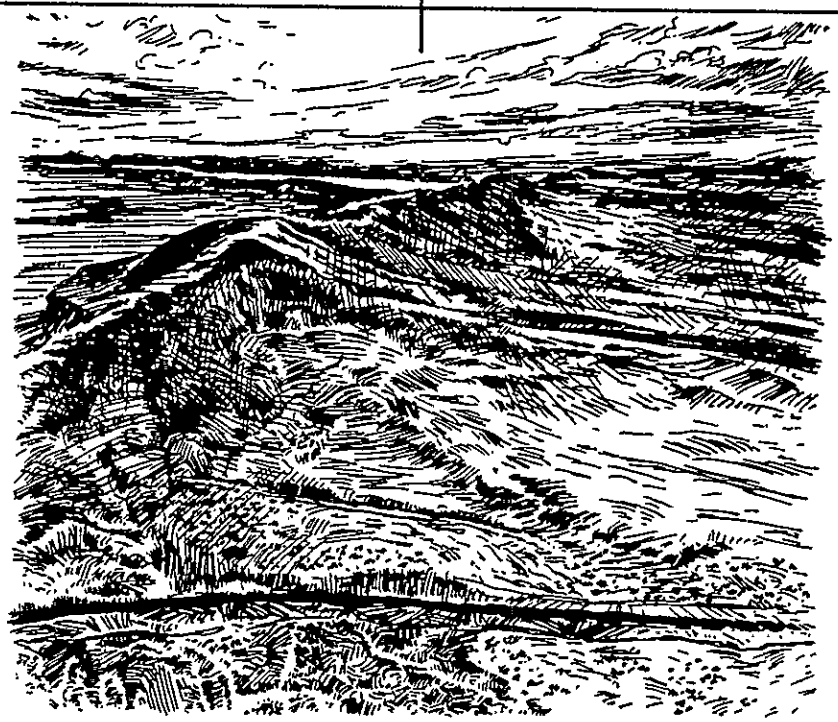
Basalt debris eroded from gullies in the ridge and lower slope terrain accumulates as alluvium in the basin and valley terrain. The most common landform resulting from this accumulation is alluvial fans. Alluvium also accumulates on flood plains and as bars along reaches of the Columbia, Snake, and Yakima Rivers, but is generally limited to immediate river margins and channels.

Extensive surface areas of the basin and valley terrain are mantled by Holocene-eolian deposits of loess and sand dunes. The most extensive network of eolian deposits is the semi-stabilized longitudinal dunes which blanket most of the southern half of the Pasco Basin. These dunes trend northeast, paralleling the strongest wind direction. The northern margin of these dunes is active and terminates to the east near Ringold Flats in a barchan dune colony. Elsewhere in the Pasco Basin, loess, sand, and other minor sand dune colonies veneer the land surface.

SEISMICITY AND TECTONICS







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CHAPTER IV
SEISMICITY AND TECTONICS

INTRODUCTION

One of the major concerns in selecting a site for a radioactive waste repository is the tectonic stability of the area and, in particular, the boundaries of stable tectonic blocks and rates of deformation. An assessment that permits some judgments about the stability of a repository over a period of confinement of radioactive isotopes can best be made by looking at indicators of present levels and patterns of tectonic activity, primarily seismicity, and reviewing the tectonic development of the Columbia Plateau and region over the past few million years.

The first part of this chapter is a review of the seismicity of the Pacific Northwest, primarily the Columbia Plateau. Records of earthquakes in the Pacific Northwest (Appendix F) go back to about 1850, but early records are very qualitative and permit only general indications of stress release in the Columbia Plateau and region. While earthquake data provide valuable information, the period of earthquake records in the Pacific Northwest is brief; therefore, geologic evidence of stability, especially during the Quaternary (Allen, 1975) is being evaluated.

A network of seismographs that enables reasonably precise locations of earthquakes appeared only in the last two decades when the need to monitor nuclear test detonations accelerated the attainment of a capability to detect and locate all types of seismic events. In this chapter, the literature on earthquakes for the Columbia Plateau and region is reviewed with emphasis on the frequency, magnitude, and pattern of stress release. The deployment of an eastern Washington regional seismograph array that began in 1969 with the establishment of a Hanford network enhanced detection and location capabilities and has considerably expanded knowledge of stress release in the Columbia Plateau.

Earthquake data are useful for assessing tectonic stability and can assist in understanding the tectonic evolution of the Columbia Plateau and region. Focal mechanism solutions for the area are reviewed as an indication of the orientation of the extant stress field and as a clue to geologic structures not exposed at the surface. Earthquake monitoring will continue in an expanded network, and down-hole arrays are planned.

A tripartite effort addressing the tectonic evolution of the Columbia Plateau and its tectonic stability was initiated by Rockwell Hanford Operations. This effort consists of: (a) a literature survey of regions surrounding the plateau to examine rock types and structures that may be present beneath the basalt and to better understand the regional tectonic framework of the plateau (Appendix G); (b) a review of the literature on interaction of lithospheric plates and intraplate blocks with emphasis on ages and patterns of deformation (Appendix H); and, (c) preliminary

interpretations of the tectonic development of the Pasco Basin based on observations and current thinking. Now that details of stratigraphy and structure are becoming known, the effort to assess tectonic stability and, in particular, the boundaries of stable tectonic blocks is being accelerated. With this expanded effort, more information on the tectonic stability of the Columbia Plateau will be available for the Site Characterization Report.

SEISMICITY SUMMARY

SEISMICITY DATA

Procedures and sources used in compiling earthquake records affect the quantity and quality of data used in preparing earthquake catalogs and in constructing epicenter and hypocenter maps and cross sections. Rockwell Hanford Operations has made use of a comprehensive catalog of earthquakes compiled by Woodward-Clyde Consultants for the Pacific Northwest (44 to 54 degrees north, 110 to 128 degrees west). The history of earthquake recording activities in the Columbia Plateau is presented in Appendix F. Epicenter maps were prepared by Woodward-Clyde Consultants in the region 44 to 49 degrees north, 115 to 125 degrees west at a scale of 1:2,000,000. In order to present major elements of earthquake data, several epicenter maps were selected. Figures IV-1 and IV-2, respectively, are epicenter maps of all earthquake data in the catalog for events less than 6 miles (10 kilometers) focal depth and for events with hypocenters at depths of 6 miles (10 kilometers) or more. Figures IV-3 and IV-4 are epicenter maps for the period 1965 to present and include all events greater than magnitude 3.0 with, respectively, focal depths less than and greater than or equal to 6 miles (10 kilometers). Figures IV-5 and IV-6 are cross sections at a scale of 1:2,000,000 along the 47.5-degree-north parallel and show events projected from within the area 45.5 to 49.5 degrees north. Figure IV-5 is a cross section showing events greater than magnitude 3.0; while Figure IV-6 displays all events greater than magnitude 2.0 for which a focal depth has been determined.

More than 20 sources were used in the compilation of the catalog used to plot these earthquake maps and cross sections; therefore, the quality of data shown is not uniform. Events reported as intensities reflect uncertainties discussed in Appendix F. Even for instrumentally recorded events, accuracy of location reflects the number and distribution of stations recording the event and the quality of the records of ground motion. An accurate focal depth is the earthquake information most difficult to obtain with precision. Focal depths can accurately be determined only for those events in which the focal depth does not exceed distance to a recording site. Therefore, detection of very shallow events requires closely spaced recording stations in order to obtain accurate depths. A large number of events on Figure IV-5 appear to occur at the surface. These events, however, did not occur at the surface, but are plotted there by the plotting program when the focal depth is unknown. That cross section illustrates that many events listed in catalogs are not precisely located. Because many earthquakes in eastern Washington are shallow (1.8 miles [less than 3 kilometers]), swarm events, closely spaced stations are necessary before an accurate location can be determined.

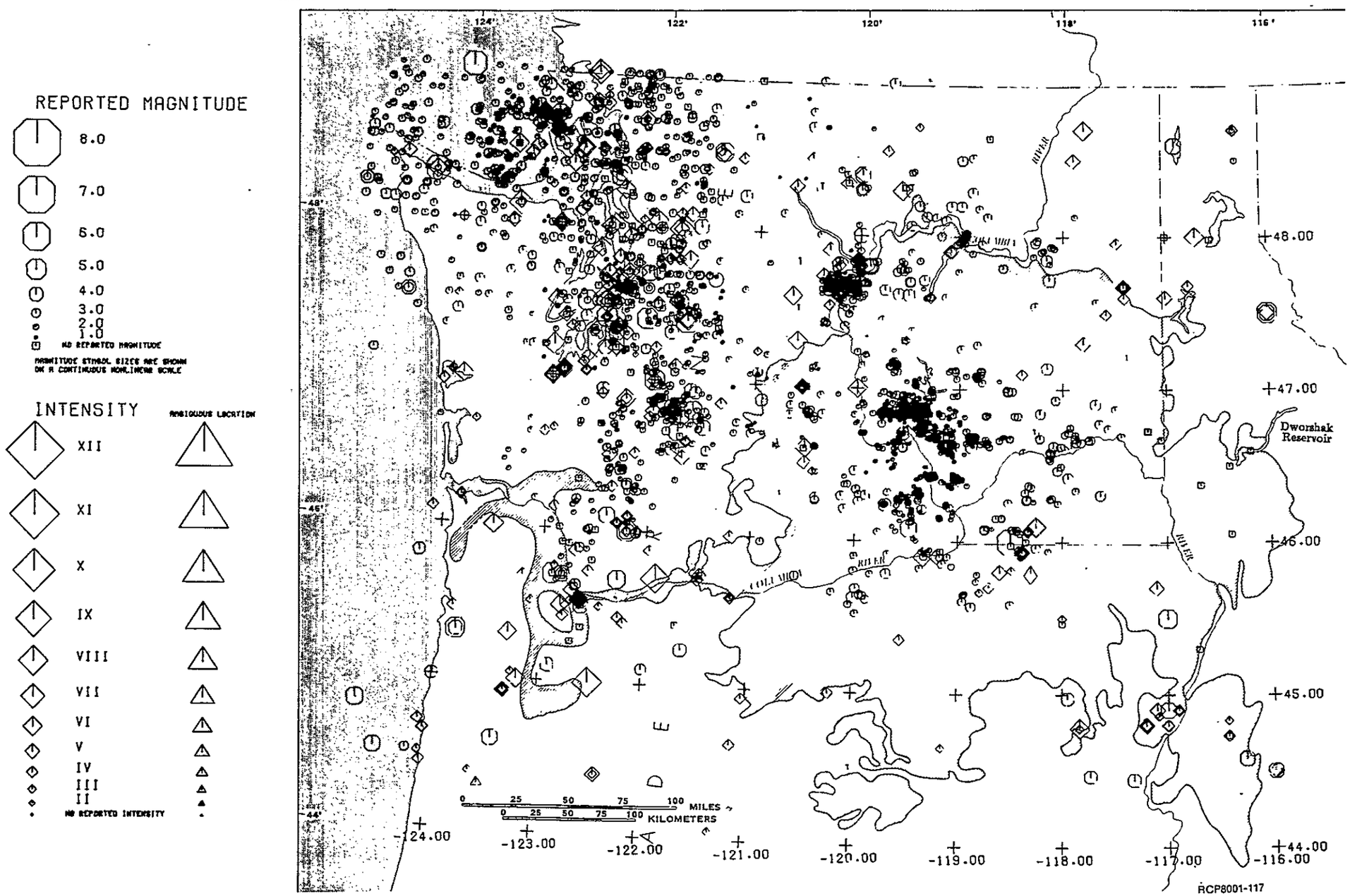

FIGURE IV-1. Historical Earthquakes with Hypocenters Less than 6 Miles (10 Kilometers) Deep.

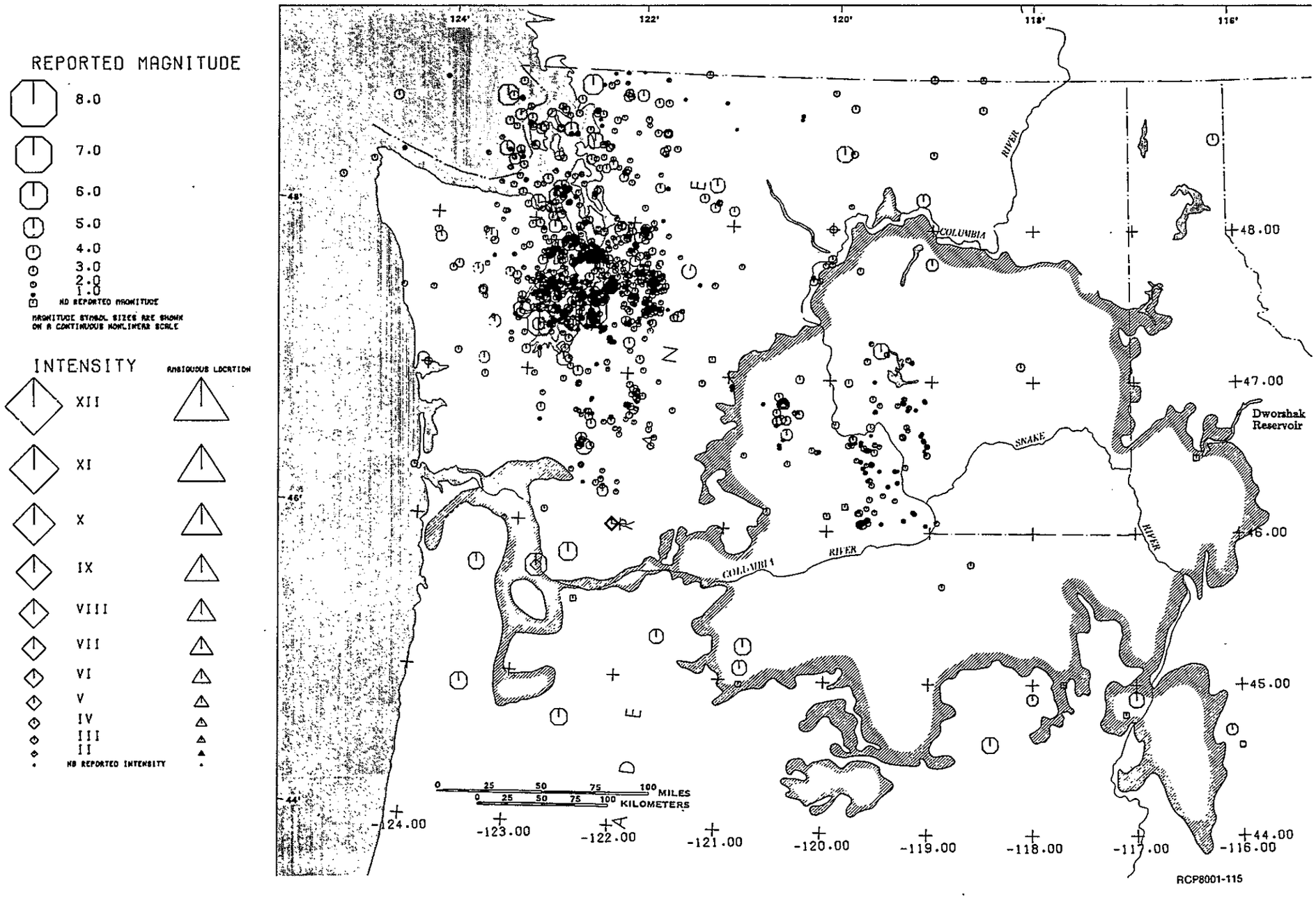

FIGURE IV-2. Historical Earthquakes with Hypocenters Equal to or Greater than 6 Miles (10 Kilometers) Deep.

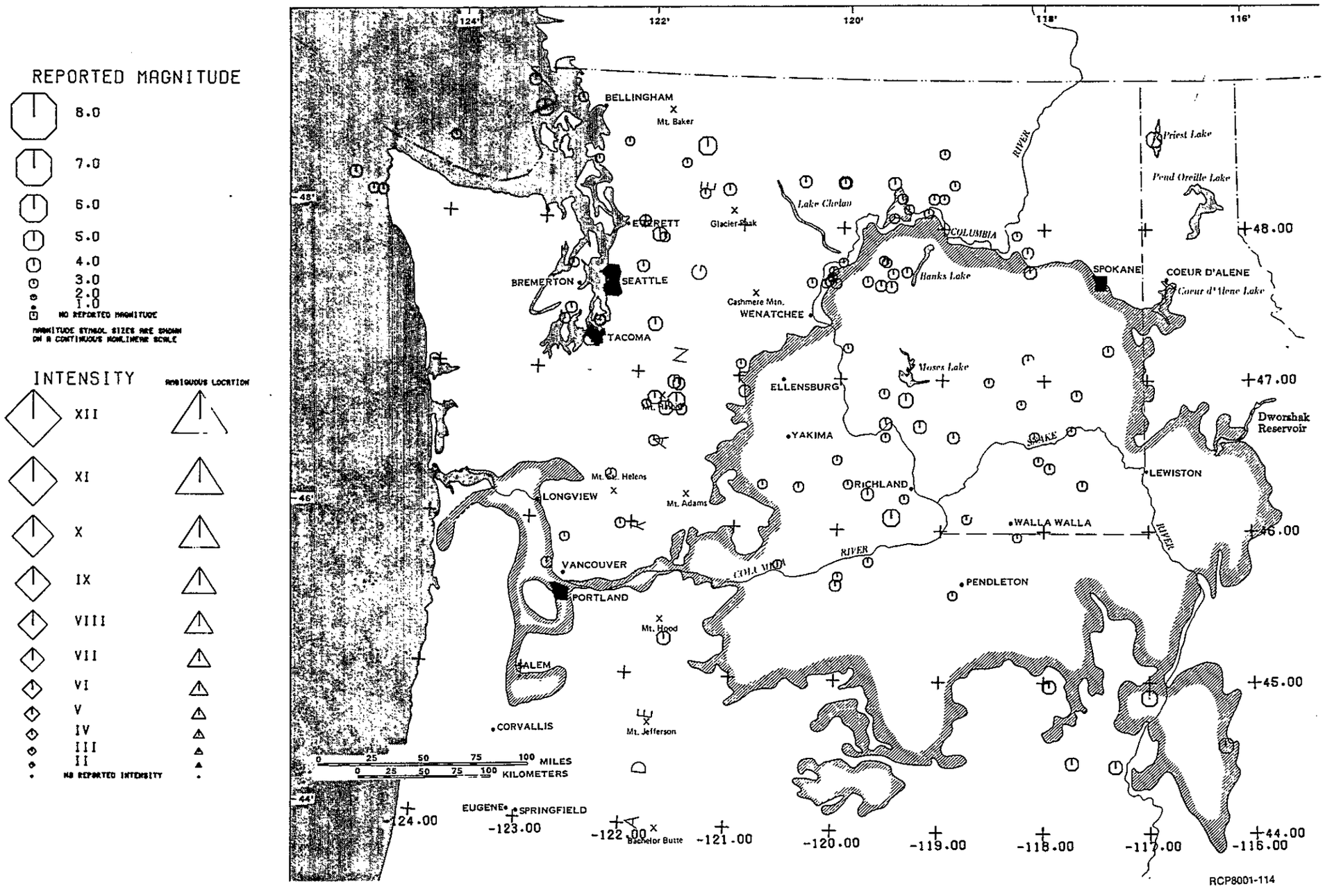

FIGURE IV-3. Earthquake Epicenters for Period 1965 and Later with Hypocenters Less than 6 Miles (10 Kilometers) Deep.

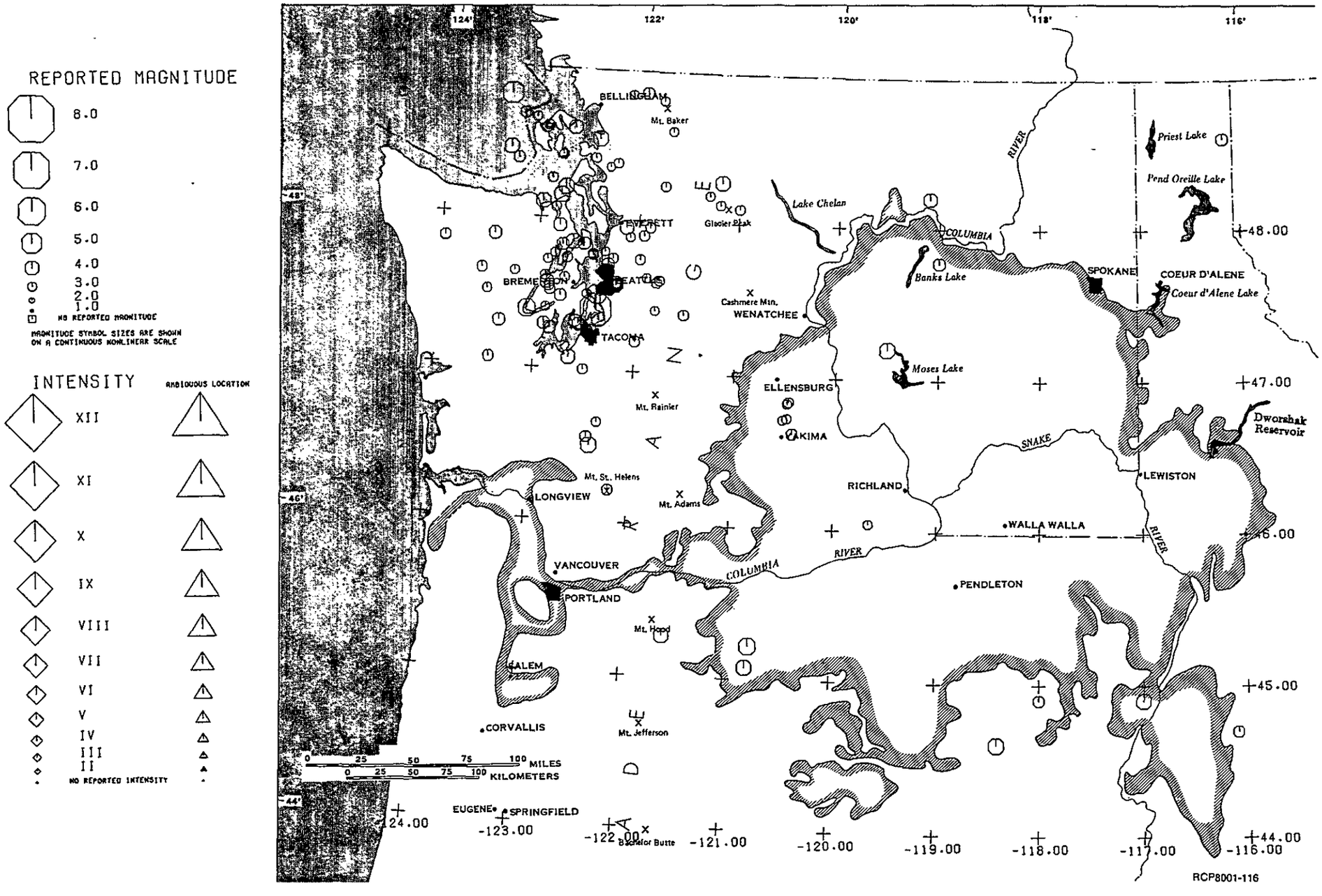

FIGURE IV-4. Earthquake Epicenters for Period 1965 and Later with Hypocenters Equal to or Greater than 6 Miles (10 Kilometers) Deep.

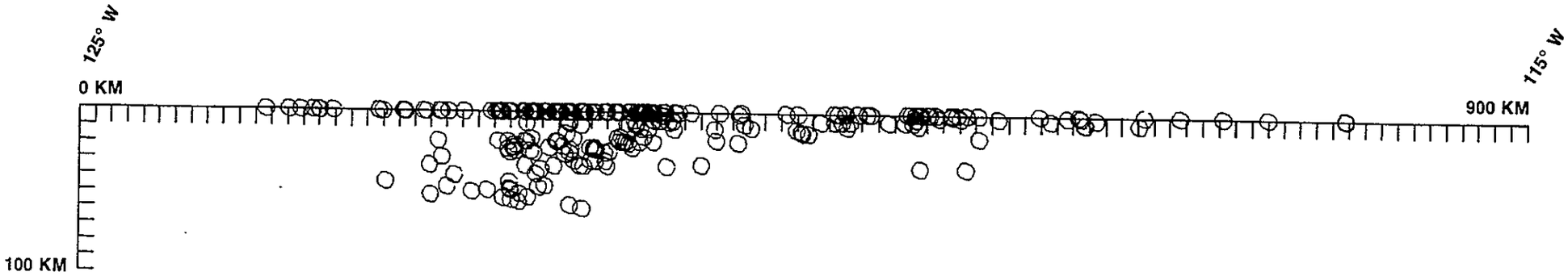

FIGURE IV-5. Cross Section along 47.5 Degrees North Showing All Events Greater than Magnitude 3.0. Earthquakes are projected from 2 degrees north and south of selected parallel between 115 and 125 degrees west.

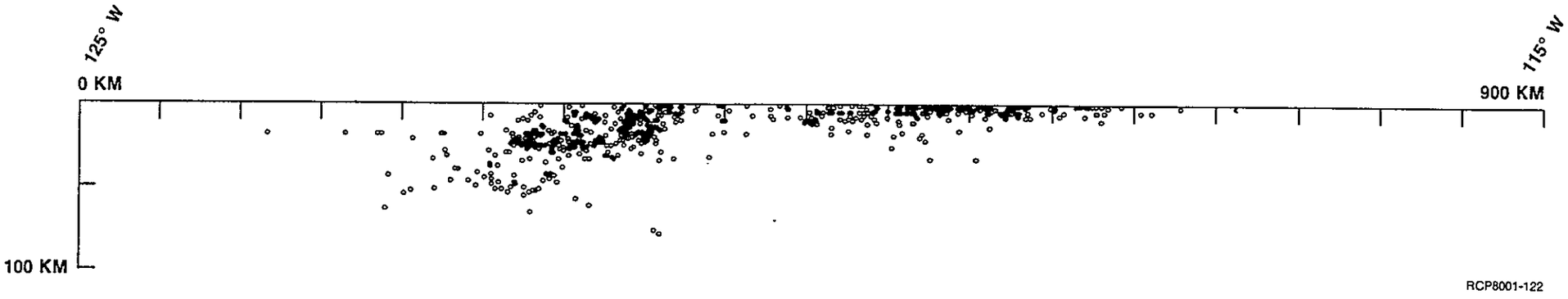

FIGURE IV-6. Cross Section along 47.5 Degrees North Showing All Events Greater than Magnitude 2.0 for which a Focal Depth Has Been Determined. Earthquakes are projected from 2 degrees north and south of selected parallel between 115 and 125 degrees west.

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DISCUSSION

Although data presented in Figures IV-1 through IV-6 vary in quality, these figures are nevertheless illustrative of patterns of activity and the contrast in stress release over the area shown. Clearly, the Puget Sound Lowland is an area of much greater earthquake activity than the Columbia Plateau in terms of total number of earthquakes reported, greater size and frequency of events, and greater focal depth of events. Although events throughout Washington State are generally shallow (less than 43 miles [70 kilometers]) and are confined to the crust, known events in eastern Washington State have occurred at depths of less than 18 miles (30 kilometers); whereas events in the Puget Sound Lowland have occurred to depths of about 55 miles (90 kilometers). Activity in eastern Washington State is mostly restricted to swarms of very shallow (less than 1.8 miles [3 kilometers]) focal depth.

Seismicity of the Columbia Plateau

The Columbia Plateau is an area of low seismicity (Berg and Baker, 1963; Couch and Lowell, 1971; Rasmussen, 1967). Historic earthquakes have been felt in only a few areas and have been small, except for two moderate-sized events; one of questionable size in 1893 and the other in 1936. An earthquake occurred near Umatilla, Oregon at 5:03 p.m. on March 7, 1893 (it may have been March 6, 1893 according to Berg and Baker, 1963). The felt area and damage were restricted mostly to Umatilla, Oregon. Newspapers from Pendleton, Oregon (34 miles [55 kilometers]) to the southeast and other towns in the vicinity did not report this event. One wall of a large stone warehouse in Umatilla, Oregon fell during this event; this earthquake was assigned a Modified Mercalli intensity VII. The local extent of the earthquake (Coffman and von Hake, 1973) suggested that its intensity was less than VII. Based on a probable limit of the felt area, it has been considered to be a maximum Modified Mercalli intensity VI (WPPSS, 1974).

The largest known earthquake in the Columbia Plateau occurred at 11:08 p.m. (local time) on July 15, 1936, when the area near Milton-Freewater, Oregon was shaken by a magnitude 5.75 earthquake. This earthquake was felt over an area of about 105,000 square miles (273,000 square kilometers) and was accompanied by a number of foreshocks and aftershocks (Rasmussen, 1967; Coffman and von Hake, 1973). The main event knocked down several chimneys, affected ground-water flow, and caused ground cracking near Walla Walla, Washington (Brown, 1937). Based on these accounts, this earthquake has been considered a large Modified Mercalli intensity VII. A number of small earthquakes (less than Modified Mercalli intensity V) have occurred in the area around Milton-Freewater, Oregon and Walla Walla, Washington, but most have not been instrumentally recorded. On April 7, 1979, at 11:28 p.m., local time, an earthquake occurred at about 46° 59.6' North, 118° 26.2' West, just south of College Place, Washington. This event was shallow, 1.8 to 3.7 miles (3 to 6 kilometers) in depth, about a magnitude 4.0, and was the largest event recorded in the area of the 1936 Milton-Freewater earthquake since the deployment of the eastern Washington State seismic recording network (Malone, 1979).

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Jones and Deacon (1966) postulated that the magnitude 5-3/4, July 15, 1936 Milton-Freewater earthquake was associated with the "Rattlesnake Mountain-Wallula-Milton-Freewater fault system." In the absence of definitive geologic evidence to the contrary, the Rattlesnake Mountain-Wallula alignment was accepted as a capable structure for the purpose of developing seismic design criteria for nuclear generating plants at Hanford (Blume and Associates, 1971). The northeast trend of isoseismals and the aftershock zone of the 1936 event were cited as evidence for association of this earthquake with the Blue Mountain uplift or the Hite fault by the Washington Public Power Supply System, Inc., but they nevertheless also accepted this feature as capable in the absence of clear evidence to the contrary (WPPSS, 1974). Figures IV-1 through IV-4 reveal no clear alignment of epicenters along the Rattlesnake Mountain-Wallula alignment, or along the entire Olympic-Wallowa Lineament. Events have occurred along the lineament, but in no greater numbers or concentrations than elsewhere in the vicinity. Figures IV-3 and IV-4 do not suggest the presence of the feature either in shallow (less than 6.2 miles [10 kilometers]) or deep events (greater than 6.2 miles [10 kilometers]). Certainly, there is no clear definition of an active structure from microearthquakes such as is true in California (Bufe and Others, 1977).

Because the area between Walla Walla and Milton-Freewater has been the scene of several felt earthquakes, Woodward-Clyde Consultants installed a microearthquake monitoring array in this area for United Engineers and Constructors (Withers and Others, 1978). The array was deployed initially in the epicenter area of the July 15, 1936 Milton-Freewater earthquake, but subsequently was relocated along the northwest flank of the Blue Mountains. No local earthquakes (secondary primary time of less than 10 seconds) were recorded; only a few blasts and teleseisms were detected.

Earthquakes of smaller size have been felt in and along the margins of the Columbia Plateau near Corfu, Yakima, Ellensburg, Wenatchee, and the Chelan-Entiat area, Washington. An earthquake occurred in the vicinity of the Saddle Mountains near Corfu on November 1, 1918. The epicenter of this earthquake is reported as 46.7° North, 119.50° West (Coffman and von Hake, 1973), which is on the south flank of the Saddle Mountains in the 100-H Area of the Hanford Site. Reports of this event suggest a location on the north side of the Saddle Mountains near Corfu (48.8° North, 119.5° West). Because this event was not instrumentally located, the compiler of an earthquake catalog probably intended the town nearest the point of maximum effects to be the epicenter, but a typographical error occurred somewhere in the process of compiling a catalog (Fifer, 1966). The original report (Anonymous, 1918) classified this event as a Rossi-Forel intensity IV which would be equivalent to a Modified Mercalli intensity IV. The currently listed intensity of V-VI may also be a typographical error (Fifer, 1966). Jones and Deacon (1966) hypothesized that active faulting and formation of a graben occurred on the north flank of the Saddle Mountains during this event, a hypothesis rejected by Jahns (1967) and Bingham and Others (1970). Corfu is one of several areas along the north flank of the Saddle Mountains in which earthquake swarms have been recorded in the past decade. As discussed later in this chapter, all of these events have been small, shallow-focus events, most of which have been below magnitude 2.0.

A number of small earthquakes (less than Modified Mercalli intensity V) have occurred and been felt in or along the flanks of the Columbia Plateau (WPPSS, 1974). A series of about 30 earthquakes occurred near Ellensburg, Washington between September 8 and December 2, 1934, the largest of which was Modified Mercalli intensity V (WPPSS, 1974). Other felt events have occurred near Ellensburg, the most recent of which occurred on August 13, 1977 and had a local magnitude of 3.6 (Stover and Others, 1979). Other felt earthquakes have occurred near Athena, Milton-Freewater, Hermiston, McNary, and Pendleton, Oregon, and Chelan, Ritzville, Othello, Wapato, and Roosevelt, Washington (WPPSS, 1974). A catalog of felt earthquakes through December 1973 is included in WPPSS (1974).

Since 1969, capability to instrumentally record and locate earthquakes has permitted a more quantitative assessment of seismicity compared with that determined from felt earthquakes. Initially, this capability was achieved along the borders of the Hanford Site where the original six stations were deployed. The network subsequently expanded and now covers all of eastern Washington State. All earthquakes greater than magnitude 2.5 (1.5 near the Hanford Site) are detected and located. Events as small as magnitude 0 can be located under favorable circumstances (Malone, 1977).

Shallow, spatially, and temporally restricted swarms of low-magnitude earthquakes are characteristic of the Columbia Plateau (Malone and Others, 1975; Bingham and Others, 1970; Rothe, 1978). These earthquakes range in magnitude from less than 0 to about 4.0, but most are less than magnitude 2.0. The focal depth of most events is less than 1.8 miles (3 kilometers). The typical pattern of earthquake swarms consists of several hundred to over 1,000 events (one-half to two-thirds of which are too small to locate) that occur in a restricted volume of generally less than 31 cubic miles (50 cubic kilometers) within a period of a few to several months. Within any one swarm, there is no major event preceded by a series of gradually increasing (in size) foreshocks and followed by a series of aftershocks that decrease in size and frequency. Plots of epicenters and hypocenters are not aligned along a plane or planar zone.

Portable seismometer arrays, consisting of several closely spaced stations, have been deployed during several earthquake swarms near Eltopia, Washington, on the Royal Slope north of Corfu, Washington, on Wahluke Slope, and at Wooded Island (Malone and Others, 1975; Rothe, 1978). Up to seven single-component seismometers, which record the vertical component of ground motion, were located in and along the periphery of areas experiencing earthquake swarms as determined from the regional array in eastern Washington State. Hypocenters for these events were all very shallow (less than 1.2 miles [2 kilometers]) and did not align along planar zones. The small size of these earthquakes precluded the determination of a focal mechanism for individual events, but composite focal mechanism solutions were performed on groups of similar data. No consistent focal planes emerged from these analyses; however, reverse faulting along fault planes of varying dip as a result of nearly horizontal, nearly north-south compression was suggested for analyses in these swarms, a stress orientation that can also satisfactorily explain many major structures in the basalt (Bond and Others, 1978; Malone and Others, 1975; Rothe, 1978).

Continuing microearthquake activity in the basalt of the Columbia Plateau indicates that stress is being relieved, but the nature of the stress and the mechanism responsible for swarm activity is not well understood. The steep dip of focal planes and the limited vertical distribution of swarm events at Wooded Island led Rothe (1978) to hypothesize that slip was occurring on columnar joints in thick, competent basalt flows, perhaps due to strain relaxation along folds. Geologic structures beneath Wooded Island are not known, but gravity data suggest that the anticlinal structure of Gable Mountain curves southeastward of the area to become parallel to the Columbia River so that it would be approximately north-south in the area of Wooded Island (Richard and Deju, 1977). The orientation of focal planes and the elongated volume in which the microearthquake activity occurs are oriented east-west, an azimuth that disagrees with the gravity anomaly trend, but which generally agrees with an east-west-trending magnetic low discussed in Chapter III. A plot of microearthquakes versus time for March 1969 through May 1976 revealed that earthquake activity increased markedly from July to a peak in November or December and declined to a minimum from March to May of each year (Brown and Isaacson, 1977). This cycle of activity, with appropriate allowance for lag time, suggests a possible correlation with irrigation as a cause of microearthquakes, perhaps by loading the crust or by generating increased pore pressure in shallow fracture zones. In 1978, a swarm began in the Saddle Mountains in January and died away in early summer, suggesting that irrigation is not the only causative factor.

Most earthquakes detected and located by the eastern Washington State array have been shallow; however, activity does occur at focal depths of 5 to 18 miles (9 to 30 kilometers). Hypocenters of deeper earthquakes below basalt in the Columbia Plateau occur in a different pattern from that of shallow events. Swarms apparently do not occur below the basalt, or at least not in the same spatial and temporal pattern. Whether deeper earthquakes are related to geologic structure is unknown, since the structure and rock types beneath the basalt are largely unknown. The deep events (more than 6 miles [9 kilometers]) are small (less than magnitude 4.5) and are apparently randomly distributed in time and space. Some deep events occur in swarm areas, while others occur between areas experiencing swarms.

Seismicity of the Region Surrounding the Columbia Plateau

Earthquakes that occur in areas of higher seismicity beyond the margins of the plateau need to be considered to assess earthquake risk within the plateau, as well as to understand the regional tectonic framework. Figures IV-1 through IV-6 illustrate that most of the earthquake activity in Washington State occurs in the Puget Sound Lowland (Rasmussen, 1967; Stepp, 1973; Crosson, 1972). This zone continues to the south in the Willamette Valley of Oregon (Crosson, 1972; Couch and Lowell, 1971) where activity diminishes south of Eugene. The zone of relatively high activity continues to the northwest into British Columbia in the area of southern Vancouver Island, the Straits of Georgia, and the Straits of Juan de Fuca (Milne and Others, 1978). Near the center of Vancouver Island, the zone of high activity appears to turn westward and join the zone of high earthquake activity along active, spreading centers and transform faults (Milne and Others, 1978; Chandra, 1974).

Earthquakes as large as magnitude 7.0 and at depths down to about 55 miles (90 kilometers) have occurred in the Puget Sound area. Historic seismicity (Figures IV-1 and IV-2), as well as instrumentally recorded

events (Figures IV-3 and IV-4), clearly show that this is an area where moderate to high levels of stress have been relieved over the nearly 150 years of record. Most earthquakes and, in fact, most larger events, occur at focal depths of more than 6 miles (10 kilometers) in distinct contrast to the Columbia Plateau (see Figure IV-6). The structure(s) responsible for this activity is deeply buried by thick, extensive Quaternary sediment, some of which is offset by faults (Waldron, 1962; Mullineaux, 1970). Bedrock beneath Puget Sound is presumably similar to the sequence exposed in the Olympic Mountains, where Pleistocene drift has been offset along faults in bedrock (Wilson and Others, 1979).

Geologic evidence from the northeastern Pacific Ocean (Raff and Mason, 1961; Silver, 1971), as well as from the Olympic and Cascade Ranges (Christiansen and Lipman, 1972; Tabor and Cady, 1978), indicates that the southeast-spreading Juan de Fuca Plate (a remnant of the larger Farallon Plate) was subducted during late Cenozoic time along a marginal trench (Atwater, 1970; Atwater and Molnar, 1973). It is not clear whether subduction is continuing, perhaps at a reduced rate, has ceased, or if the Juan de Fuca Plate is decoupled from the American Plate (Crosson, 1972; Davis, 1977). Cross sections (Figures IV-5 and IV-6), with existing data, do not suggest the presence of a Benioff Zone. Davis (1977) has suggested that earthquake activity in Puget Sound is localized along a zone where the angle of descent of the Juan de Fuca Plate changes from about 14 degrees to about 40 degrees.

Focal mechanism solutions of earthquakes in the Puget Sound area do not show any consistent mechanism and thus do not help resolve the question of subduction (Davis, 1977). Thrust faulting along a west-northwest-striking, gently south-dipping fault plane in the April 1949 magnitude 7.1 earthquake (Hodgson and Storey, 1954) contrasts with normal faulting along a northwest-striking, more steeply dipping fault plane (Algermissen and Harding, 1965) that was determined for the magnitude 6.5 earthquake of April 1965. Thrust or strike-slip faulting resulting from generally north-south compression was determined for smaller events in the Puget Sound region using the composite focal mechanism technique (Crosson, 1972).

East of the Columbia Plateau, earthquake activity appears to be relatively low, except for a zone extending northwestward from the generally north-trending Intermountain Seismic Belt, across southern Idaho north of the Snake River Plain into eastern Oregon. This latter zone, known as the Idaho Seismic Belt, is an area of shallow earthquakes known from felt reports and more recently from instrumental records (Smith and Sbar, 1974; Vincent and Applegate, 1978) and extends through the Idaho Batholith Province. Earthquakes in this area are generally shallow, less than 9 miles (15 kilometers), low-to-intermediate magnitude (magnitude less than 6.1), frequently of swarm type, and correlate in part with post-Miocene faults where geologic mapping is of reasonable quality (Vincent and Applegate, 1978). The Snake River Plain appears to be an area of low earthquake activity from both historical felt reports and instrumental surveys (Smith and Sbar, 1974; Pennington and Others, 1974).

Focal mechanism solutions have been performed on a number of events outside the Columbia Plateau and these provide some evidence of the nature of contemporary stress relief. Combined with geologic data from late Cenozoic rocks and sediments, these fault plane solutions may be useful in developing a tectonic history and tectonic models of the geologic evolution of the Columbia Plateau and surrounding region. Focal mechanism solutions from the Cascades west to the continental slope suggest that the area is experiencing north-south compression (Crosson, 1972; Chandra, 1974). The geometry of ridges and transform faults in the northeastern Pacific Ocean indicates that the area has been one of subduction in geologically recent times and that a possible change to strike-slip transform faulting similar to that which occurred earlier in California is recent or is in progress (Atwater, 1970; Atwater and Molnar, 1973; Crosson, 1972; Riddihough and Hyndman, 1976). The northeast Pacific Ocean basin is a complex of small plates interacting in an as yet undetermined manner (Atwater, 1970; Silver, 1971). In contrast to oblique compression along the western coast of North America, tension prevails along the Intermountain Seismic Belt, indicating the area is extending in an east-west direction (Sbar and Others, 1972; Smith and Sbar, 1974). A similar stress field occurs in the Great Basin. East-west extension implies that the axis of maximum compression is oriented north-south.

An east-west-trending, elliptical area extending from the southeastern end of Lake Chelan and south along the Columbia River toward Entiat and east toward Waterville, Washington has been affected by local, felt earthquakes of up to Modified Mercalli intensity VI and by low-magnitude, instrumentally recorded earthquakes (Rasmussen, 1967; Bor, 1977; Withers and Others, 1978; Malone, 1977, 1978). The area is along the western margin of the Columbia Plateau where basalt thins and pinches out to the west on Mesozoic and early Tertiary rocks. Instrumentally recorded events range up to about magnitude 4.0; focal depths range up to about 6 miles (10 kilometers) (Bor, 1977; Malone, 1978). Detectability in this area is good, enabling events of less than magnitude 1.0 to be located (Malone, 1978). Focal mechanism solutions do not reveal a consistent orientation of rupture plane, suggesting that failure is occurring on different planes of varying orientation. Limited data suggest that the earthquakes align along a broad zone which strikes east-northeast and dips at about 60 degrees beneath the basalt (Withers and Others, 1978). Calculations of stress drop and seismic moment suggest that a magnitude 5.8 earthquake may be a maximum event in this area, occurring along a rupture plane of a few hundred feet (meters) in length (Bor, 1977).

One of the largest earthquakes that was felt over a large area of the Pacific Northwest occurred on December 14, 1872 in a remote mountainous area of sparse population. This earthquake was not recorded by instruments, so that its size and location had to be determined from few written records, some of which appeared days to months after the event. Different interpretations of the sparse data have led to several locations for this earthquake in different earthquake catalogs. Little information was known about this event and scant attention was paid to it until the early 1970's. Prior to this time, it had been listed in several catalogs with sizes ranging from intensity VI to IX and locations varying from Puget Sound to southern British Columbia. As recently as 1973, this event was listed in a cumulative earthquake catalog for the United States as a Modified Mercalli intensity VI

that occurred at various times in the period December 14 through 16, 1872 in Puget Sound and had a felt area of 150,000 square miles (390,000 square kilometers) (Coffman and von Hake, 1973).

Even though the felt area listed was more than double that of intensity VII events listed on the same and adjoining catalog pages, it remained unquestioned until it became an issue in siting nuclear power plants in the Pacific Northwest. Concern about seismic design for such proposed plants has led to extensive investigations regarding the December 14, 1872 earthquake. This investigation has included a review of felt reports and historic accounts, geologic investigations in the suspected epicentral area, geologic mapping and investigation in and along the margins of the Columbia Plateau, geophysical investigations, remote sensing analysis, and deployment of portable, sensitive earthquake detection arrays.

A panel of experts was formed to review felt reports and accounts of the December 14, 1872 event. An isoseismal map of that event was prepared. The panel was chaired by Dr. Howard Coombs (Professor Emeritus of Geology, University of Washington) whose colleagues were:

Dr. Otto W. Nuttli, Professor, Geophysics, St. Louis University, St. Louis, Missouri;

Dr. David B. Slemmons, Professor, Geology, University of Nevada, Reno, Nevada;

Dr. William G. Milne, Earth Physics Branch, Department of Energy, Mines and Resources, Victoria Geophysical Observatory, British Columbia.

The panel concluded that the 1872 earthquake occurred in the area enclosed by the Modified Mercalli intensity VIII isoseismal line (from Lake Chelan on the south to southern British Columbia on the north) in the North Cascades-Okanogan Highlands area. It apparently had a focal depth greater than 6 miles (10 kilometers), was followed by several aftershocks, and was probably a low-stress-drop earthquake. The resultant isoseismal map indicates that the earthquake was felt over an area of about 501,800 square miles (1,300,000 square kilometers), but the large felt area may have been the cumulative effect of the main shock plus several aftershocks. Landslides seem to have occurred as a secondary effect. Many reported slides presumed to have occurred as a result of the 1872 earthquake took place in areas of intensity lower than in the epicenter. Therefore, the slides may have resulted from low frequency, long-period ground motion that commonly occurs at distances of tens to hundreds of miles (tens to hundreds of kilometers) from the epicenter (Coombs and Others, 1976). Results of extensive geological and geophysical investigations relevant to the December 14, 1872 earthquake are summarized by Coombs and Others, 1976. Their main conclusions are:

(a) The December 14, 1872 earthquake occurred in a meizoseismal area extending from Lake Chelan to southern British Columbia that includes the epicenter assigned by Milne (1956);

(b) The event was followed by two to four aftershocks over a wide area during the night of December 14 and 15; the large reported felt area may be the cumulative effect of several widespread earthquakes;

(c) If the large felt area is a result of the main shock, it must have been about magnitude 7.0 and a Modified Mercalli intensity VIII over a broad area; if the large felt area is a composite of the main shock plus several aftershocks, then the main shock was probably slightly less than magnitude 7.0;

(d) After careful examination and investigation, no positive evidence of Quaternary displacement was found along any faults in the epicentral area, with the possible exception of the Hope-Straight Creek zone of faulting in northern Washington and southern British Columbia;

(e) Surface displacement, which would have occurred in the epicentral area for a shallow (less than 5-mile [8-kilometer]) focal depth, magnitude 7.0 earthquake was not observed in the meizoseismal area;

(f) No evidence of fault displacement was found along the margin of the Columbia Plateau where basalt rests on older deformed rocks.

Subsequent reviews and hearings in the late 1970's by the U.S. Nuclear Regulatory Commission resulted in some agreement on the impact of the December 14, 1872 earthquake. The questionable merit of using landslides as a sole indication of high intensity led to assignment of a maximum Modified Mercalli intensity VIII to this event. Furthermore, it was agreed that the epicenter is in a broad region in the North Cascades-Okanogan Highlands which is a distinct tectonic province separate from the Columbia Plateau in the sense of the guidelines contained in Title 10, Code of Federal Regulations, Chapter 100, Appendix A. It is considered unlikely that such an event could occur in the Columbia Plateau (McMullen and Kelleher, 1978) and, therefore, the 1872 earthquake did not affect the seismic design criteria for nuclear power plants on the Hanford Site.

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TECTONICS

INTRODUCTION

Geological studies during 1977 were primarily on stratigraphy and structure of the Columbia Plateau with emphasis on the Pasco Basin. The tectonic studies recently completed by the Washington Public Power Supply System, Inc. (1974, 1977) are judged by Rockwell Hanford Operations' geologists to be a sufficient initial assessment of the tectonic stability of the Columbia Plateau. Additional tectonic studies are planned to refine the existing data on tectonic development.

Nonetheless, some observations can be made regarding the tectonic stability of the Columbia Plateau and Pasco Basin, particularly as they concern repository siting and evaluation of the Hanford Site. This section of the report is a listing of important observations along with some key interpretations. A chronology of deformation on the Columbia Plateau is presented, followed by a discussion of important structures identified in the Pasco Basin and evidence for their age of latest movement.

CHRONOLOGY OF DEFORMATION

Deformation on the plateau had apparently begun by at least late Grande Ronde time (approximately 15 million years before present) and continued at least through Pliocene time. The distribution of lava flows and interbeds suggests that a regional westward paleoslope developed across the plateau toward the present-day Cascade Range by late Grande Ronde time. This paleoslope was possibly maintained by slow westward tilting (Swanson and Others, 1979b), as was suggested by a westward thickening of magnetostratigraphic units N_2 and R_2 of the Grande Ronde Basalt. Regional tilting by Wanapum time (approximately 13.6 to 14.5 million years ago) is reflected most clearly by the distribution of the Roza Member which was extruded from the Roza linear vent system and flowed predominantly westward in response to this paleoslope. The westward paleoslope is also reflected in the regional dip surface of the Priest Rapids units which are exposed throughout most of northeastern Washington. By the end of Lower Monumental time (approximately 6 million years before present), westward tilting had ceased, as evidenced by similar modern and ancestral gradients of the Snake River upstream from Devils Canyon (Swanson and Wright, 1978).

The formation of structures in southeastern Washington State (i.e., the Lewiston and Troy Basins) also began at least as early as the end of Grande Ronde time. These structures were superposed on the continuing, regional, westward tilting. Ross (1978) and Price (1977) have shown evidence for the formation of the Troy Basin (Figure II-33) as early as the R_2-N_2 magnetic reversal of Grande Ronde time. The Lime Kiln fault developed before Wanapum time (Camp, 1976) and possibly near the end of Grande Ronde (R_2) time (Reidel, 1978b). This conclusion is further supported by the absence of flows younger than the basalt of Dodge (an early Wanapum Basalt) along the crest of the Saddle Butte structure (Camp, 1976; Price, 1977; Reidel, 1978b; Ross, 1978).

Folding in the Yakima Fold Belt also began as early as the end of Grande Ronde time, as evidenced by the thinning of the Vantage Member of the Ellensburg Formation toward the crest of Naneum Ridge anticline in the Wenatchee Mountains (Tabor and Others, 1977).

The earliest evidence of formation of the Yakima Folds in the Pasco Basin is in Frenchman Springs time (Reidel, 1978a) along a northwest-southeast trend near Smyrna Bench in the Saddle Mountains. Shannon and Wilson (1973b) concluded that the earliest structures in the Arlington, Oregon area were also of northwest-southeast trend. Deformation on east-west trends apparently began in Roza time. Based on flow and interbed distribution, moderate deformation continued through Wanapum and Saddle Mountains times. Folding during Saddle Mountains time is apparent from unconformities along Yakima Ridge (Holmgrem, 1967); however, most folding clearly post-dates Elephant Mountain time. More intense deformation apparently began 6 to 8 million years before present (Shannon and Wilson, 1973a; Bentley, 1977a). An age limit of 3.5 to 4.5 million years for deformation has been suggested (Shannon and Wilson, 1973, 1977a, 1977b; Kienle and Others, 1977b; Waitt, 1977b). Most folding is probably of late Miocene and Pliocene age and most faulting in the Columbia Plateau in Washington State appears to be associated with folding.

The age of deformation in the Goldendale, Washington area (located in the southern portion of the Yakima Fold Belt) was evaluated by Shannon and Wilson (1973a). Displacement along the Goldendale fault was dated as between 3.5 and 4.5 million years before present (Simcoe volcanic flows having a potassium-argon age of 3.5 million years before present are unfaulted). Following a study of the relationship between the Goldendale fault and other northwest-trending faults in that area and the Columbia hills structure, Shannon and Wilson (1977a) suggested: (a) that final movement along the faults was largely an accommodation of response to the same forces that produced the folding; and, (b) that the end of folding and the final movement of the faults of that structure were contemporaneous (i.e., approximately 3.5 million years before present).

Most deformation in the Pasco Basin seems to have occurred in post-Elephant Mountain time and probably post-Ice Harbor time (approximately 8.5 million years before present) (Brown and McConiga, 1960; WPPSS, 1977; Bond and Others, 1978; Jones and Landon, 1978; Reidel, 1978a). Deformation occurrred on both the east-west and northwest-southeast trends (Reidel, 1978a).

Deformation of the Ringold Formation is interpreted from well data (Grolier and Bingham, 1978; Routson and Fecht, 1979; Tallman and Others, 1979) and was observed in outcrops along ridges at the margins of the Pasco Basin where the dip of the Ringold is conformable with that of the basalt (McConiga, 1955; Brown and McConiga, 1960). Pliocene deformation of the Ringold Formation in the Pasco Basin corresponds to that determined outside the Pasco Basin (Shannon and Wilson, 1977a); however, the extent of involvement appears to decrease from lower Ringold to upper Ringold time (Brown and McConiga, 1960; Routson and Fecht, 1979; Tallman and Others, 1979). Note: To assign deformation rates during Ringold time comparable to those suggested for basalts, it is necessary to determine sedimentation rates of the Ringold Formation as well as observe the deformation of upper Ringold sediments that overlie anticlinal structures in the basalt. The oldest sediments overlying basalt, other than the Ringold, were involved in deformation to some degree. Faults in the Kittitas Valley offset the Thorp gravel dated at 3.7 million years before present, but not the overlying 0.13 million years before present Kittitas drift (Waitt, 1979a). Toppenish Ridge contains scarps that may be faults which have not yet been dated (Campbell in Rigby and Othberg, 1979), but appear young. A small reverse fault southeast of Walla Walla offsets gravels and a weathered loess, but is covered by an undeformed younger loess (Webster in Rigby and Othberg, 1979).

No tectonic deformation of the Hanford formation was observed during reconnaissance mapping in the Pasco Basin. Trenches at the Wallula Gap Fault (Jones and Fecht, 1977) and on Gable Mountain (Bingham and Others, 1970) show no observable deformation of Quaternary sediments. Brown (1970) suggested the possibility of tectonic deformation of Touchet Beds on the eastern end of Yakima Ridge where the dip of the beds reflects the underlying folds. Similar deformation was also suggested by Brown (1968) at Finley Quarry.

Slemmons and Glass (in WPPSS, 1977) and Slemmons (in WPPSS, 1977) studied topographic maps and remote sensing imagery of parts of the Columbia Plateau and north Cascades to identify potentially active structures. They concluded that the Kittitas Valley contains "youthful-looking" features, possibly of fault origin, and that the Saddle Mountains (the northern boundary of the Pasco Basin), Badger Mountain, and Beezley anticline "appear to be the most youthful structures east of the Columbia River" (Glass, 1977). Similar conclusions were also drawn during an analysis of U-2 coverage of this same area by Sandness and Others (in press) who further noted features of possible tectonic significance on Toppenish Ridge and in the Walla Walla Basin area.

Major Tectonic Structures in the Pasco Basin

The most prominent structural features in the Pasco Basin are the east-west Yakima Folds. These structures and their associated faults have long been recognized. The Yakima Folds have been generally attributed to north-south compression, and have received close scrutiny by the Washington Public Power Supply System, Inc. regarding their tectonic stability (1974, 1977). Geologic mapping by Rockwell Hanford Operations is in general agreement with the findings of Washington Public Power Supply System Inc. Mapping by Rockwell Hanford Operations has, however, revealed details about subtle structures associated with the Yakima Folds not emphasized in previous studies. These structures are northwest-trending folds, probably locally faulted or with disseminated fractures that cross-cut and, in some places, are coincident with northwest-trending segments of Yakima Folds. Northwest-trending, right lateral, strike-slip faults near Goldendale, Washington (Newcomb, 1970) are Pliocene in age (Shannon and Wilson, 1977a).

The northwest-trending structures are judged important to repository siting and evaluation in the Pasco Basin because: (a) they might extend across parts of the Pasco Basin away from the Yakima Fold hinge zones; (b) they might influence ground-water flow paths and movement rates; and, (c) the age of most recent movement is not known. Thus, there are at least two categories of important tectonic structures in the Pasco Basin: (a) the Yakima Folds; and, (b) the northwest-trending structures that locally cross-cut and coincide with the Yakima Folds. Four Yakima Folds structures (the Saddle Mountains structure, the Umtanum Ridge-Gable Mountain structure, the Yakima Ridge structure, and the Rattlesnake Mountain-Wallula structure) occur within and along the margins of the Pasco Basin.

Yakima Folds Structures. The Saddle Mountains structure is one of the longest individual structures within the Yakima Fold Belt subprovince. The steep limb of this generally asymmetric fold is faulted along much of its length (Plate III-1). This fault is named the Saddle Mountains fault in the northern Pasco Basin. The age of the Saddle Mountains fault (Bingham and Others, 1970) is post-Ringold, but pre-Pinedale (12,000 to 25,000 years ago).

Microearthquake swarms may be spatially associated with the Saddle Mountains structure, although most epicenter locations lie north of the structure (Malone, 1978). The Saddle Mountains structure is shown on a

map of young faults in the United States (Howard and Others, 1977) as having had displacement in the last 1.8 million years.

Indications are that most deformation on Umtanum Ridge near Priest Rapids Dam was post-Wanapum time and pre-Pomona time. Mapping by Goff for Rockwell Hanford Operations during 1977 on the Umtanum Ridge-Gable Mountain structure is generally consistent with this interpretation, but indicates at least some parts of the structure may have been deformed through Elephant Mountain time (Goff and Myers, 1978). The eastern Umtanum Ridge segment of the Umtanum Ridge-Gable Mountain structure is thus interpreted to have experienced most of its deformation in pre-Pomona time, and is probably an older Yakima Fold relative to the other Yakima Folds in the Pasco Basin.

Geologic mapping in the Gable Mountain-Gable Butte area by Fecht (1978), compiled as part of Plate III-1, showed two faults previously recognized by Bingham and Others (1970). One is a northerly trending reverse fault and the other is a northeasterly trending reverse fault. The latter fault has been trenched (Bingham and Others, 1970) revealing a fault plane that generally dips to the south and does not offset glaciofluvial sediments dated at greater than 40,000 years. Core drilling south of Gable Mountain at DB-10 revealed 2 reverse faults with approximately 160 feet (49 meters) of combined throw. The age of latest movement on these faults is unknown. Interpretations made on the basis of reflection seismic results indicate these faults might be a subsurface continuation of southeast-trending structures on Gable Mountain (see Chapter III and Fecht, 1978).

Geologic mapping on Rattlesnake Mountain by Bond and Others (1978), compiled as part of Plate III-1, indicated a 32-foot (10-meter) wide, northwest-trending fault zone along the north flank. The nature, extent, and age of this northwest-trending fault zone have been a subject of much discussion, especially since it lies along the Olympic-Wallowa Lineament (Raisz, 1945). In large part, the different opinions regarding this zone have resulted from varying interpretations of limited, discontinuous exposures and features such as breccias, slickensides, slope, and drainage (Bingham and Others, 1970; Bond and Others, 1978; WPPSS, 1974; Jones and Deacon, 1966). The nature of deformation (i.e., folding or faulting and the type of faulting) and the relationship of this structural trend to possible older structures in the basement rocks beneath the basalt are questions which remain to be resolved.

The Wallula Gap fault (Gardner, 1977) is a west-northwest-trending fault which bisects the angle formed by the Rattlesnake Mountain-Wallula alignment and the Horse Heaven Hills where they converge at Wallula Gap. The fault was originally inferred to exist by Mollard on the basis of examination of aerial photographs (Mollard in Jones and Deacon, 1966). Field examination of breccias, aligned topographic scarps, ground-water springs, and apparent truncation of basalt flows exposed in canyons along the north slope of the Horse Heaven Hills suggested the presence of a reverse fault (Bingham and Others, 1970); an interpretation different from that of Brown (1968) who suggested that observed features were easily explained by an erosionally modified monocline. Trenches were excavated

by Rockwell Hanford Operations across the trace of the Wallula Gap fault at Yellepit Station on the west side of the Columbia River. They were mapped and studied in detail by Jones and Fecht (1977) and also examined by Farooqui (WPPSS, 1977). The trenches revealed a complex zone of gouge and tectonically brecciated basalt up to 260 feet (79 meters) wide, across which flows of the Frenchman Springs Member are juxtaposed against flows of the Umatilla Member. The sand and gravel beds of the Hanford formation overlie the fault zone and are apparently not deformed, as determined by Gardner, Jones, and Fecht in work for Rockwell Hanford Operations in 1978.

Northwest-Trending Structures. Geologic mapping in the Saddle Mountains, described in Chapter III and compiled as part of Plate III-1, revealed that northwest-trending structures cross-cut the east-west-trending Saddle Mountains structure. Thinning of late Wanapum Basalt units across the axis of one of the northwest-trending structures, the Smyrna anticline (Plate III-1), suggests it began to form in late Frenchman Springs time (Reidel, 1978a). This was followed by the rise of the east-west-trending Saddle Mountains structure in later Wanapum time. The Smyrna anticline and other northwest-trending structures continued development with associated faulting at least through Elephant Mountain time. The extent of these northwest structures away from the hinge zone of the Saddle Mountains structure and their age of latest movement are two important concerns. The northwest-trending structures might be associated solely with the development of the Saddle Mountains structure. Alternatively, the northwest-trending structures might be associated with a more regional system and the individual structures of this regional system might extend across the anticlinal flanks and synclinal regions of the Yakima Folds. Depending on the age of latest movement along individual structures, or long segments of individual structures, the youngest overlying basalt flows may or may not be deformed. Thus, the northwest-trending structures mapped by Reidel (1978a) in the Saddle Mountains might extend to the southeast across the Pasco Basin. Circumstantial evidence for such a trend includes: (a) the southward bend of the Umtanum Ridge-Gable Mountain structure in the central Pasco Basin; (b) the straight segment of the Columbia River north of the city of Richland; (c) the northwest-trending Baxter, Parsons, and Rankin Canyons in the White Bluffs; and, (d) alignment of the continuation of this trend with Van Sycle Canyon and the Warm Springs area (Fecht, 1978; Reidel, 1978a; Jones and Landon, 1978), where faulting has been recognized through field mapping by J. N. Gardner for Rockwell Hanford Operations during 1977 (Plate III-1) and shown by Newcomb (1970).

CONCLUSIONS

Much geologic evidence from the regional and Pasco Basin studies suggests some tectonic deformation began as early as late Grande Ronde time (approximately 14 to 15 million years before present). This deformation was localized along Yakima Fold trends and northwest-trending structures. The rate of tectonic deformation (i.e., an increase in structural relief) increased locally along these same trends, but was generally subdued through Wanapum time (approximately 13.6 to 14.5 million years before present). The rate of deformation was greatest in the Pasco

Basin after late Saddle Mountains time (approximately 8.5 to 10.5 million years to approximately 5 million years before present). The extent of involvement of Ringold sediments in deformation appears to decrease from lower to upper Ringold units, suggesting that deformation continued into Ringold time possibly at a reduced rate. Upper Ringold sediments (more than 3.5 million years old) along the White Bluffs appear to be only slightly tilted, but here they overlie relatively gently dipping basalt.

The Miocene to Pliocene development of the Yakima Folds generally has been attributed to north-south compression. Fault plane solutions (mostly composited from low-magnitude events in shallow swarms) indicate that the central Columbia Plateau is under a general north-south compression today.

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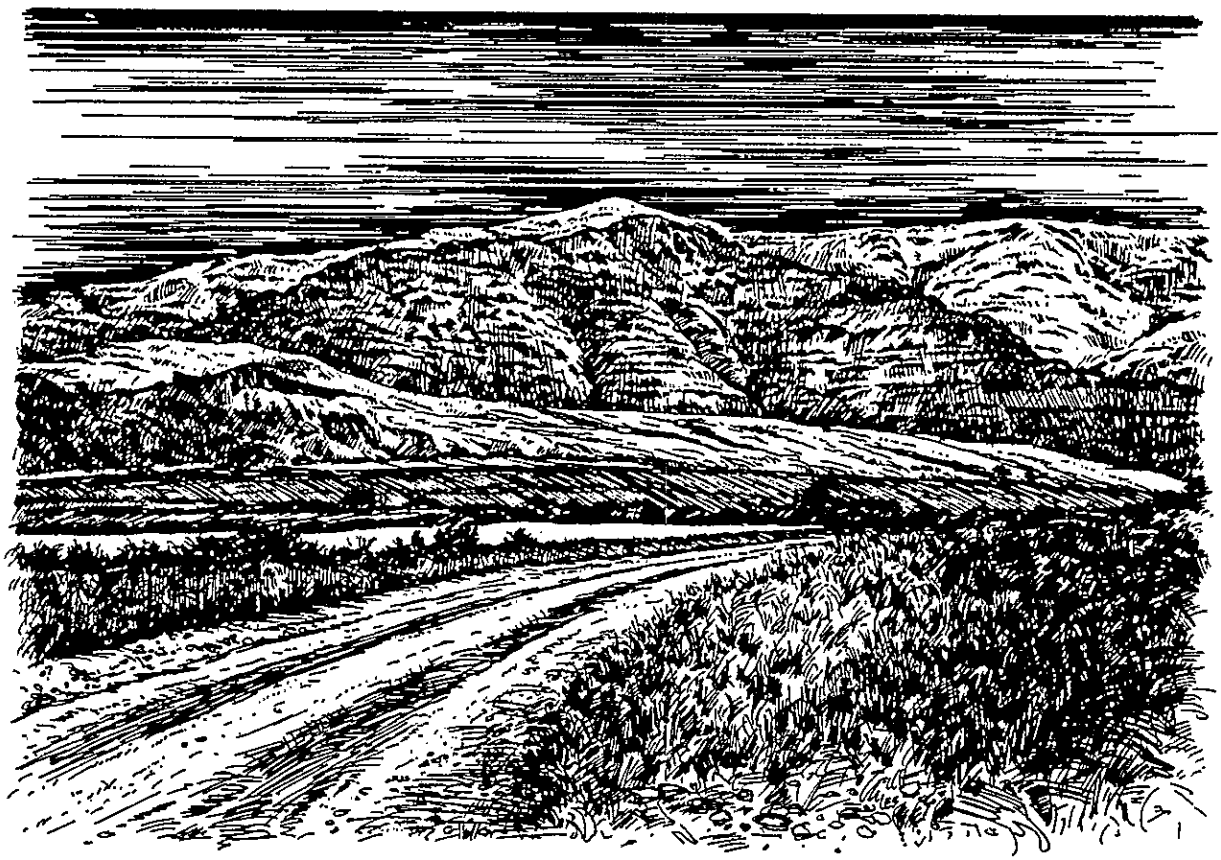
APPENDICES



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APPENDIX A

DESCRIPTION OF STUDY TASKS

APPENDIX A

DESCRIPTION OF STUDY TASKS

This appendix details the work conducted to date in each task within the work breakdown structure shown in Chapter I, Table I-3. The rationale behind the work within each task is also discussed.

REGIONAL STUDIES

LITERATURE SEARCH

Since the turn of the century, studies of the basalts of the Columbia Plateau have been carried out under the auspices of governmental, university, and private agencies. When Rockwell Hanford Operations' Basalt Waste Isolation Project's regional geology effort was formally initiated, a knowledge of available data was needed: (a) to prevent duplication of effort; and, (b) to evaluate the magnitude of additional stratigraphic, tectonic, and structural studies which were required to formulate a regional geologic picture of the Columbia Plateau. As part of the literature review process, the Washington State Department of Natural Resources' Division of Geology and Earth Resources, the Idaho State Bureau of Mines and Geology, and the Oregon State Department of Geology and Mineral Industries were contracted to conduct surveys of Columbia Plateau literature available for their respective states. The surveys involved a review of published and unpublished documents available from local, state, and federal agencies, public utilities, universities, and private industry. The over 3,000 references gleaned from this literature search are compiled in three bibliographies (Tucker and Rigby, 1978; Strowd, 1978; Bela, 1979) published by each of the state geologic surveys. Each bibliography is divided into two major parts; Part I is an alphabetical listing of all references, and Part II is a subject index. The subject index is divided into the 19 topical categories listed in Table A-1.

Upon completion of the literature search, a series of index maps (scale 1:250,000) was also produced by each state agency. Index map titles are listed in Table A-2. The references used in the formulation of the index maps are keyed to the bibliographies. Both the bibliographies and index maps served as a basis for the formulation of further regional geologic studies.

SURFACE GEOLOGIC MAPPING

Columbia River Basalt Group

Preparation of a regional reconnaissance geologic map of the Columbia River Basalt Group (scale 1:250,000) was initiated through a compilation of all existing maps and by the (re)mapping of defined areas. Thus far, geologic mapping of the Washington State portion of the Columbia Plateau (east of the Cascade Range) (Figure A-1) has been completed.

TABLE A-1. Subject Index Topics Used for Columbia Plateau Bibliographies.

Pre-Basalt Stratigraphy
Geology Marginal to the Columbia Plateau
Basalt Stratigraphy
Post-Basalt Stratigraphy
Basalt Laboratory Studies
Geologic Mapping
Structural Geology
Seismicity and Tectonics
Geophysical Studies
Remote Sensing Studies
Hydrologic Studies
Paleontological and Archeological Findings
Mineral Resources
Environmental and Engineering Geology
Geomorphology and Physiography
Regional Geologic Studies
Basalt References
Bibliographies
Test Wells

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TABLE A-2. Index Map Topics.

Geographic Areas and Scales of Available Geologic Mapping

Geographic Areas Covered by Geophysical Surveys

Locations of Oil and Gas Wells

Mineral Occurrences, Metallic, and Non-Metallic

Locations of Tunnels, Trenches, and Other Basalt Excavations

Geographic Localities for Specific Geologic Information Including

- Measured Stratigraphic Sections
- Outcrop Descriptions
- Type Localities
- Chemical Analyses
- Petrographic Descriptions
- Paleomagnetic Analyses
- Radiometric Dates

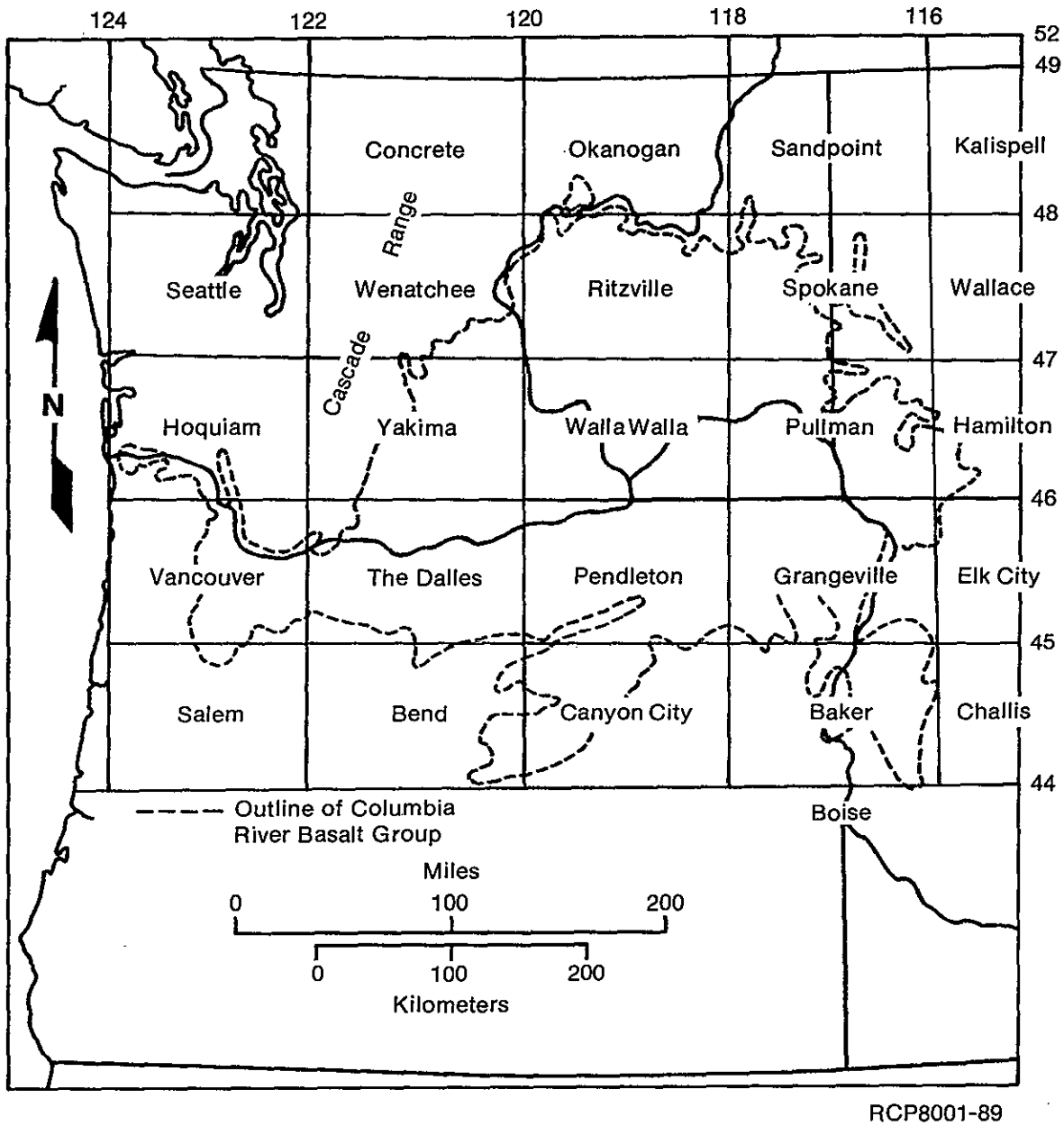

FIGURE A-1. Army Map Service 1- by 2-Degree Quadrangles (Scale 1:250,000).

The U.S. Geological Survey-Western Division was responsible for the coordination of regional mapping of the Columbia River basalt. Prior to the initiation of basalt mapping under the Basalt Waste Isolation Project, D. A. Swanson, U.S. Geological Survey, Columbia River Basalt Mapping Coordinator, was requested to conduct a review and evaluation of the status of previous basalt mapping within the Columbia Plateau. As part of this review, areas of the plateau were classified into one of two categories: (a) areas mapped sufficiently; and, (b) areas mapped insufficiently or unmapped. Areas of the second category were further subdivided and prioritized primarily on the basis of structural complexity. In addition, the review involved a determination of the locations of available reference sections and the locations of proposed additional sections. The results of this review served as a guide to determine areas of the Columbia Plateau requiring mapping under the Rockwell Hanford Operations' project and the order in which these areas should be investigated.

Considerable progress toward completing a reconnaissance geologic map of the Columbia River Basalt Group, has been made at the time of preparation of this report. Mapping of that part of the Columbia River basalt within Washington State is essentially complete; mapping, in a preliminary form, is 50 percent complete for Oregon and 50 percent complete for Idaho. Mapping has been conducted by full-time and temporary personnel of the U.S. Geological Survey, listed as follows: D. A. Swanson, T. L. Wright, J. L. Anderson, G. R. Byerly, R. D. Bentley, J. N. Gardner, P. R. Hooper, V. E. Camp, and W. H. Taubeneck.

Field mapping was done on existing U.S. Geological Survey 7.5- and 15-minute topographic maps and was compiled for publication on Army Map Service 1- by 2-degree quadrangle sheets (Figure A-1). The mapping was conducted with the aid of aerial and satellite photography, as well as with the support of chemical analyses performed by Washington State University and the U.S. Geological Survey. Older geologic maps were consulted, but recent advances in stratigraphic knowledge of the basalt required extensive remapping. Mapping was relatively rapid, and generally consisted of extrapolating between exposures rather than walking out contacts. The maps are thus termed reconnaissance, even though they accurately portray most significant features. In addition to the distribution of stratigraphic units, the mapping was conducted to determine the locations of dikes and to provide structural data such as the locations of faults, folds, and lineaments.

The formal stratigraphic nomenclature and units used in the mapping follow the framework recently established by Swanson and Others (1979b); see Chapter II, Figure II-4. The criteria used to recognize specific stratigraphic units include field characterization, petrography, magnetic polarity (using a portable fluxgate magnetometer), and chemical composition. Petrography and magnetic polarity can be evaluated in the field and, taken together in overall stratigraphic context, are generally reliable. Chemistry was used as a guide to check and correct field identifications.

Included in this report is a set of 10 geologic maps (Plates II-1 through II-10), compiled on Army Map Service 1- by 2-degree quadrangles covering that portion of the Columbia River Basalt Group exposed within Washington State. Stratigraphic and structural information gleaned from an examination of these maps is discussed in Chapter II.

Late Cenozoic Sediments

The Washington State Department of Natural Resources' Division of Geology and Earth Resources was responsible for the preparation of a regional geologic map of late Cenozoic sediments within the Washington State portion of the Columbia Plateau (east of the Cascade Range, Figure A-1). The initial step in this effort was a review and evaluation of all available geologic publications concerned with the late Cenozoic sediments within the study area. References evaluated as part of this review are included in the annotated portion of the Washington State Columbia Plateau bibliography (Rigby and Tucker, 1978). This literature review essentially revealed that, although site-specific studies of the late Cenozoic sediments were considerable, field studies required to formulate a regional late Cenozoic overview and synthesis were lacking.

The primary purpose of the late Cenozoic reconnaissance mapping effort was to initiate the development of a late Cenozoic stratigraphy which can be used to evaluate the age of structures within the Columbia Plateau, Washington State. Preparation of the reconnaissance map (exclusive of the Pasco Basin area) was initiated in March 1978 and was completed in July 1979. To provide such a map, the study area (Figure A-1) was divided into four roughly equivalent areas or quadrants. Geologists familiar with the late Cenozoic geology of each quadrant were selected from various universities in the state of Washington to perform the mapping as follows: E. P. Kiver and D. F. Stradling (northeast quadrant); L. G. Hanson (northwest quadrant); N. P. Campbell (southwest quadrant); and, G. D. Webster (southeast quadrant). K. L. Othberg, J. G. Rigby, and G. B. Tucker of the Washington State Department of Natural Resources' Division of Geology and Earth Resources provided technical guidance and administrative support to the program.

Based upon a review and evaluation of previous work, publications by Bingham and Grolier (1973), Grolier and Bingham (1978), and Tabor and Others (1977) were adopted as stratigraphic standards for surficial mapping. The stratigraphic nomenclatures presented in these publications were modified accordingly by the mappers to develop a workable stratigraphic framework that could be used to carry out field work in their respective areas.

Field mapping was done on U.S. Geological Survey 7.5- and 15-minute quadrangles. The mapping was performed with the aid of black and white, stereo, aerial photographs (scale 1:62,500). In addition, the annotated bibliography and accompanying index maps (Rigby and Tucker, 1978) provided the mappers with a knowledge of geologic references available for their respective areas. Due to the reconnaissance nature of the study, most field work was restricted to areas accessible by roadways. Mapping was done at the rate of 1 to 2 7.5-minute quadrangles or equivalent per day per mapper.

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Field mapping recorded on the 7.5- and 15-minute quadrangles was compiled on Army Map Service 1- by 2-degree sheets (Figure A-1). Due to the reduction in scale (from 1:24,000 or 1:62,500 to 1:250,000), it was necessary to combine smaller, original mapping units that bore a relationship to one another into larger, more extensive units. The more generalized compilation stratigraphy, discussed in Chapter II, is based on a synthesis of the stratigraphic units used within each of the 4 quadrants and was developed with the input and concurrence of the entire regional geologic mapping team. Because of the reduction in scale, it was also necessary to delete isolated outcrops and geomorphic features of only limited extent from the compilation map. However, copies of the original 7.5- and 15-minute maps and field notes are maintained on file by Rockwell Hanford Operations for purposes of reference. In keeping with the surficial nature and intent of the mapping effort, only structures which involve the deformation of late Cenozoic sediments are shown on the compilation maps. The reconnaissance late Cenozoic geologic map set, and accompanying explanatory text, are included as Plates II-11 through II-19.

Analysis of Satellite and Aerial Imagery. The objective of the remote sensing effort is to identify structures and other geologic features which may have a significant bearing on the tectonic setting of the Columbia Plateau. The study consists, essentially, of visual interpretations or analyses of available satellite and aerial imagery. Geologic features of greatest interest in the regional study (faults, folds, and joints) typically have a linear expression on satellite and aerial photographs. Consequently, the methodology employed is sometimes characterized as lineament analysis. Pacific Northwest Laboratory was responsible for carrying out remote sensing studies (i.e., lineament analysis of satellite and aerial imagery) in support of Rockwell Hanford Operations' regional geologic studies effort. Members of the Pacific Northwest Laboratory remote sensing team included G. A. Sandness, J. L. Lindberg, C. S. Kimball, B. L. Scott, and J. A. Stephan.

Pacific Northwest Laboratory has completed the following remote sensing studies to date: (a) literature survey and compilation of results from previous remote sensing studies; (b) indexing available imagery; (c) Landsat imagery acquisition and analysis; (d) U-2 imagery acquisition and analysis; and, (e) delivery of lineament maps to field geologists.

The first phase of the remote sensing project was initiated in October 1977 and involved the collection, centralization, and evaluation of available reports and maps relating to previous remote sensing studies in or around the Columbia Plateau. The literature survey included a search of computer data bases such as NTIS and GEOREF. In addition, 11 governmental agencies were contacted and visited; 28 reports and maps relating to geologic remote sensing and 39 supplementary geologic reports relating to major construction projects were identified and acquired.

Photolineament maps obtained during the literature search (Figure A-2) were digitized*, combined, and replotted by computer at a scale of 1:250,000. The composite photolineament map set was reproduced at this scale to provide overlays for the Army Map Service 1- by 2-degree quadrangles (Figure A-1) which serve as the topographic base for regional reconnaissance geologic maps. The primary need for this composite photolineament map set was to assist Rockwell Hanford Operations' regional mapping efforts and to provide a background for Pacific Northwest Laboratory's own photolineament analysis. A reduction of this compilation map, produced at a scale of 1:2,000,000, is shown in Figure A-2.

During the first phase of the remote sensing program, a survey of available satellite and aerial imagery was also made. A photography index of existing coverage was subsequently compiled. The index consists of plots and numerical information concerning photography acquired and held by various agencies. Imagery cited in this index, and on file with Pacific Northwest Laboratory, is listed in Table A-3.

A primary objective of the literature survey was to make some basic assessments of the potential usefulness of existing documents, maps, and imagery to photolineament interpretations of the Columbia Plateau. The data gleaned from this search served as the basis for the formulation of Rockwell Hanford Operations' regional remote sensing effort. Thus far, acquisition of new remote sensing data falls into three categories: (a) Landsat analysis; (b) U-2 analysis; and, (c) field support and verification studies.

At the initiation of the remote sensing effort, Landsat imagery was the most important form of satellite imagery available for regional geologic studies in the Pacific Northwest. Its importance was due to the fact that, at the time, it provided the only complete coverage of the Columbia Plateau and surrounding area. To conduct an analysis of this photography, Pacific Northwest Laboratory enlarged 10 computer-processed Landsat scenes of the Columbia Plateau to a scale of 1:250,000. From July through September 1978, Pacific Northwest Laboratory's efforts were focused on examining these Landsat scenes to identify lineaments and to refine the composite photolineament maps. Preliminary versions of these Landsat photolineament maps, or first-order lineament maps, were completed at the end of fiscal year 1978. The maps were produced as transparencies at a scale of 1:250,000 in order to overlay the Army Map Service topographic base.

Landsat lineament maps based only on an interpretation of currently available satellite imagery, however, have several deficiencies. Examples of these deficiencies are the inclusion of non-geologic or non-tectonic lineaments and the inability to detect many lineaments that can be observed in higher resolution imagery. The purpose of performing

*Digitizing: the process of recording the locations and dimensions of photolineaments on a magnetic tape for use in computer-process interpretation and plotting.

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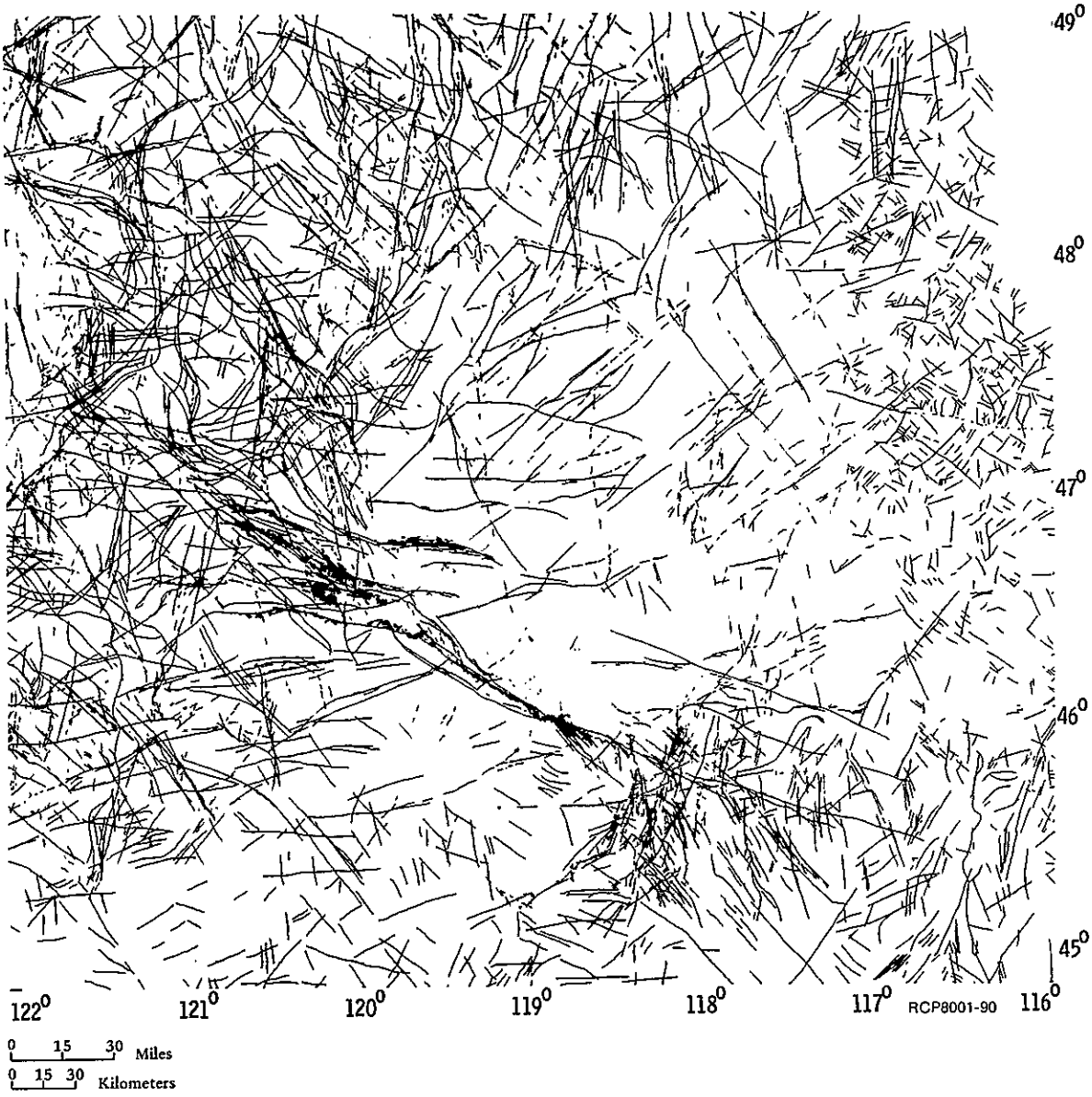

FIGURE A-2. Photolineaments Included in Pacific Northwest Laboratory Compilation Lineament Map Set (sources: Mollard in Jones and Deacon [1966]; Klosterman [1974]; Glass and Slemmons [1977]; Day [1974]; Brewer [1977]; Colcord and Bernath [1974]; Lawrence and Carter [1974]; and, Glass [1977]).

TABLE A-3. List of Data Base Imagery Maintained by Pacific Northwest Laboratory.

IMAGE TYPE	SPATIAL RESOLUTION	SCALE	COLOR	B&W	ORIGINAL FORMAT	COVERAGE OF COLUMBIA PLATEAU	SOURCE(1)
NOAA	1 km	1:1,000,000	Yes	Yes	Digital	Complete	NOAA
Landsat MSS	80 m	1:250,000	Yes	Yes	Digital	Complete	EDC
Landsat RBV	40 m	1:250,000	No	Yes	Photo-Negatives	Complete(2)	EDC
Skylab 190A	30 m	1:250,000	Yes	Yes	Photo-Negatives and Transparencies	Partial	EDC
Skylab 190B	15 m	1:250,000	Yes	No	Photo-Negatives and Transparencies	Partial	EDC
SLAR	<50 m	1:250,000 1:350,000	No	Yes	Prints and 70-mm Negatives	Partial	WPPSS, JPL
U-2 Photographs	2 m	1:128,000	Yes	Yes	9-Inch Transparencies	Complete	NASA/ Ames
Other Aerial Photographs	<1 m	1:63,360	Yes	Yes	9-Inch Transparencies	Partial	Regional Agencies

(1)Explanation of Sources:

NOAA - National Oceanographic and Atmospheric Administration, Washington, D.C.;
EDC - EROS Data Center, Sioux Falls, South Dakota;
WPPSS - Washington Public Power Supply System, Inc., Richland, Washington;
JPL - Jet Propulsion Laboratory, Pasadena, California;
NASA/Ames - NASA/Ames Research Center, San Jose, California;
Regional Agencies - Washington State, Department of Natural Resources, Olympia, Washington; U.S. Bureau of Reclamation, Ephrata, Washington.

(2)Scenes on order.

the analyses of aerial photographs as a part of Rockwell Hanford Operations' remote sensing study was to, at least partially, remedy such deficiencies.

The ideal aerial photographs for geologic remote sensing exhibit both high-spatial resolution and a wide field of view. For purposes of this regional remote sensing study, the optimum balance between resolution and scale is exhibited by U-2 photography. The 6.6-foot (2-meter) resolution of U-2 imagery permitted geologic interpretations at a level of detail consistent with the scope of the regional mapping program. Yet, the number of photographs to be analyzed is held to a reasonable level by the 2-inch-per-mile (5.1-centimeter-per-kilometer) scale of the U-2 photographs.

At the initiation of the remote sensing effort, U-2 photography was available only for approximately 20 percent of the Columbia Plateau. The National Aeronautics and Space Administration's (NASA) Ames Research Center was approached to determine the feasibility of a U-2 overflight to provide coverage for the entire plateau. The research center agreed to make such a photographic mission under the sponsorship of the U.S. Department of Energy. Between July 13 and July 31, 1978, 6 photographic surveys were flown over the plateau. The flight resulted in nearly 800 black and white and color infrared 9-inch (22.9-centimeter) format images.

This newly acquired U-2 photography covering the Washington State portion of the Columbia Plateau was utilized by Pacific Northwest Laboratory to produce second-generation photolineament maps at a scale of 1:250,000. The second-generation maps are based on a refinement of the initial first-order Landsat photolineament maps. The photolineaments recorded on the second-generation maps were classified according to the types of imagery or other data sources from which they were derived and according to the recognizable characteristics that they exhibit in photographic imagery. The coding scheme used for lineament classification in this remote sensing project is reproduced in Table A-4. The coded lineament classification consists of one or more letters to specify each image type or data source in which the lineament was recognized, and one or more numbers to describe the characteristics of the lineament. Second-generation photolineament maps completed for the Washington State portion of the Columbia Plateau are included as Plates II-21 through II-30.

An important aspect of the regional geologic studies effort is the integration of remote sensing products with ongoing field studies. To aid the regional mapping effort, field geologists were issued the compilation photolineament maps and first-order Landsat photolineament maps at the initiation of the fiscal year 1979 field season. The maps were used to delineate sites or areas where field geologists can effectively focus mapping efforts in order to evaluate features of possible structural significance. In addition, field geologists were issued U-2 and larger scale photographs for selection portions of their study areas as an aid to their mapping work.

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TABLE A-4. Photolineament Classification System.

LETTER CODE	IMAGE OR DATA TYPE
N	NOAA
L	Landsat
U	U-2
S	Skylab
R	Side-Looking Airborne Radar
A	Aerial Photographs Other Than U-2
M	Magnetic Anomaly or Lineament
K	Known Fault
F	Data from Current Field Work

NUMBER CODE	DESCRIPTION OF LINEAMENT
Ø	Cultural Feature
	Erosional Feature without Apparent Tectonic Significance
	Lighting Artifact
	Random Alignment of Features
1	Linear Color or Tonal Pattern on Discontinuity
2	Linear Textural Discontinuity
3	Straight Stream or River Section or Alignment
4	Linear Topographic Features or Alignment of Topographic Features
5	Stratigraphic Discontinuity
6	Linear Patterns of Volcanic Features
7	Probable Joint

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Alternately, field personnel initiated an evaluation of the second-order photolineament maps available for Washington State and noted: (a) those lineaments that do coincide with structures; (b) those lineaments that do not coincide with structures; and, (c) the appropriateness of the classification of the photolineaments that are shown. This cooperative approach was necessary to permit an integration of the remote sensing and field mapping tasks, and to provide a means for developing increasingly effective criteria for the interpretation of remote sensing and geologic data. The results of this integration effort were not completed in time for inclusion in this report.

PASCO BASIN STUDIES

SURFACE GEOLOGIC MAPPING AND RELATED STUDIES

The geologic mapping and related studies in the Pasco Basin included: (a) literature search; (b) compilation of a geologic map of the Pasco Basin from surface mapping of basalt and sediment exposures; (c) structural analysis of eastern Umtanum Ridge; (d) examination of intraflow structures in the Grande Ronde Basalt; and, (e) analysis of satellite and aerial imagery.

Literature Search

The U.S. Department of Energy and public utilities have supported many geologic studies within the Hanford Site and across the Pasco Basin. Although the results of some of these studies have been published in scientific journals, most have been documented in limited distribution reports. Many of these reports are listed in the bibliography and reference section of a report prepared by Deju and Others (1977); this report also includes references to many of the reports included in the bibliographies prepared by Washington, Oregon, and Idaho for the regional geologic studies. Study of these reports assisted in the planning and prioritizing of work during 1977 to 1979.

Surface Geologic Mapping - Columbia River Basalt Group

Geologic mapping in the Pasco Basin was conducted by Rockwell Hanford Operations and its subcontractor geologists. Results of this mapping were compiled as a 1:62,500-scale geologic map of the Pasco Basin (Plate III-1). Individuals and groups were assigned specific mapping areas for which they were individually responsible. Because the objectives for mapping basalt outcrops are fundamentally different from objectives for sediment mapping, different procedures were used in each case.

Basalt outcrops were mapped at a scale of 1:24,000 because they are surface exposures of the rock being considered as host rock for an underground repository. Basalt mapping emphasized the identification of basalt units, tracing of contacts between basalt units, and the discrimination and mapping of tectonic and primary basalt structures. Basalt units were field-identified by fluxgate magnetic polarity and hand-specimen petrology, supplemented by outcrop features and

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stratigraphic position. Many unit identifications were checked by X-ray fluorescence analyses, supplemented for some samples by energy dispersive X-ray chemical analyses. Duplicate samples and unused portions of samples selected for chemical analyses were maintained for future and reference use. Sample locations were shown on base maps. Sample collection points were marked and photographed in the field for documentation of each sampling site. For a few quadrangles, existing 1:62,500-scale U.S. Geological Survey topographic maps were enlarged to 1:24,000. Black-and-white aerial photographs at scales of 1:60,000 and 1:63,000 and color and black-and-white infrared U-2 photography at scales of 1:60,000 and 1:30,000, respectively, were used extensively. Individual structures were described and interpretations were made. concerning their lateral and vertical extent. The search for evidence which might indicate dikes, old fracture zones, or other structures in the Pasco Basin subsurface was emphasized.

Surface Geologic Mapping - Late Cenozoic Sediments

Sediment outcrops were mapped in a reconnaissance fashion at a scale of 1:62,500. Definition of sediment units mapped is preliminary and may be modified during subsequent mapping. An attempt was made to map surficial sediment exposures where the sediments at the surface were thicker than 3 feet (1 meter). Sediments are important to the Basalt Waste Isolation Project primarily for what they reveal about tectonic movement to date, chronology of the growth of folds, and movement along faults.

All sediment identification was performed in the field, including interpretation of geomorphic and stratigraphic relationships. Field mapping was to delineate textural facies of each formation or group. The Ringold Formation was mapped as gravel, sand, silt, and/or clay and the Hanford formation (informal name) was differentiated as gravel, sand, and rhythmically bedded sand and silt. Combination of some map units was necessary for the final compilation. For example, gravel and sand of the Hanford formation are collectively termed the Pasco Gravels. No attempt was made to differentiate older loess from recent loess.

Structural Analysis of Umtanum Ridge

Structural analysis of Umtanum Ridge included measurement and description of several stratigraphic sections within Grande Ronde Basalt on the north-facing slope of the ridge. Chemical analyses were made and magnetic polarity of selected flows was determined to aid in the recognition of mappable units. These flows were then mapped at a scale of 1:3,000 on vertical, aerial photographs. The high resolution of these photographs allowed the accurate location of prominent fault planes, flow contacts, and joints.

Orientations of layering, tectonic joints, faults, and slickenside lineations were measured with a Brunton compass and plotted on overlays of the photographs. Three-dimensional geometries of these elements were then analyzed by stereographic projections and mosaics on cross-sectional canyon walls.

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Study of Basalt Intraflow Structures

The general character of intraflow structures in the Grande Ronde Basalt flows at Sentinel Gap, Emerson Nipple, and north of Vantage was studied by constructing stratigraphic sections at a scale of 1 inch = 10 meters. Standard field methods were used. The data were supplemented by aerial observations and by study of oblique aerial photographs.

Fractures were measured in drill core according to standard operating procedures which basically involve the recording of the orientation, position, length, width, filling, and physical appearance of each fracture. The data are recorded in a standard format suitable for automatic data processing. Surface fractures were recorded in a manner similar to that used for drill cores. The objective in collecting the fracture data from outcrops was to help analyze the fracture data collected from drill cores. Comparison was made by measuring the fracture along a series of vertical segments.

Horizontal measurements were made by laying out 25 feet (7.5 meters) of tape horizontally across the outcrop, counting and recording major primary cooling joints, and then describing the following features: fracture fillings, if any; fracture curvature (1 to 10 scale); column perfection (1 to 10 scale); preferred orientation (if one exists); amplitude and wavelength of pinch-and-swell features (if present).

Vertical measurements were made by selecting a starting point at the base of a flow and measuring in vertical intervals of 5 feet (1.5 meters) the position and orientation of each fracture intersecting the imaginary line between the beginning and end points of the interval, and describing the same features seen offset along the horizontal interval. Intervals are concentrated in such a manner that they "continuously" sample as much of the flow as possible.

Textures of basalt samples from surface outcrops at Sentinel Gap were examined in reflected and transmitted light using standard petrographic techniques. The volume percent of glass (usually tachylite) was visually estimated and the nature of the glass was determined--primarily by examining the texture and abundance of crystallites. In addition, the morphology of the major minerals was observed with particular attention to the morphology of opaque phases.

The samples were selected based on intraflow structure boundaries or selected in a series that approximated equal spacing of samples. For example, in flows that show a sharp contact between entablature and colonnade, samples were taken adjacent to the contact on either side to see if the intraflow structure change was reflected in textural changes in the basalt.

Analysis of Satellite and Aerial Imagery

The analysis of satellite and aerial imagery for the Pasco Basin was done as part of the same work done in the region. This work is described above.

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BOREHOLE STUDIES

Borehole studies in the Pasco Basin consisted of preparing or obtaining: (a) drillers' logs, cable tool samples, drilling rate records, and chip samples; (b) borehole geophysical logs; (c) core logs and core samples; and, (d) fracture logs. Results from the borehole studies were used for interpretation of stratigraphic relationships and preparation of subsurface maps. Subsurface data were obtained from cable tool and rotary-drilled water holes of various depths which were drilled for various purposes (Figure A-3, Table A-5). The data are variable in detail and reliability. Therefore, all available information from an individual borehole was carefully scrutinized before inclusion into the overall borehole data base.

Cable tool and rotary sediment wells have been drilled at more than 400 locations on the Hanford Site. About 175 of these 400 wells reach or penetrate to the top of the basalt bedrock (Summers and Schwab, 1977). These 400 sediment wells were drilled to monitor possible ground-water contamination across the Hanford Site; they do not include the approximately 900 additional wells drilled for detailed monitoring or characterization of small, specific areas within the Hanford Site.

Cable tool and rotary water-supply wells have been drilled at many locations within the Pasco Basin outside the Hanford Site for domestic, agricultural, and industrial water supply. Many wells penetrate the top of the basalt bedrock in the Pasco Basin.

Available information from both Hanford Site sediment wells and Pasco Basin water-supply wells consists of drillers' logs and cable tool samples or rotary chip samples (Table A-5). Logs from these sediment wells and analyses of samples from them have been used to establish glaciofluvial and Ringold Formation sedimentary relationships in the 200 Areas of the Hanford Site and in mapping the top of basalt surface within the Hanford Site. Other drillers' logs from wells to basalt outside the Hanford Site (Summers and Weber, 1978) have been compiled and used in construction of the top-of-basalt contour map (Plate III-4a).

The many deep rotary boreholes drilled in the Pasco Basin can be subdivided into three groups: (a) the 26 boreholes drilled in the 1920's and 1930's to develop the Rattlesnake Hills gas field (one of these, Walla Walla Number 6 [WW-6], is the deepest and most important for purposes of these studies); (b) RSH-1, a petroleum exploration hole; and, (c) the 4 rotary holes drilled for deep hydrologic testing of the basalt beneath the Hanford Site.

Records and information obtained from deep rotary test holes generally includes a drilling rate log, a lithology log, chip samples, and borehole geophysical logs. Drilling rate logs were valuable for maintaining stratigraphic control during drilling because drilling rate is closely related to rock density, assuming variables such as drill string pressure and rotation rate are maintained constant. Drilling fluid return rates were also obtainable and are important because a "lost circulation zone" implies possible high porosity and/or permeability.

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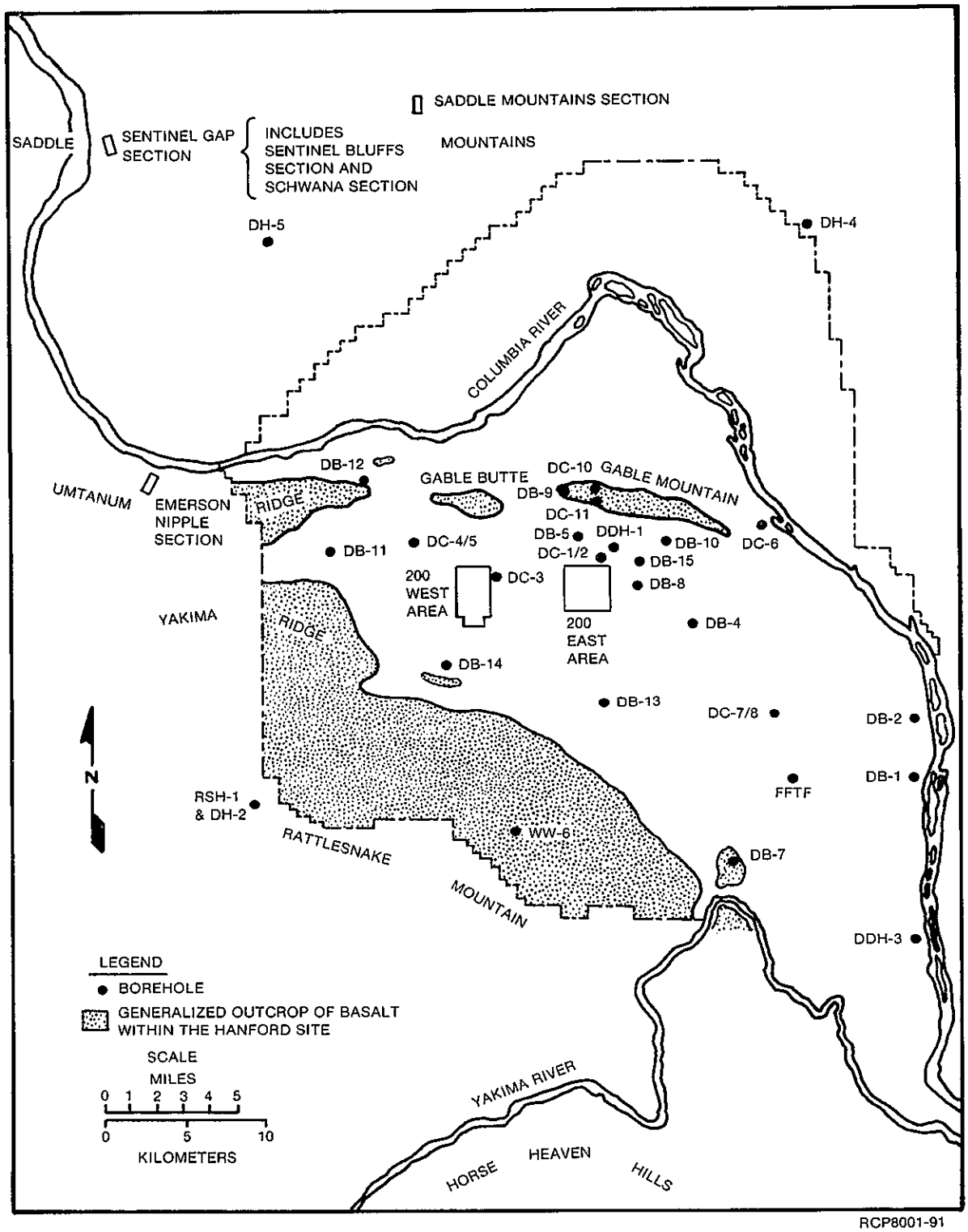

FIGURE A-3. Pasco Basin Boreholes and Surface Locations. Deep rotary boreholes are Walla Walla Number 6 (WW-6), RSH-1, DC-1, DC-3, DC-5, and DC-7. Core holes are all prefixed DC-6 (except DC-5 and DC-7), DB-, DH-, and DDH-. FFTF is a borehole drilled at the Fast Flux Test Facility. Cable tool holes and rotary-drilled water wells are not shown.

TABLE A-5. Pasco Basin Borehole Geological Data.

BOREHOLE DESIGNATION	TYPE	DEPTH	LOCATION	AVAILABLE INFORMATION
Sediment Wells	Cable Tool & Rotary	Mostly less than 700'	Hanford Site	Available samples (Additon, 1977) Driller's logs (Summers & Schwab, 1977)
Water Supply Wells	Cable Tool & Rotary	Mostly less than 2,000'	Pasco Basin	Available driller's logs, test data, & location map, (Summers & Weber, 1978)
Rattlesnake Gas Wells 26 Boreholes	Cable Tool & Rotary	Mostly less than 1,000', One @ 2,212' One @ 3,660'	North slope Rattlesnake Mountain	Driller's logs (Summers & Weber, 1978) WSDOE Columbia Plateau well records (BWIP Library)
RSH-1	Rotary	10,660'	T11N,R24E,15R1 LN 402000, E 2179700* Lat 46°26.02'* Long 119°47.23*	Summary report (Raymond & Tillson, 1968) Geophysical logs (BWIP Library & WSDOE Files) Hydrological tests (Gephart & Others, 1979) Location from topographic map ±200' (USGS Maiden Springs, 7-1/2')
ARH-DC-1	Rotary	5,661'	PN 48000, W 48200 LN 453178, E 2247001* Lat 46°34'19"* Long 119°31'06"*	Hole history (Fenix & Scisson, 1972b) Geophysical logs (BWIP Library) Hydrological tests (LaSala & Doty, 1971) Interpretation (ARHCO, 1976) Location based on DC-2 survey
DC-2	Core	3,300'	PN 47968, W 48255 LN 453146, E 2246947 Lat 46°34'18" Long 119°31'05"	Hole history (Fenix & Scisson, 1977a) Core & core pictures (BWIP Sample Repository) Physical & thermal tests (Colorado School of Mines, 1978b) Hydrological tests (Hydrological Integration Report, in press) Geophysical, lithological, geomechanical logs & geochemical analysis (BWIP Library)
DC-2-A1	Deviated Core	Continuous from 2,992' to 3,345'	Same as DC-2	Hole history (Fenix & Scisson, 1978a) Core & core pictures (BWIP Sample Repository) Lithological & geomechanical logs (BWIP Library)
DC-2-A2	Deviated Core	Continuous from 2,923' to 3,374'	Same as DC-2	Hole history (information not complete) Core & core pictures (BWIP Sample Repository) Hydrological tests (Hydrological Integration Report, in press) Geophysical, lithological & geomechanical logs (BWIP Library)
DC-3	Rotary	3,635'	PN 43802, W 70156 LN 448924, E 2225057 Lat 45°33'39" Long 119°36'19"	Hole history (Fenix & Scisson, 1977b) 215' of 4" core & core pictures (BWIP Sample Repository) Cutting samples (BWIP Sample Repository) Geophysical & lithological logs (BWIP Library)

Table A-5 (continued)

BOREHOLE DESIGNATION	TYPE	DEPTH	LOCATION	AVAILABLE INFORMATION
DC-4	Core	3,998'	PN 49385, W 85207 LN 454468, E 2209990 Lat 46°34'36" Long 119°39'53"	Hole history (information not complete) Core & core photographs (BWIP Sample Repository) Geophysical, lithological & geomechanical logs (BWIP Library) Hydrological tests (Hydrological Integration Report, in press) Geochemical & paleomagnetic sample results (BWIP Library)
DC-5	Rotary	3,990'	PN 49455, W 85131 LN 454538, E 2210067 Lat 46°34'36" Long 119°39'53"	Hole history (Fenix & Scisson, 1978c) Cutting samples (BWIP Sample Repository) Geophysical & lithological logs (BWIP Library) Hydrological tests (Hydrological Integration Report, in press)
DC-6	Core	4,336'	PN 54127, W 17721 LN 459384, E 2277465 Lat 46°35'16" Long 119°23'47"	Hole history (Fenix & Scisson, 1979a) Core & core photographs (BWIP Sample Repository) Geophysical, lithological & geomechanical logs (BWIP Library) Hydrological tests (Hydrological Integration Report, in press) Geochemical & paleomagnetic results (BWIP Library)
DC-7	Rotary	4,099'	PN 14910, W 14839 LN 420174, E 2280448 Lat 46°28'49" Long 119°23'12"	Hole history (Fenix & Scisson, 1977c) Cutting samples (BWIP Sample Repository) Geophysical & lithological logs (BWIP Library) Hydrological test results (Hydrological Integration Report, in press)
DC-8	Core	4,100'	PN 14956, W 14862 LN 420220, E 2280425 Lat 46°28'49" Long 119°23'13"	Hole history (Fenix & Scisson, 1979b) Core & core photographs (BWIP Library) Geophysical, lithological & geomechanical logs (BWIP Library) Hydrological tests (Hydrological Integration Report, in press) Geochemical & paleomagnetic sample results (BWIP Library)
DC-10	Angle Core 26.6°	456'	PN 62468, W 53244 LN 467633, E 2241920 Lat 46°36'42" Long 119°32'15"	Hole history (Fenix & Scisson, 1977d) Core & core photographs (BWIP Sample Repository) Lithological & mechanical logs (BWIP Library) Geochemical sample results (BWIP Library) Physical & thermal tests (Duvall and Others, 1978)
DC-11	Core	385'	PN 60693, W 53026 LN 465859, E 2242144 Lat 46°36'24" Long 119°32'12"	Hole history (Fenix & Scisson, 1978b) Core & core photographs (BWIP Sample Repository) Lithological & geomechanical logs (BWIP Library) Geochemical sample results (BWIP Library) Physical & thermal tests (Colorado School of Mines, 1978)
DDH-1	Core	1,165'	PN 49367, W 48347 LN 454545, E 2246851 Lat 46°34'32" Long 119°31'6"	Core & core photographs (BWIP Sample Repository) Lithological log & geochemical results (ARHCO, 1976) Geophysical logs (BWIP Library)

Table A-5 (continued)

BOREHOLE DESIGNATION	TYPE	DEPTH	LOCATION	AVAILABLE INFORMATION
DDH-3	Core	3,540'	PS 30383, E 15232 LN 374958, E 2310635 Lat 46°21'18" Long 119°16'11"	Core & core photographs (BWIP Library) Lithological logs & geochemical results (ARHCO, 1976) Geophysical logs (BWIP Library) Paleomagnetic analysis (Packer & Petty, 1979) Hole history (Fenix & Scisson, 1970)
DH-2	Core	600'	T11N,R24E,15R2 LN 401900, E 217990* Lat 46°26.01'* Long 119°47.22'*	Lithological log & geochemical results (ARHCO, 1976) Core & core photographs (BWIP Sample Repository) Geophysical logs (BWIP Library) Locations from topographic map ±200' (USGS Maiden Springs, 7-1/2')
DH-4	Core	4,776'	T15N,R28E,30Q LN 520550, E 2287750* Lat 46°45.31'* Long 119°21.15'*	Core & core photographs (BWIP Sample Repository) Lithological logs & geochemical results (ARHCO, 1976) Geophysical logs (BWIP Library) Paleomagnetic analyses (Packer & Petty, 1979) Physical & thermal tests (Colorado School of Mines, 1978) Hole history (Fenix & Scisson, 1972a) Locations from topographic map ±200' (USGS Corfu, 15')
DH-5	Core	5,002'	T15N,R24E,28N LN 519000, E 2168500* Lat 46°45.2'* Long 119°49.6'*	Core & core photographs (BWIP Sample Repository) Lithological logs & geochemical results (ARHCO, 1976) Geophysical logs (BWIP Library) Paleomagnetic analysis (Packer & Petty, 1979) Physical & thermal tests (Colorado School of Mines, 1978) Hole history (Fenix & Scisson, 1972a) Locations from topographic map ±500' (USGS Beverly SE, 7-1/2')
DB-1	Core	990'	PH 1633, E 13573 LN 406970, E 2308894 Lat 46°26'34.03" Long 119°16'28.74"	Hole history (Fenix & Scisson, 1974) Core & core photographs (BWIP Sample Repository) Geophysical logs, lithologic logs & geochemical data (BWIP Library)
DB-2	Core	924'	PN 15323, E 12713 LN 420592, E 2282573 Lat 46°28'52.32" Long 119°22'41.81"	Hole history (Fenix & Scisson, 1974) Core & core photographs (BWIP Sample Repository) Geophysical logs, lithologic logs & geochemical data (BWIP Library)
DB-4	Core	1,403	PN 34673, W 27437 LN 439904, E 2267799 Lat 46°32'5.00" Long 119°26'9.19"	Hole history (Fenix & Scisson, 1974) Core & core photographs (BWIP Sample Repository) Lithological logs & geochemical data (BWIP Library)

Table A-5 (continued)

BOREHOLE DESIGNATION	TYPE	DEPTH	LOCATION	AVAILABLE INFORMATION
DB-5	Core	908'	PN 51889, W 52377 LN 457056, E 2242815 Lat 46°34'57.45" Long 119°32'3.54"	Hole history (Fenix & Scisson, 1974) Core & core photographs (BWIP Sample Repository) Lithological logs & geochemical data (BWIP Library)
DB-7	Core	812'	PS 16279, W 23534 LN 388963, E 2271833 Lat 46°23'41.58" Long 119°25'21.44"	Hole history (Fenix & Scisson, 1974) Core & core photographs (BWIP Sample Repository) Lithological logs & geochemical data (BWIP Library)
DB-8	Core	1,076'	PN 41994, W 42063 LN 447188, E 2253154 Lat 46°33'18.78" Long 119°29'37.32"	Hole history (information not complete) Core & core photographs (BWIP Sample Repository) Lithological logs & geochemical data (BWIP Library)
DB-9	Core	589'	PN 62200, W 56200 LN 467350, E 2239000 Lat 46°36.62" Long 119°33.09"	Hole history (information not complete) Core & core photographs (BWIP Sample Repository) Lithological logs & geochemical data (BWIP Library) Location from topographic map ±500'(USGS Corral Canyon, 15')
DB-10	Core	893'	PN 51236, W 35886 LN 456446, E 2259308 Lat 46°34'49.36" Long 119°28'7.55"	Hole history (information not complete) Core & core photographs (BWIP Sample Repository) Lithological logs & geochemical data (BWIP Library)
DB-11	Core	1,046'	PN 49426, W 100348 LN 454470, E 2194850 Lat 46°34'37.16" Long 119°43'30.58"	Hole history (information not complete) Core & core photographs (BWIP Sample Repository) Lithological logs & geochemical data (BWIP Library)
DB-12	Core	643'	PN 63009, W 95020 LN 468067, E 2200144 Lat 46°36'50.86" Long 119°42'12.84"	Hole history (information not complete) Core & core photographs (BWIP Sample Repository) Lithological logs & geochemical data (BWIP Library)
DB-13	Core	1,292'	PN 17333, W 47318 LN 422513, E 2247963 Lat 46°29'15.85" Long 119°30'56.01"	Hole history (information not complete) Core & core photographs (BWIP Sample Repository) Lithological logs & geochemical data (BWIP Library)
DB-14	Core	1,038	PN 25080, W 79512 LN 430178, E 2215749 Lat 46°30'35.24" Long 119°38'35.20"	Hole history (information not complete) Core & core photographs (BWIP Sample Repository) Lithological logs & geochemical data (BWIP Library)

LN & E are Lambert North & East Co-ordinates
PN, S, E, & W are Hanford Co-ordinates Plant North, South, West & East
*Location approximate

Sampling, description, and chemical analysis of basalt chips were used to define major stratigraphic intervals in rotary holes as drilling proceeded. Chips were analyzed for TiO_2, CaO, and BaO within a few hours of collection on an energy dispersive X-ray fluorescence system. These key oxides, together with known stratigraphic relations and the drilling rate log, were used to identify stratigraphic units such as the Umatilla Member and horizons such as the contact between the Wanapum Basalt and the Grande Ronde Basalt and the contact between Sentinel Bluffs flows and Schwana flows. Identification of these stratigraphic horizons during drilling was necessary to track drilling progress, to locate casing points and hydrologic test intervals, and to assure that objective stratigraphic horizons had been reached when holes were drilled to their total depth.

Six deep, rotary boreholes have been drilled in the Pasco Basin; WW-6, RSH-1, ARH-DC-1, DC-3, DC-5, and DC-7 (Figure A-4). The first borehole, WW-6 was drilled to 803 feet (∿245 meters) in 1926 and deepened to 3,660 feet (∿1,115 meters) in 1933. The only information available at this time on this hole is a driller's log. Borehole RSH-1 was drilled to 10,665 feet (∿3,250 meters) in 1956-1957 and was reentered in 1967. Available information has been summarized and includes limited chemical, palynologic, and petrologic characterization of drilling returns and sidewall cores, and a complete suite of geophysical logs. This information and the information derived from nearby DH-2 were used to construct the stratigraphic column for RSH-1. Results of recent hydrologic testing in RSH-1 are given by Gephart and Others (1979).

Rotary boreholes DC-5 and DC-7 were drilled during late 1977 and early 1978 as hydrologic test holes; each was paired with an adjacent core hole, DC-4 and DC-8, respectively. The stratigraphic relationships observed in these boreholes (Figure A-4) are based on drilling rate logs and geophysical logs for DC-5 and DC-7 and geochemistry and paleomagnetic directional measurements for DC-4 and DC-8. Information available for DC-5 and DC-7 includes geophysical logs, drilling rate logs, and hole histories.

Four series of core holes have been drilled on the Hanford Site. The first series was 5 holes drilled during the initial feasibility studies from 1969-1973. Two were relatively shallow holes, DDH-1 (1,165 feet [355 meters]), and DH-2 (600 feet [183 meters]), and were drilled to define the upper stratigraphy of nearby deep rotary holes, ARH-DC-1 and RSH-1. The other 3, DDH-3, DH-4, and DH-5, were deep holes (greater than 3,000 feet [900 meters]) drilled to examine the stratigraphy of the Grande Ronde Basalt. Many fundamental stratigraphic relationships were recognized from the initial petrographic and geochemical analyses on samples from these 3 core holes.

The second series of core holes was begun in 1977. The first core hole, DC-2, was drilled to 3,300 feet (∿990 meters). It was sited near an existing deep rotary hole, ARH-DC-1, to allow cross-hole testing and to verify the stratigraphic section penetrated by ARH-DC-1. During 1978, 2 slant holes were drilled from DC-2 to allow coring and hydrologic testing through the Umtanum unit at an angle of approximately 25

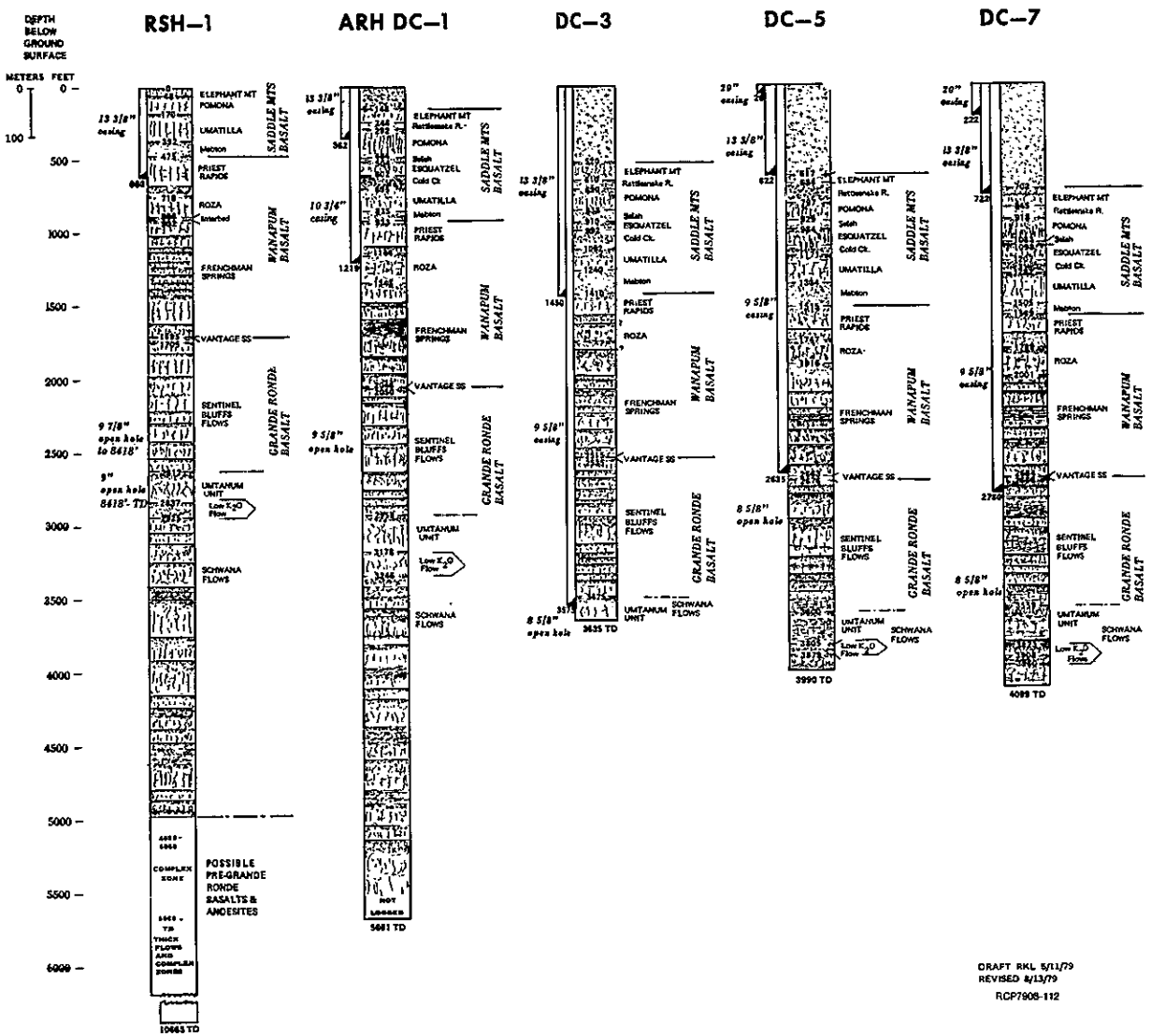

FIGURE A-4. Stratigraphic Summaries, Rotary Boreholes (no stratigraphic summary report available for Walla Walla Number y).

degrees. Next in this second series were 3 deep core holes, DC-4, DC-6, and DC-8, and 2 shallow test holes, DC-10 and DC-11; all drilled during 1978. The 3 deep core holes have been geophysically logged and gyroscopically surveyed. Lithologic, fracture, chemical, and paleomagnetic analyses have been made from core from these 3 core holes. Core holes DC-10 and DC-11 were drilled as test and characterization holes for the Near-Surface Test Facility excavations.

The third series of core holes is the DB series (Figure A-5). The 13 DB holes average about 1,000 feet (∿300 meters) deep and were drilled through the Saddle Mountains Basalt and into or through the Mabton interbed.

The fourth series consists of 12 core holes which penetrate through the Ringold Formation only. Paleomagnetic analyses have been done on 6 of these core holes. These core holes are in the DH series (except DH-1 and DH-2); they are not listed on Table A-5.

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Drillers' Logs, Cable Tool Samples, Drilling Rate Logs, and Chip Samples

The driller's logs contain information on the texture and lithology of the sediments. Samples were taken at 5-foot (1.5-meter) intervals to detect major changes in texture. This information was used to define major stratigraphic units and facies changes over 80,000 sediment samples (mostly cable tool samples were taken from the approximately 400 sediment wells and from the closely spaced, shallow monitoring wells on the Hanford Site [Additon, 1977]).

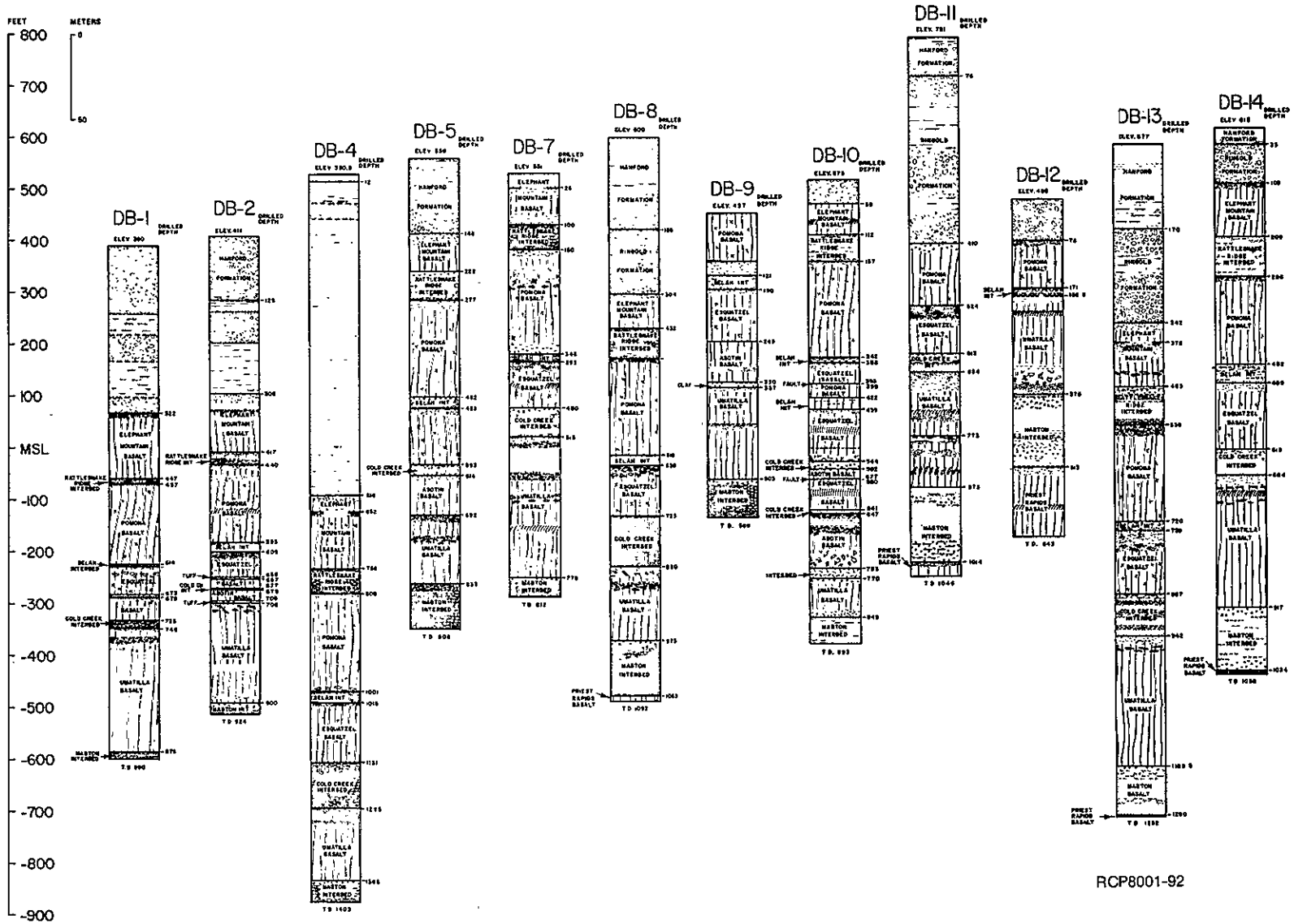
Borehole Geophysical Logging

Geophysical logging is a useful method for establishing stratigraphic relationships, especially when confirmed by other kinds of chemical or physical analysis. Most geophysical borehole logging in the Pasco Basin boreholes has been by different operators; these include several commercial oil field logging companies, the Washington State University's Geohydrology Group, and Pacific Northwest Laboratory. The variability in equipment types, logging methods, and reporting formats hampers positive comparisons.

A wide range of logs were run; these included standard logs such as temperature, sonic, gamma-gamma density, neutron porosity, caliper, natural gamma, resistivity, spontaneous potential, and scintillation probe, and special-purpose logs such as magnetic susceptibility, induced polarization, borehole gravity, borehole televiewer, dipmeter, flowmeter, and radioactive tracer.

The most useful logs for stratigraphic correlation have been the sonic, density, porosity, and natural gamma (gamma ray) logs. Sonic density and porosity logs are useful for showing some intraflow variations in physical properties.

FIGURE A-5. Stratigraphic Summaries, DB Holes.



Core Logging and Sampling

Core drilling is a primary means of collecting subsurface data in the Pasco Basin. Core holes have been drilled up to 5,000 feet (∿1,500 meters) by standard methods with very good recovery.

Core holes have been instrumental in developing stratigraphic interpretations measuring rock mechanical and hydrological properties and waste-rock chemical interactions. Stratigraphic relationships in core holes have been interpreted using information from lithologic logging, core photography, and chemical, petrographic, and paleomagnetic characterization. Lithologic logging included a description of the structure, texture, mineralogy, and alteration of the basalt core. This information was entered on standard forms to facilitate documentation and comparison. All core was photographed in color before sampling or storage to record the original state of the core.

Core samples were chosen at selected intervals with a minimum of one core sample per evident flow. Samples were analyzed for major element content by X-ray fluorescence and trace element content by neutron activation analysis. Thin sections and polished sections were prepared and limited studies on these sections were performed using transmitted light and reflected light microscopy and by electron microprobe. Results of the chemical analysis were used with other criteria to identify and correlate basalt units.

Fracture Logging

Over 12,000 feet (∿3,600 meters) of core fractures have been described and logged. Fractures were examined and length, strike, dip, width, filling, appearance, mineralogy, and roughness were recorded for computer analysis. Relative orientation of the core from individual flows was made using the remanent magnetic direction measured with a fluxgate magnetometer. This orientation was used to establish an arbitrary "north," and the strike directions of fracture were measured relative to this "north." This procedure gave internally consistent "north" direction for some flows, but for other flows it did not (Packer and Petty, 1979). The method is under evaluation. Up-direction arrows were routinely marked on all core segments to prevent core from being returned to the core box upside down after examination.

Core analysis for engineering properties is on a non-routine basis by subcontract. Results are available from several core holes.

Geophysical Surveys

Geophysical surveys were made over selected areas of the Pasco Basin by Rockwell Hanford Operations and subcontractors. Locations of major geophysical surveys are shown in Figure A-6.

Geologic conditions within the Pasco Basin required that different types of geophysical surveys be utilized (Table A-6). The survey types used were mainly on the depth to target, the amount of detail required,

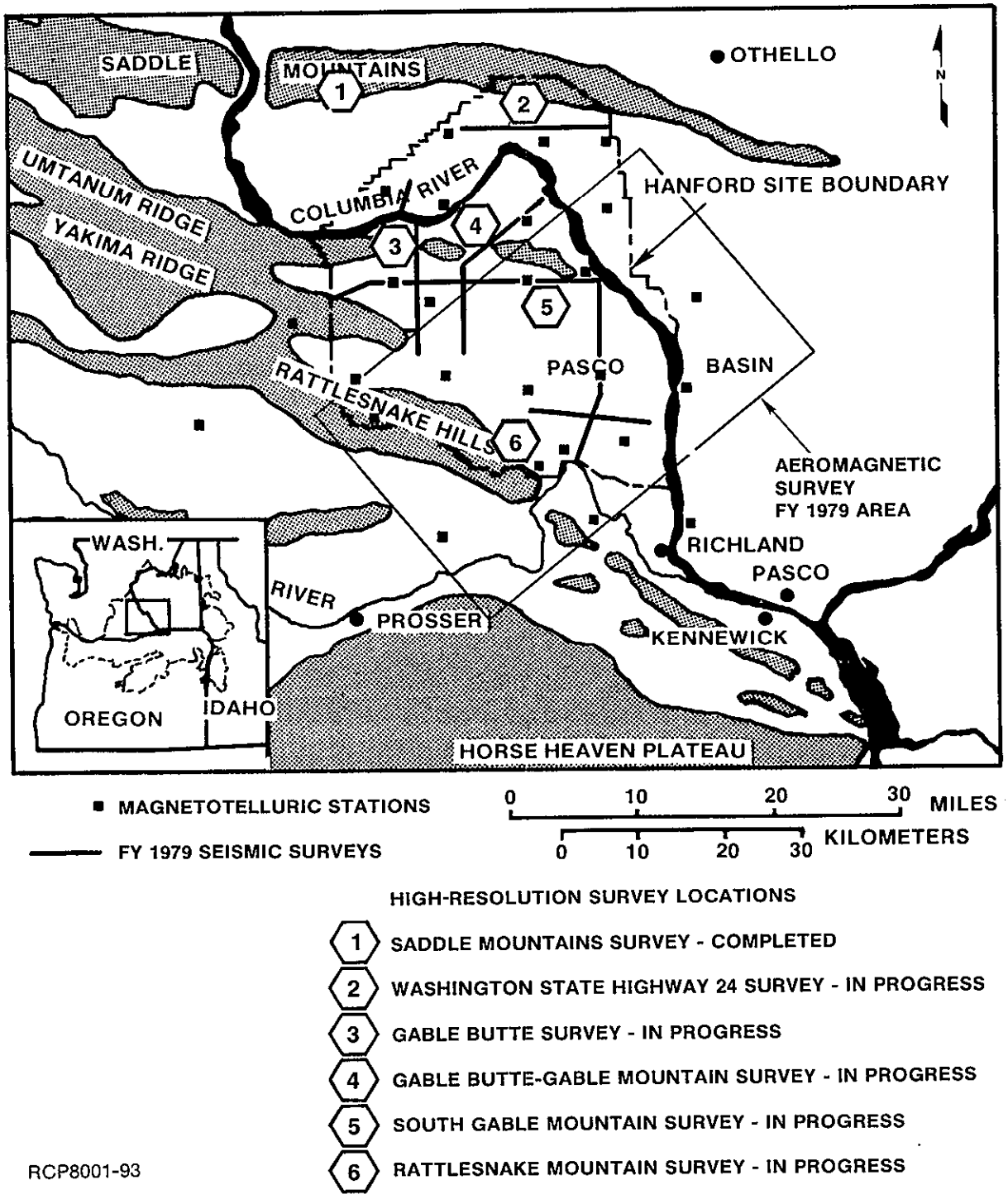


FIGURE A-6. Locations of Pasco Basin Geophysical Surveys.

TABLE A-6. Categories of Geophysical Surveys and Subsurface Regions of Investigations--Pasco Basin.

GEOPHYSICAL SURVEY TYPE	SUBSURFACE REGION OF INVESTIGATION: Less than about 500 Feet (150 Meters): 200 to 500+ Feet (60 to 150+ Meters)	Less than about 500 Feet (150 Meters): 500+ to 5,000 Feet (150+ to ∿1,500 Meters)	Greater than about 5,000 Feet (∿1,500 Meters)
High-Resolution Surveys			
Ground Magnetic Survey	X		
Turam Survey	X		
Direct Current Resistivity Survey	X		
Gravity Survey	X		
Refraction Seismic Survey	X		
Standard Surveys			
Aeromagnetic Survey	X	X	X
Reflection Seismic Survey (VIBROSEIS)	X	X	
Magnetotelluric Survey	X	X	X
Gravity Survey	X	X	X

and the expected geologic conditions along the survey route. The first type of geophysical surveys were termed high-resolution surveys. These surveys were ground surveys performed by Rockwell Hanford Operations' geophysicists and were designed to locate faults, folds, erosional channels, and related geologic structures in the uppermost Saddle Mountains Basalt flows and in the 200 to 500 feet (60 to 150 meters) of sediments which cover these basalts. The high-resolution surveys were used to trace specific structures identified through drilling, other geophysical surveys, and surface geologic mapping. The second type of geophysical survey was termed standard surveys (Table A-6). These surveys were designed to obtain geologic information from depths of approximately 200 to 500 feet (60 to 150 meters) below the surface to as deep as the crust-mantle boundary. These surveys were subcontracted to firms providing that type of service.

High-Resolution Surveys. Six types of high-resolution geophysical surveys were used in the Pasco Basin: (a) the ground magnetic survey; (b) the Turam survey; (c) the galvanic resistivity survey; (d) the self-potential survey; (e) the gravity survey; and, (f) the refraction seismic survey. Each of these surveys responds to specific geophysical parameters within the subsurface. High-resolution geophysical surveys were completed across the Saddle Mountains syncline and are in progress at five other locations (Figure A-6). Results from the Saddle Mountains survey are described in Appendix B.

Standard Surveys. Four types of standard geophysical surveys were used in the Pasco Basin. Three of these techniques (reflection seismic, gravity, and aeromagnetic surveying) are suitable for identifying relatively shallow features from the ground surface to about 4,000 feet (1,200 meters) deep. The fourth method, magnetotelluric surveying, is responsive to both the shallow and the deep regions and provides an integrated picture of the total section being investigated.

Seismic reflection, aeromagnetic, and magnetotelluric surveying were tested onsite to evaluate their applicability to specific needs. These initial tests led to reflection seismic, aeromagnetic, and magnetotelluric surveys and to plans for multi-level aeromagnetic and gridded reflection seismic surveys. Methodology and results from the aeromagnetic, reflection seismic, and magnetotelluric surveys are described in Appendices C, D, and E.

ANALYTICAL SUPPORT STUDIES

Analytical support studies were used mainly to assist in the identification of the various basalt stratigraphic units (flows, members, and formations) and to aid in refinement of knowledge of the sediment stratigraphy. Correct identification of basalt units, often difficult because of their overall similarity, was needed to interpret structural and stratigraphic relationships and trace the lateral continuity of units.

X-Ray Fluorescence

Selected rock samples were shipped to the Basalt Research Laboratory, Department of Geology, Washington State University for major oxide X-ray fluorescence analysis. Included with each shipment of 25 samples was an internal standard consisting of Umatilla Basalt (Additon, 1977).

Samples were prepared and analyzed following standard operating procedures for the laboratory (Hooper and Others, 1976). Total precision of the analytical techniques used was estimated by Hooper and Others (1976) for 13 sets of beads analyzed over a short period of time. Instrumental precision for an 8-hour operating period was estimated by Reidel (1978b). An estimate of the inter-analytical variation and bias for analysis used in this study over the 1978-1979 period is shown in Table A-7.

Neutron Activation

Neutron activation analyses of basalt samples were performed by G. Goles, University of Oregon. The procedures followed are outlined in his 1978 report.

Paleomagnetics

Basalts. In both basalt core and outcrop sampling, emphasis was placed on obtaining the freshest material possible by avoiding flow tops and bases and altered or fractured zones. Samples and outcrops were obtained using a non-magnetic, diamond-tipped drill. The process consisted of drilling the cores 3 to 5 inches (4.6 to 12.7 centimeters) in length, 0.98 inch (2.5 millimeters) in diameter, and orienting them in situ. For outcrop samples, the azimuth was measured to an accuracy of ±2 degrees using a compass mounted on a copper sleeve (Coe and Others, 1978) or a sun compass (Beck and Others, 1978). Sampling of drill cores was with a laboratory drill press modified to drive a water-cooled diamond bit. Depths below surface of all core samples were recorded. Additional details of the drill core sampling procedures are given in Beck and Others (1978) and Packer and Petty (1979).

All samples collected by Packer and Petty (1979) were analyzed using a 3-axis superconducting rock magnetometer with a dynamic range of 10^{-8} to 1 electromagnetic units per cubic centimeter. The magnetometer was directly interactive with a mini-computer that recorded and computed the precision of the measurement and calculated and stored the results on magnetic tape. Samples collected by Beck and Others (1978) and Coe and Others (1978) were analyzed on a spinner magnetometer.

Samples were demagnetized and remeasured in increasing levels of peak alternating magnetic fields. Samples collected by Packer and Petty (1979) were demagnetized while being spun about 3 axes. Coe and Others (1978) and Beck and Others (1978) used a 4-axis tumbler to ensure the sample rotation is a maximum number of orientations.

TABLE A-7. Interanalytical Run* Variation and Bias for Fiscal Years 1978 and 1979.

OXIDE	MEAN	1 STANDARD DEVIATION
SiO_2	54.89	0.27
AL_2O_3	14.59	0.14
TiO_2	2.27	0.01
Fe_2O	10.62	0.08
MnO	0.19	0.001
CaO	6.89	0.05
MgO	3.48	0.05
K_2O	1.83	0.04
Na_2O	2.93	0.22
P_2O_5	0.35	0.02

*Variation obtained for 43 separate sets of analyses for the fiscal year 1978 and 1979 data from BCRP-1 internal standard of Washington State University.

Sediment. A field reconnaissance located the best sediment exposures for sampling. Exposures were screened on the basis of access, completeness of section, absence of complex landsliding, minimal talus cover, and minimal weathering. The lithologies of the sections sampled were described. Finer grained sediments were, if present, preferentially selected for sampling. Core sections were selected using lithologic logs. Horizons to be sampled were chosen at the core repository by inspection of the cores after removing their foil wrapping. Cores that retained moisture and those containing finer grained sediments were preferentially sampled.

Details of the sampling procedure and analytical methods are given in Packer and Johnston (1979).

Caliche Dating

Caliche-coated pebbles and cobbles were broken at the sampling site to evaluate the relative density and purity of the carbonate component. Samples were scraped to obtain caliche closest to the surface of the clast. Whenever possible, only this portion of the caliche coating was used for laboratory analysis.

Laboratory processing closely followed the methods of Ku and Others (1979), except for the strength of the acid used in leaching the carbonates. In lieu of 1 normal HCl used, 0.1 normal HCl was used. During leaching, pH of the solution was kept constant to within 1 pH unit. Leaching with more dilute HCl was because the samples analyzed were low in carbonate content compared to those previously studied by Ku (1965). It was thought that the relatively dilute acid would minimize the effects of detrital contamination. The leachate and residue (0.1 normal HCl insoluble) fractions were separated by centrifuge and radiochemical analyses of ^{234}U, ^{238}U, and ^{230}Th were made on the solution aliquots of both the leachate and residue. Procedures for the isolation and purification of the uranium and thorium isotopes follow those described by Ku (1965). Sources of the purified uranium and thorium were counted in an alphaspectrometer equipped with silicon surface-barrier detectors. The alpha energy resolution is 60-80 thousand electron-volts at 5.5 million electron-volts. Corrections were applied for detrital contamination, and probable and maximum ages were calculated according to the scheme of Ku and Others (1979).

Carbon-14 Age Dating

The potential for finding datable ^{14}C material in the late Cenozoic sediments of the Pasco Basin is limited. Other dating techniques show that the Ringold Formation is too old for ^{14}C dating, and the Hanford formation sediments do not usually contain acceptable organic matter because of mixing during turbulent deposition. Datable matter was collected according to recommendations by Teledyne Isotopes Laboratory and laboratory analysis was by their procedure.

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APPENDIX B

SADDLE MOUNTAINS SYNCLINE GEOPHYSICAL SURVEY

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APPENDIX B

SADDLE MOUNTAINS SYNCLINE GEOPHYSICAL SURVEY

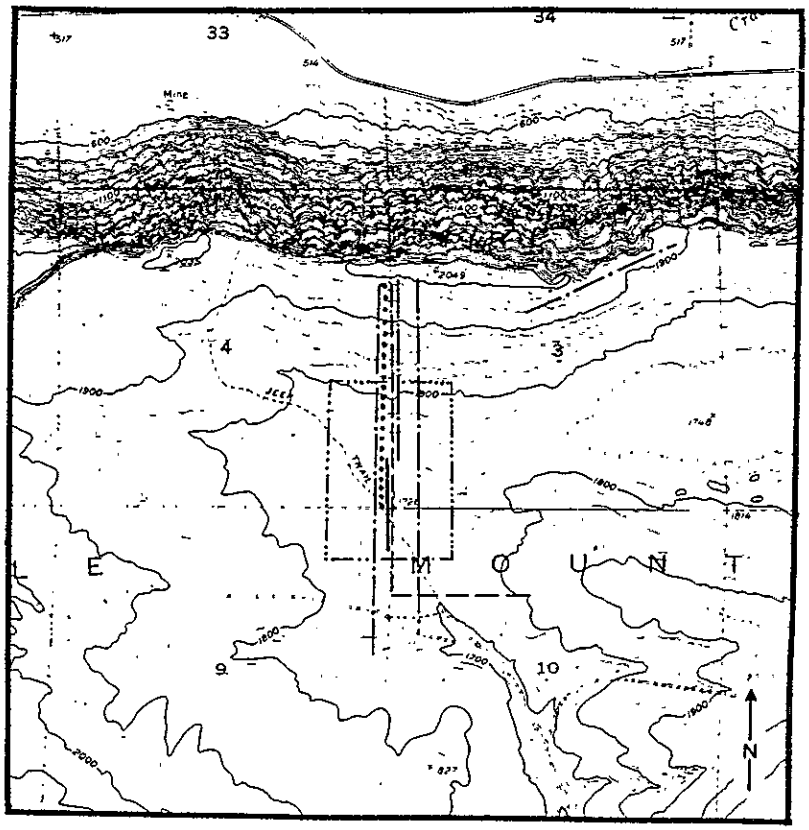
The Saddle Mountains syncline survey area is located approximately 2 miles (3 kilometers) east of Sentinel Mountain along the north-south boundary between Sec. 3, 4, 9, and 10, T15N, R24E (Figure B-1).

High-resolution geophysical techniques used in the Saddle Mountains syncline survey included direct current resistivity, gravity, ground magnetic surveys, refraction seismic, and turam surveys. One technique did not by itself provide conclusive interpretation, but several techniques evaluated together did yield a reasonably conclusive subsurface structural and stratigraphic interpretation.

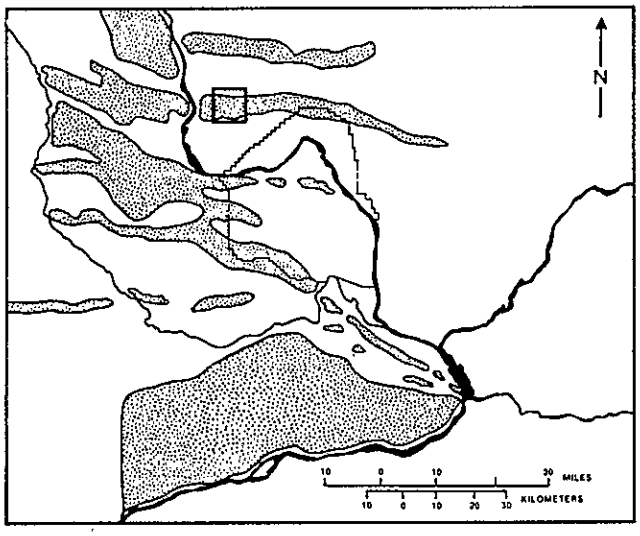
Figure B-2 shows plots of the geophysical data collected. Figure B-2a is a geologic north-south cross section along the survey line; it is based upon all techniques used, although locations of the deeper units shown are based primarily upon gravity modeling and outcrops on the north face of the Saddle Mountains. Figure B-2b is a comparison of observed Bouguer and calculated gravity values based upon the Figure B-2a cross section. A good match between observed and calculated values is evident except on the ends of the survey line. Discrepancies near the ends of the line are due to "tailing-off" effects and conditions beyond the survey line.

Figure B-2c shows ground magnetic data taken along two north-south traverses. These traverses suggest several features. At about the 2,900-foot (884-meter) locations, both curves exhibit a symmetrical, bell-shaped response. The symmetrical geometry of this response and its coincident location on both lines suggest an east-west-trending, nearly vertical structure influencing the magnetic field. Considering the geologic setting, the most probable structure would be a fault zone in the underlying basalt.

Figure B-2d represents the geoelectric cross section generated by 16 vertical, electrical sounding stations using direct current resistivity measurements with the Wenner array. Numerous, highly variable geoelectric units within the upper 9 to 15 feet (∿3.0 to 4.5 meters) are grouped together due to the difficulty in separating them at this scale. A readily apparent correlation of geoelectric units appears in the upper 100 feet (30 meters) north of Station 5. A highly resistive layer paralleling the land surface shows good correlation with diminishing thickness to the south. High resistivities in conjuction with low velocities found by seismic refraction data suggest the layer to be composed of dry, poorly consolidated sediments, perhaps caliche-bearing, similar to the Ellensburg interbed cropping out nearby on the north face of the Saddle Mountains. The thin layer of highly variable resistivity overlying this unit probably represents the surface layer of loess which is widespread in this area.



GEOPHYSICAL SURVEY LOCATIONS



INDEX

SURVEY TECHNIQUES

- Seismic Refraction
- Gravity
- Land Magnetic
- Direct Current Earth Resistivity
- Turam

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FIGURE B-1. Location Map, Saddle Mountains Geophysical Survey.

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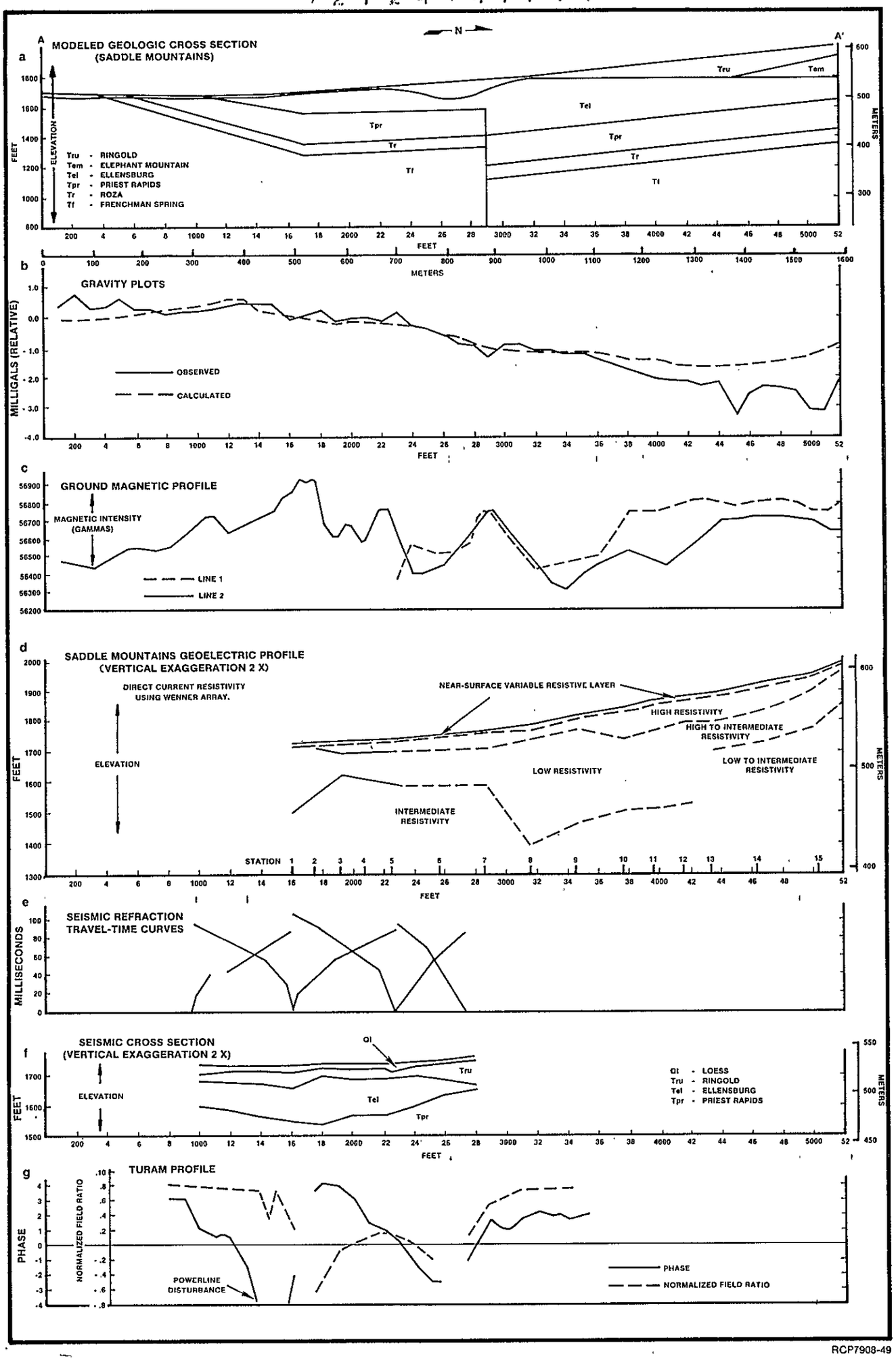

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FIGURE B-2. Saddle Mountains Geophysical Survey Results.

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Possible evidence for termination of Elephant Mountain Basalt can be seen in Stations 13 through 16. A moderately high resistivity unit, averaging 100 feet (30 meters) thick, can be extended no farther south than Station 13. The moderately high resistivity and thickness of this layer are within the expected range of basalt flows. Resistivities equivalent to those of this layer are much deeper in the section to the south of Station 13. Geoelectric units directly underlying this layer are relatively lower in resistivity, a feature which may be indicative of the Ellensburg interbed.

Figures B-2e and B-2f show seismic refraction data and interpretation between Stations 1 through 5. The seismic data are in good agreement with resistivity data for these stations. Stations 3 and 5 indicate highly resistive layers at a depth which correspond with a high-velocity seismic layer interpreted to be basalt. Station 7 contains a comparable resistivity layer at approximately the same elevation as Station 5. Immediately north of Station 7 is a deepening of the high resistive layers. Stations 8 through 11 all possess highly resistive layers at depths well below those in Stations 3 through 7. Because of the abruptness of this change between Stations 7 and 8, this discontinuity may represent structural offset or a steep paleotopographic feature in the basalts. The top of basalt in the synclinal axes is 150 to 200 feet (45 to 60 meters) deep. Seismic velocities indicate a well-consolidated sedimentary unit immediately above the basalt; then a sequence of moderately consolidated and unconsolidated surface sediments.

Figure B-2g shows data collected using the turam method. The structural offset near the 2,800-foot (853-meter) location suggested by gravity and magnetics is supported by anomalous responses with the turam method. Parallel turam traverses indicate a west-northwest strike as shown in Figure III-44.

Figure III-44 shows two structural features mapped by the above geophysical surveys. The axis of the Saddle Mountains syncline was located by the geophysical surveys about 200 feet (60 meters) north of Sec. 9 and 10, T15N, R24E; this is slightly south of the earlier inferred location. A minor fault was located about 1,000 feet (∿300 meters) north of the synclinal axis. This fault is probably associated with an anticlinal structure to the west.

Figure III-44 also shows a north-south gravity-modeled cross section through the study area. The top of basalt along with the syncline and fault locations are clearly indicated by all geophysical techniques used.

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APPENDIX C

AEROMAGNETIC SURVEY

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APPENDIX C

AEROMAGNETIC SURVEY

An aeromagnetic survey was flown over the central Pasco Basin by Quigson Prospects, Ltd., Tulsa, Oklahoma under contract to Rockwell Hanford Operations. The survey was flown in 9 separate missions between April 6 and April 21, 1979.

The aeromagnetic survey area (Plates III-6a to 6d) is 20 x 30 miles (32 x 48 kilometers). The survey was flown at a constant elevation of 4,000 feet (5,220 meters) along 44 northeast-southwest profiles approximately 32 miles (52 kilometers) long and 65 northwest-southeast profiles approximately 22 miles (35 kilometers) long that form an orthogonal grid pattern with a line spacing of approximately 0.5 mile (1 kilometer) (Plate III-6a). The survey area was "overflown" to reduce edge effects in the data processing.

The survey was flown with a twin-engine Piper Navajo equipped with a "stinger-mounted" proton precession magnetometer. The magnetometer sensor and associated electronics were coupled to a data acquisition system recording on 0.5-inch (1.3-centimeter) magnetic tape using a 9-track, 800 bit-per-inch format. A Doppler navigation system was used in the survey by trigger recording at a constant interval of 328 feet (100 meters) to locate all data points within 328 feet (100 meters). Corrections were applied to the data to cancel the effects of diurnal field changes, magnetotelluric interferences, and errors due to position.

The total magnetic field map (Plate III-6a) was produced by Quigson Prospects, Ltd. using the following procedures. Profile data were first corrected in straight-line fashion by an iterative process until the mean profile intersection mis-tie was at a minimum. In the second step, the profile was tilted linearly to a new minimum mean-profile intersection mis-tie. In the third step, intersection locations were moved one recording interval to again minimize profile intersection mis-ties (because all data are digital, locations are known to plus or minus one station interval; i.e., 328 feet [100 meters]). This process accomplished "loop-tying" of the data field. Corrected data were in profile form and were converted to a square grid for contouring. The computer grid unit dimension was approximately 1,000 feet (300 meters). Data were machine-contoured to produce the magnetic field map. The vector gradient map and the third- and eighth-order residual maps (Plates III-6b and 6c, respectively) were derived from the total magnetic field map. (Additional information on the data processing procedure is filed in the Basalt Waste Isolation Project Library.)

Preliminary interpretations of the areomagnetic maps have been made by Quigson Prospects, Ltd. and Rockwell Hanford Operations' geophysicists. Only qualitative interpretation of structures has been made to date (Plate III-6d). These interpretations are discussed in the structure section of Chapter III, mainly in the subsection on the structure of the central Pasco Basin.

The southwest quarter of the aeromagnetic survey area and Gable Mountain-Gable Butte area is characterized by moderate to extreme topographic relief, a thin veneer of sediment cover, and abundant outcrops of basalt. The remaining part of the survey area is covered by a relatively thick, sedimentary sequence which buries regions of moderate structural and topographic relief on the top-of-basalt surface. This area presents problems of interpretation due to the little-known magnetic properties of the sediments and structural control by the basalts on sediment deposition. However, because no anomalies in the total field map appear to correlate with the Ringold Formation exposures along Ringold Coulee and in the bluffs along the Columbia River in the eastern part of the aeromagnetic survey area, Ringold Formation sediments are assumed to have negligible effects in producing significant aeromagnetic anomalies. The effect of the Hanford formation on aeromagnetic anomalies is unknown.

Anomalies over the sediment-blanketed areas superficially resemble anomalies over the bedrock exposed areas, and linear highs and lows separated by moderate horizontal vector gradients are throughout the survey area. Overall, however, the gradients over sediment-covered areas are much more subdued than gradients over bedrock areas. This is a function of the radial distance from source to sensor and does not necessarily imply less structural complexity.

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APPENDIX D

REFLECTION SEISMIC SURVEY

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APPENDIX D

REFLECTION SEISMIC SURVEY

Reflection seismic surveying is the measurement of subsurface velocity variations caused by changes in density and elastic properties. At the Hanford Site, seismic reflections can be expected to occur at the boundaries between sediment fill and top-of-basalt section, between some thick interbeds and basalt flows, and between some thick basalt flows and thin basalt flows. These anticipated reflections are based on synthetic seismograms created from test shots made in boreholes.

The reflection seismic surveying technique was tested at three locations on the Hanford Site in fiscal year 1978 (Edwards in BWIP, 1978). The results of this test were used to design a survey which was to be made in fiscal year 1979. The fiscal year 1979 survey covered a total of 87 line-miles (140 line-kilometers) and was performed by Seismograph Service Corporation of Tulsa, Oklahoma using a VIBROSEIS energy source. This energy source was selected because it is a controlled energy source and produced data in a reliable, high-frequency band.

Figure D-1 shows routes of the reflection seismic survey lines. These survey lines were selected to concentrate data in the central Pasco Basin, to help locate known or suspected structures, and to provide profiles between boreholes. Processing and analysis of the seismic data were focused on continuously mapping the top of basalt and obtaining deeper reflections, if possible.

RECORDING PARAMETERS

Based on a test of the seismic reflection surveying method as reported by Heineck and Beggs (1978), the following survey and recording parameters were used.

Recording Unit

Number of Channels	- 48
Gain Mode	- Instantaneous floating point
Low-Cut Filter	- 27 hertz; 36 decibels per octave slope
Hi-Cut Filter	- 124 hertz; 72 decibels per octave slope
Notch Filter	- 60 hertz
Record Length	- 11.25 seconds (VIBROSEIS source)
Sample Rate	- 2 milliseconds

Detectors

Geophone Type	- 40-50 hertz
Number Per Trace	- 18-24
Pattern Length	- 100 feet (30.5 meters) (6-foot [2-meter] maximum uniform spacing)

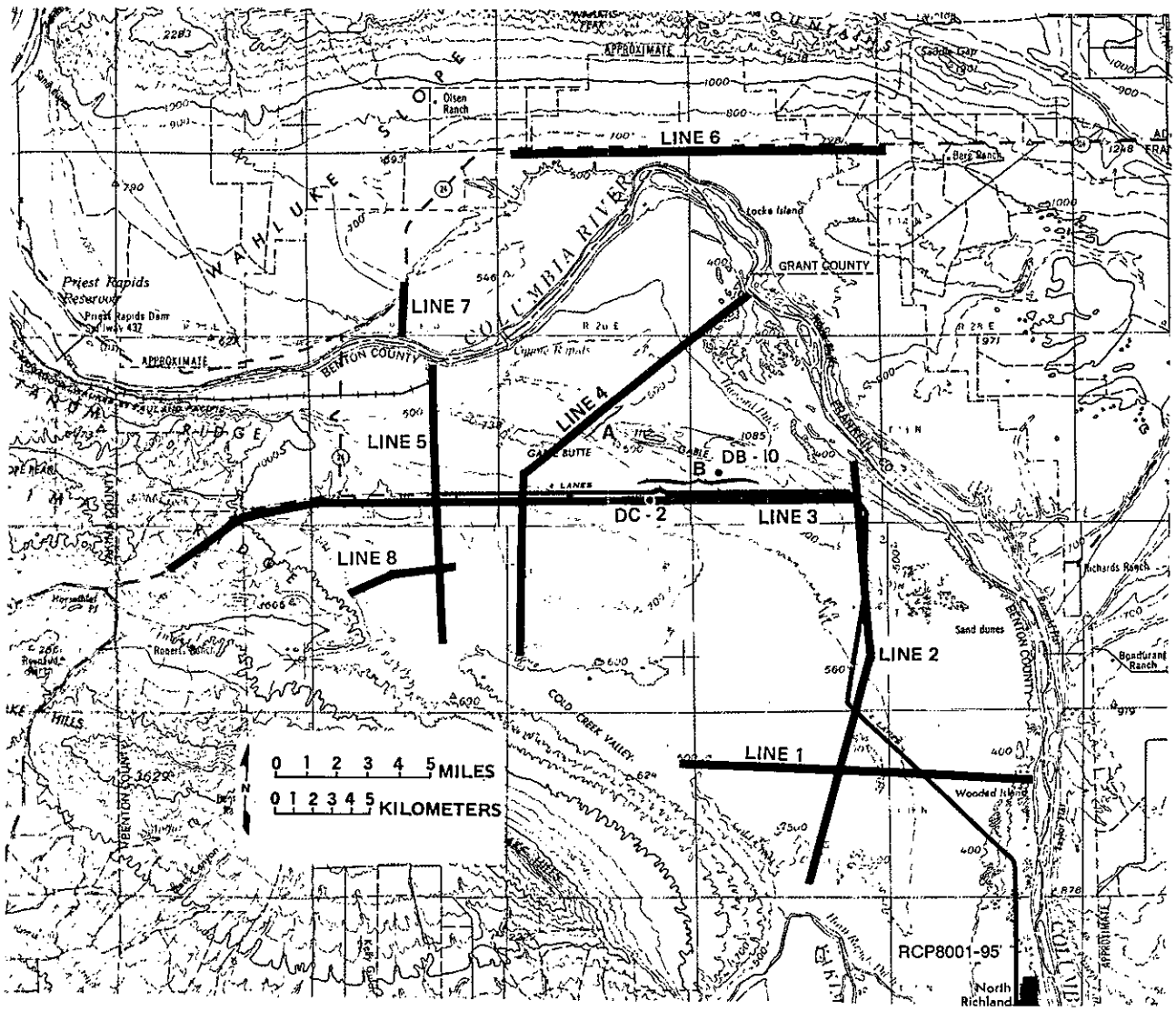

FIGURE D-1. Reflection Seismic Survey Lines.

Spread Geometry

Configuration	- Split-straddle, 3-station gap between traces 24 and 25
Station Interval	- 50 feet (15 meters)
Near Trace Offset	- 100 feet (30.5 meters)
Far Trace Offset	- 1,250 feet (381 meters)

VIBROSEIS Source

Sweep	- 30-120 hertz
Duration	- 10 seconds
Listening Time	- 1.25 seconds
Vibrator Pattern	- 3 in tandem 37 feet (11 meters) apart
Number of Sweeps	- 14 per vibrator pattern
Pattern Length	- 150 feet (46.5 meters) (1,200 percent coverage)

These parameters, as outlined, maximize broad-band, high-frequency data and minimize noise patterns.

Field records were delivered to an onsite data processing system for field processing. Processing steps as performed by the onsite system and by the home office of Seismograph Service Corporation are presented below.

DATA PROCESSING

Onsite processing was accomplished through use of trailer-mounted equipment which was equivalent to that used during the fiscal year 1978 experimental program. Computer hardware included a Raytheon 704, 24 kilobyte central processing unit, an array transform processor, 2 vacuum tape drives, two 75-megabyte disks, a teletype, a card reader, and an electrostatic plotter. Using the Phoenix computer system, rapid analysis and evaluation of recorded data through the brute stack and final stack were provided.

All post-stack refinements were made at the home office. Refinements included application of a program called Coherence Filtering to each of the eight lines of profile. Wavelet processing and wave equation migration were also conducted on selected segments of the post-stack data. In addition to these programs, film displays of final sections were generated.

Figure D-2 represents a flow diagram of the sequence and parameters used in processing data. For the most part, data processing followed guidelines established by the experimental program. However, there were several exceptions, some of which resulted from procedural changes or which utilized new programs and techniques; others were concerned with parameter refinements. These are explained below.

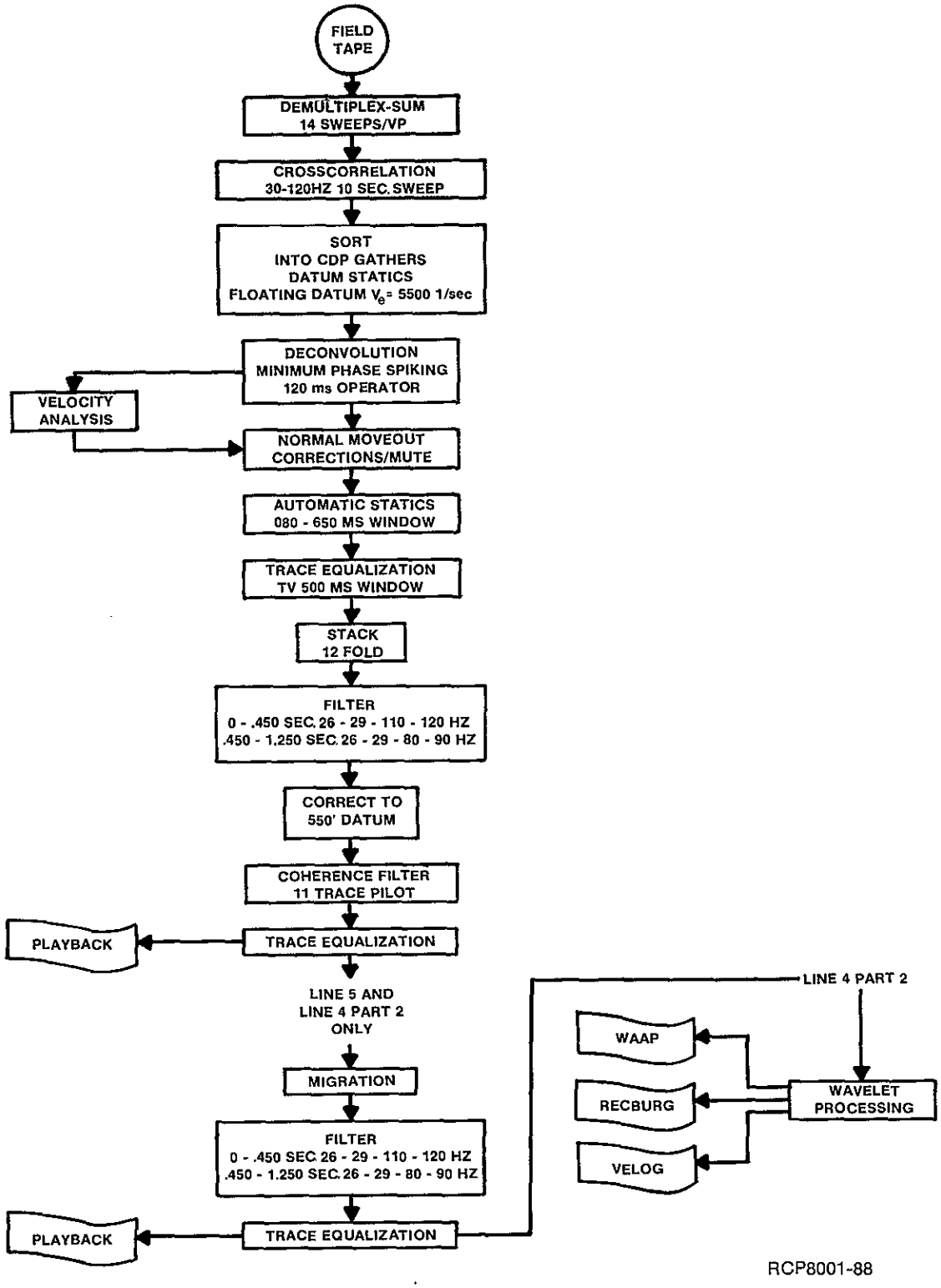

FIGURE D-2. Generalized Processing Flow Diagram.

Datum

Surface elevations vary from 400 to 1,200 feet (122 to 366 meters) above sea level across the survey area. To minimize time corrections to datum, a floating or variable datum was selected (usually within 50 feet [15 meters] of the surface elevation over a given area). This gave a more accurate determination of normal move out corrections and of muting pattern and enhanced the quality of shallow basalt reflections. These operations were performed on pre-stack or preliminary stack data. Final stack sections were tied to a constant datum of 550 feet (168 meters) above sea level, so time data from any section would be related to other sections.

Correction Velocity

A correction velocity to datum of 5,500 feet (1,675 meters) per second was determined from borehole velocity surveys and velocity analysis during data processing.

Deconvolution

Minimum phase spiking deconvolution was used instead of predictive deconvolution and total operator length was reduced from 200 milliseconds to 120 milliseconds. These parameters were selected from comparison of several deconvolution operators which included zero-phase deconvolution, predictive deconvolution with various gap lengths, and post-stack wavelet processing. Because of extreme variations in near-surface geophysical properties caused by fluctuations in weathering, thickness, and velocity as noted throughout the Hanford Site, reflection signal frequency and character also varied significantly. Spiking deconvolution was used to balance frequencies and to produce maximum uniformity of reflection character along with enhancement of higher frequency data. As a result of reflection sparsity below the top of basalt, wavelet processing did not perform as well as pre-stack minimum phase deconvolution. In general, wavelet processing is better suited to areas having several reflecting horizons, so that input signal phase can be statistically determined.

Coherence Filter

Random noise was attenuated through use of post-stack coherence filter instead of spatial deconvolution. The coherence filter is a recent development and has produced results superior to spatial deconvolution. The filter operates by creating a coherency or pilot trace from a scan along specified angles of dip for several adjacent traces. For these data, scans were generated along dips ranging from -8 milliseconds per trace (25-foot [7.5-meter] interval) to +8 milliseconds per trace over 11 adjacent traces. The coherence trace is then added to the original center trace of the 11 traces, and thus enhances both steep-dipping and flat- or gentle-dipping events. Random noise or coherent events with dips greater than 8 milliseconds per trace were attenuated. In very "noisy" areas, such as below about 600

milliseconds, few, if any, coherent events are present and the coherence filter appears to have randomly enhanced event lineups, especially near the scan of dip limits in these zones.

Stacking Velocities

Stacking velocities were generally revised from those used for experimental work. Although results from check-shot surveys conducted during the project were not completed in time for full incorporation into the processing, some initial results suggest that velocities used in earlier experimental work were somewhat low, especially in the upper basalt layers. Subsequent velocity revisions used in current processing appear to have emphasized and more adequately located the top of basalt; a prime objective. However, in so doing, it appears that shallower events in some areas may have been degraded.

Wave Equation Migration

Work segments were selected for wave equation migration study using a finite difference approximation of the wave equation. No significant interpretational differences were noted; therefore, other survey lines on the project were not "migrated."

Wavelet Processing

One "migrated" section was wavelet processed to demonstrate the ability of the program to estimate reflection coefficients in this area and to derive acoustic impedance displays. However, these results should be considered tentative and are not accurate representations of interval velocities and/or densities because of an inadequate statistical input due to lack of data.

RESULTS

Seismograph Service Corporation personnel performed field interpretations during the survey. They were also requested to use their limited knowledge of the local geology, in conjuction with their past experience and judgment, to make preliminary interpretations during final processing at their home office in Tulsa, Oklahoma. The final processing and preliminary interpretation of the records were completed and the results delivered to Rockwell Hanford Operations. These records are currently being interpreted by Rockwell Hanford Operations' geophysicists and geologists who are integrating the results with existing subsurface maps and with the results of other recently completed geophysical surveys. Results from this work were not available in time for inclusion in this report. Examples are given below to illustrate how the Seismograph Service Corporation preliminary interpretations and final-processed data are being integrated.

It is often incorrectly assumed that the seismic section is geometrically directly related to the geologic section. In reality, several plausible geologic sections can be interpreted from the same seismic section. A seismic section plots wave response to earth

impedance contrast as variations in amplitude versus time. In the computer processing of the seismic data, apparent velocities are chosen to produce the highest output amplitude response on the seismic section. This interpretive process assigns velocities to events on the section from which apparent velocities to the events, and therefore the depths, can be derived. The seismic and geologic sections derived are sensitive, therefore, to velocity variations.

Figure D-3 is a sample of the Seismograph Service Corporation reflection seismic record along line 4 in the area of Gable Mountain (Figure D-1). This record is representative of the quality of the data collected. On Figure D-3, steeply dipping seismic events between vibrator points (VP's) 1080 through 1110 are bounded by 2 nearly flat data zones on either side. Seismograph Service Corporation interpreted the basalt as sharply folded between VP's 1080 and 1110. However, Figure D-4, which shows the migrated true-time position of the events, indicates the "fold" collapses into an even shorter wavelength. Figures D-5 and D-6 show estimates of the impedances and interval velocities for the same area and indicate the response is fairly flat across the zone of steeply dipping events between VP's 1080 and 1110. The steeply dipping events on Figure D-3 could, therefore, be the seismic response to a point source expressed as diffractions on the seismic records. Diffractions usually are produced by high-velocity picks in the interpretation of the computer analyses. Consequently, an alternate interpretation by the Rockwell Hanford Operations' geological and geophysical staff shows an erosional formation of the uppermost basalt flow(s) between VP's 1080 and 1110 and a gentle dip to the northeast (Figure D-7). This interpretation is shown on Plate III-5, cross section E-E', and contrasts sharply with the steeply dipping fold limb interpreted by Seismograph Service Corporation.

Figure D-8 shows an interpretation of a segment of line 3 (Figure D-1) by Seismograph Service Corporation. This section runs from near core hole DC-2 to near core hole DB-10. The seismic section near DC-2 shows a normal, flat-lying section of weak data bounded by an anomalous zone around VP 680. East of this zone is a heightened response area where the top of basalt has been tentatively identified. East of VP 500, located due south of DB-10, 2 apparent faults are associated with an anticlinal fold centered near VP 455. Current geologic studies show that DB-10 penetrated a repeated geologic section interpreted as 2 reverse faults (see Chapter III, Structure). The apparent faults at VP's 480 and 430 might be related to the 2 faults penetrated by DB-10.

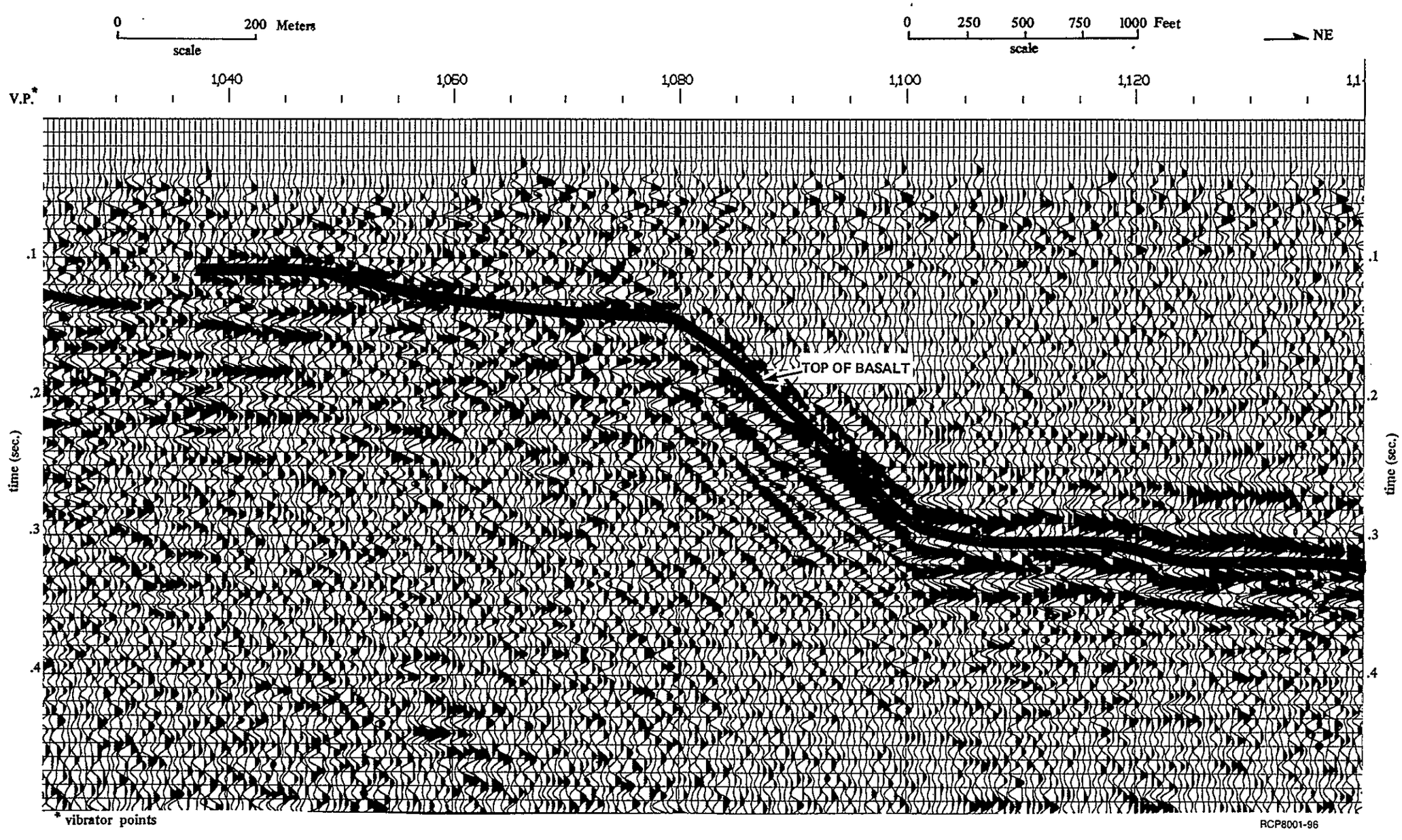

FIGURE D-3. Reflection Seismic Section, Gable Mountain and Gable Butte Area, Line 4, Interpreted by Seismograph Service Corporation.

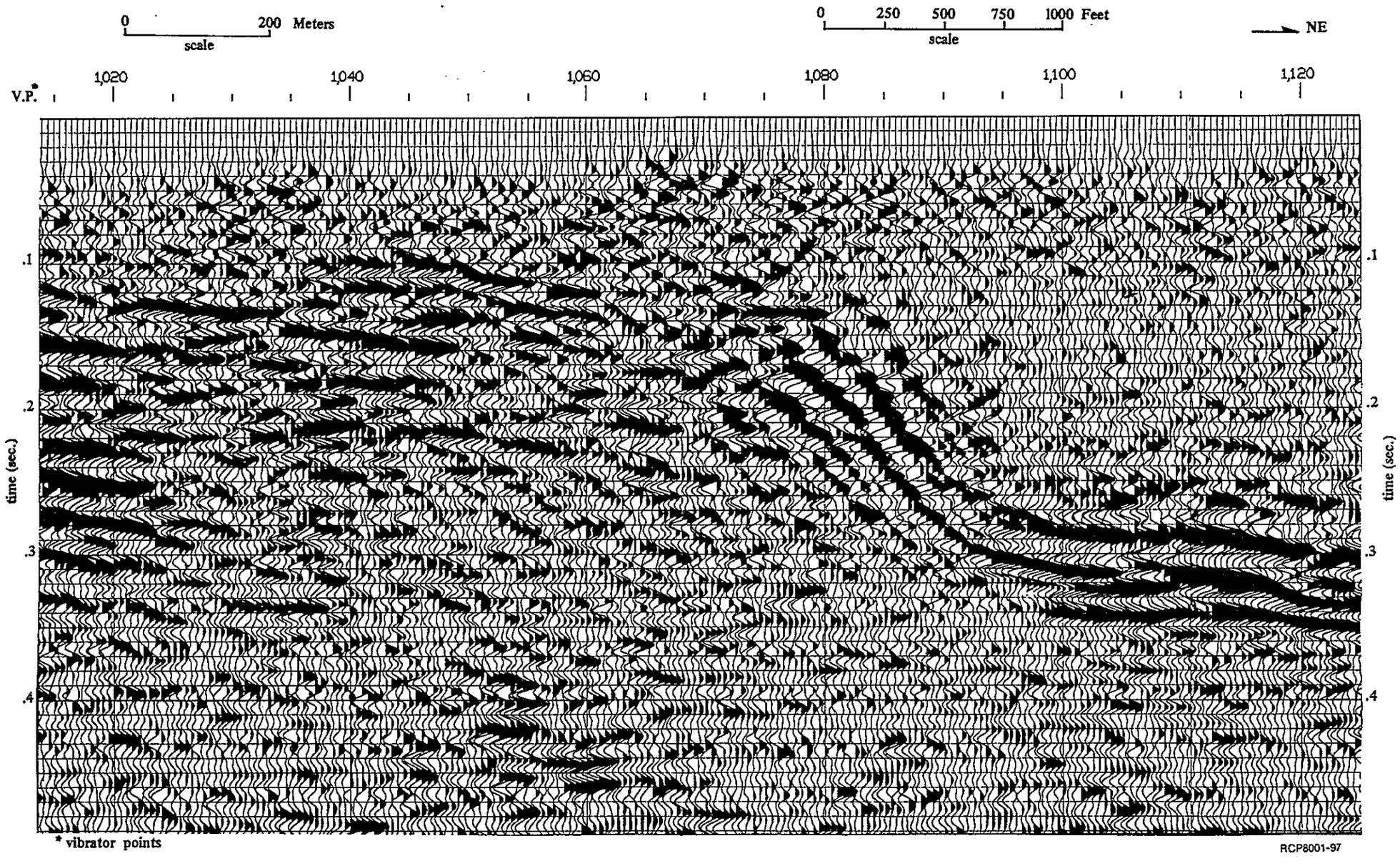

FIGURE D-4. Wave Equation Migrated Section, Gable Mountain and Gable Butte Area, Line 4.

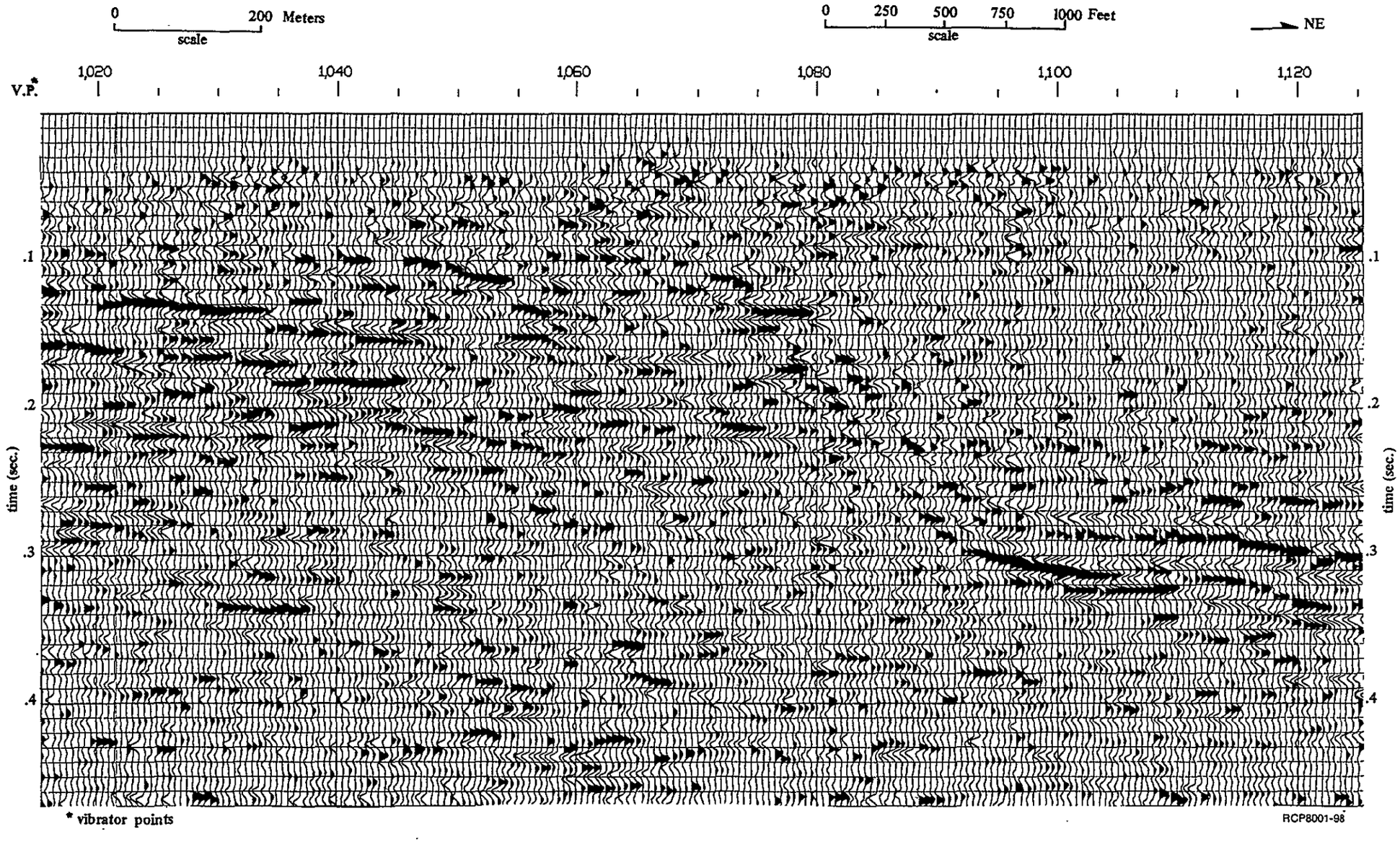

FIGURE D-5. Reflection Coefficient (Earth Impedance) Estimates, Gable Mountain and Gable Butte Area, Line 4.

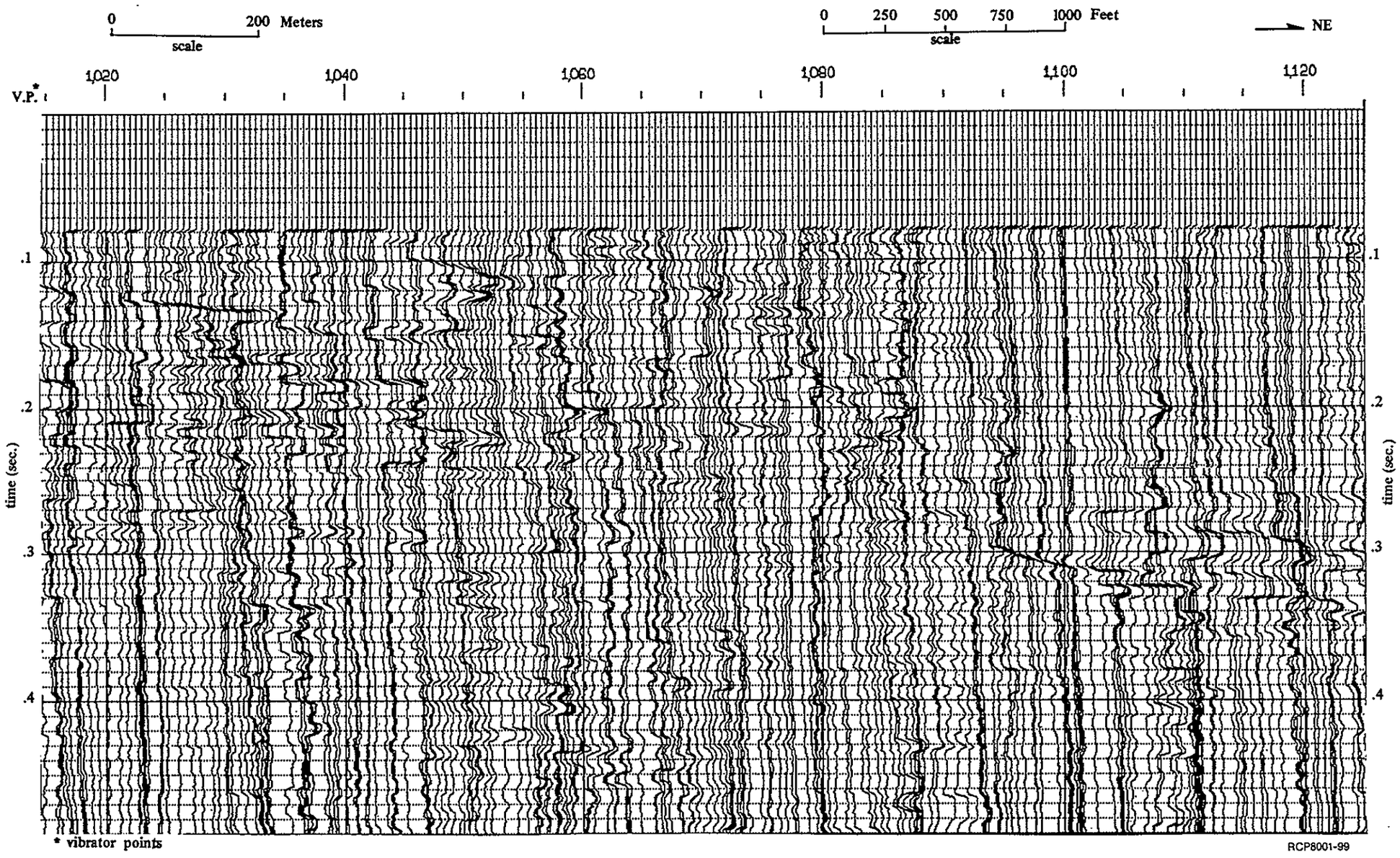

FIGURE D-6. Interval Velocity Estimates, Gable Mountain and Gable Butte Area, Line 4.

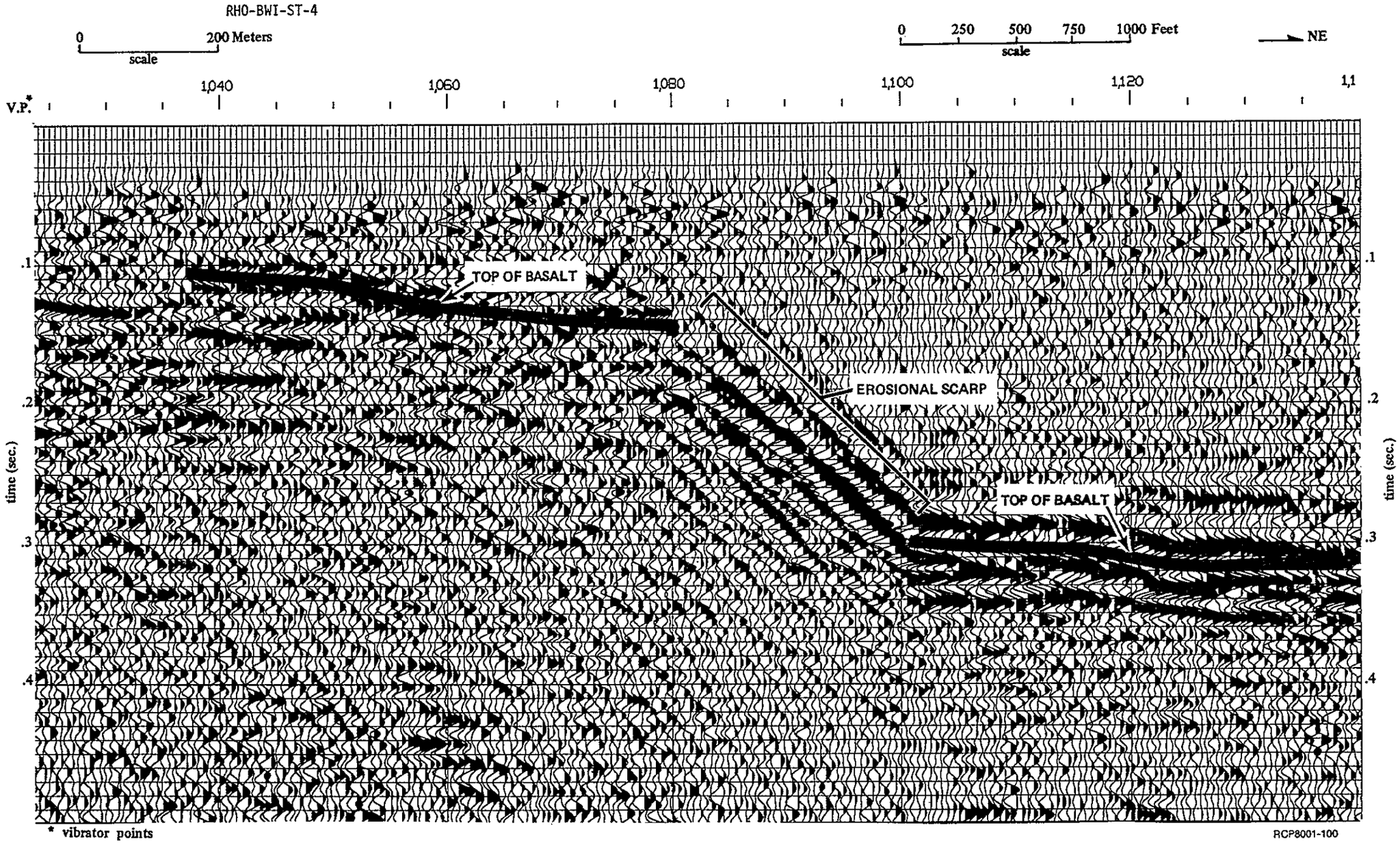

FIGURE D-7. Reflection Seismic Section, Gable Mountain and Gable Butte Area, Interpreted by Rockwell Hanford Operations' Geophysicists and Geologists.

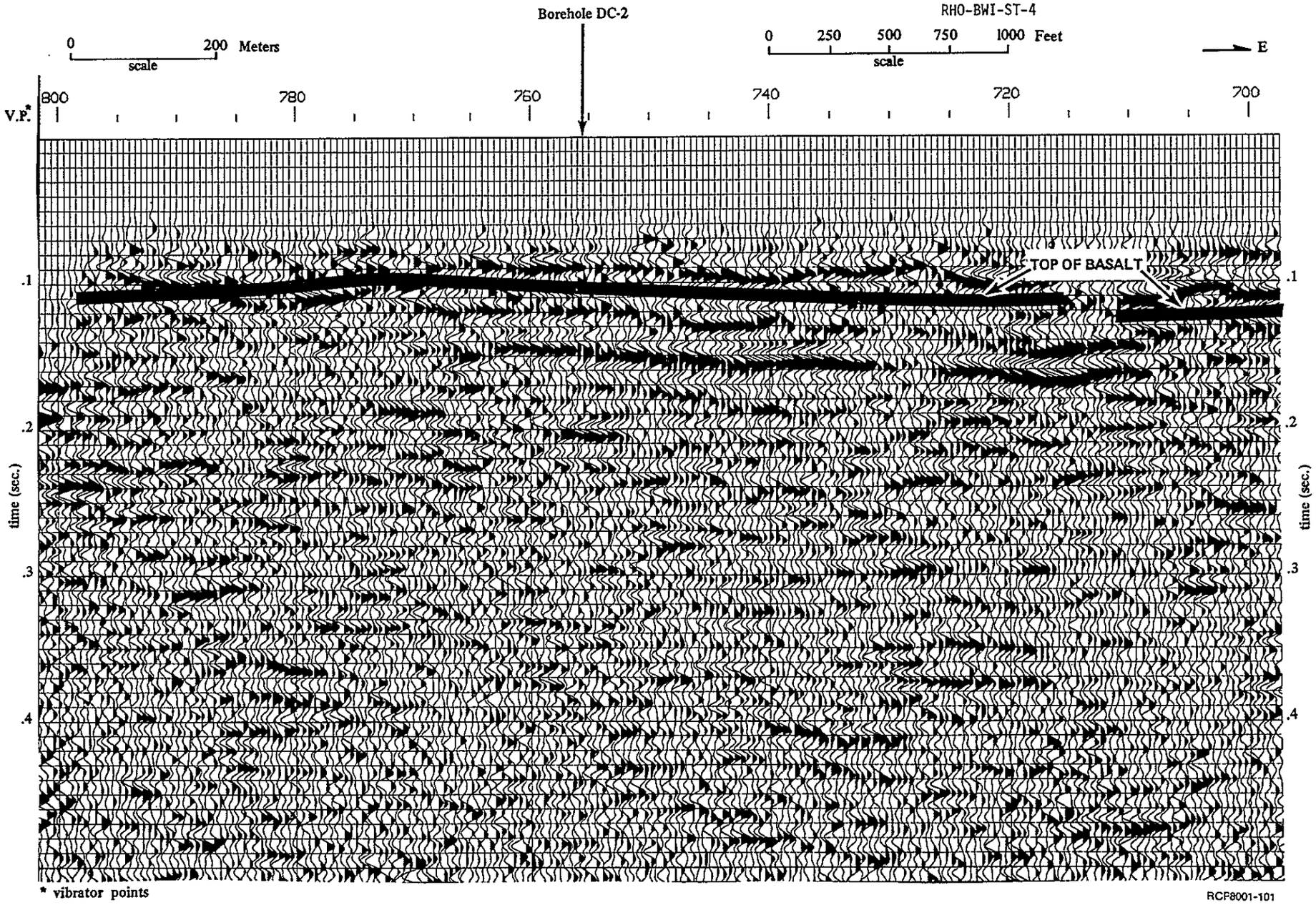

FIGURE D-8. Reflection Seismic Section, Gable Mountain and Gable Butte Area, Line 3 (Sheet 1).

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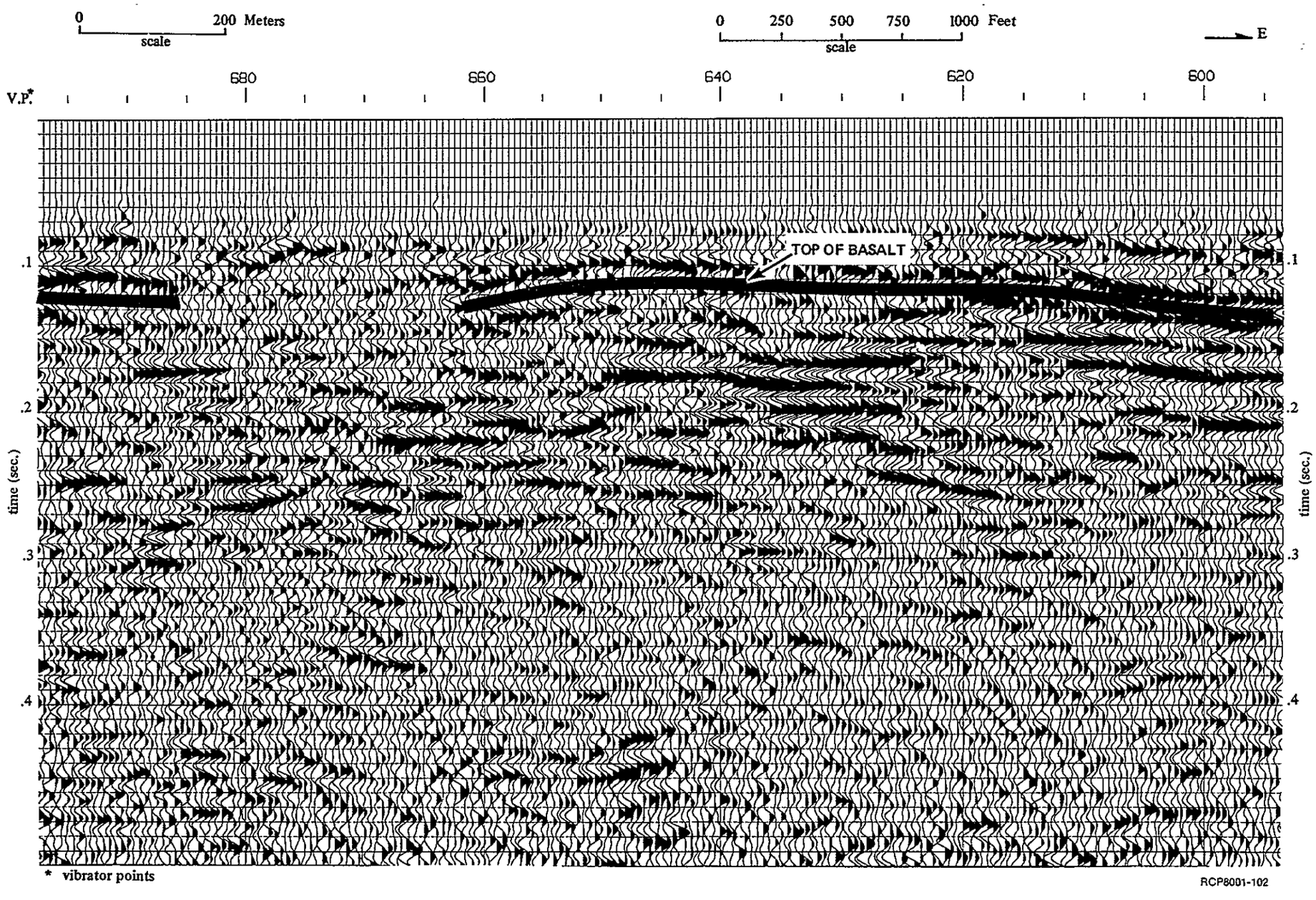

Figure D-8 (continued)

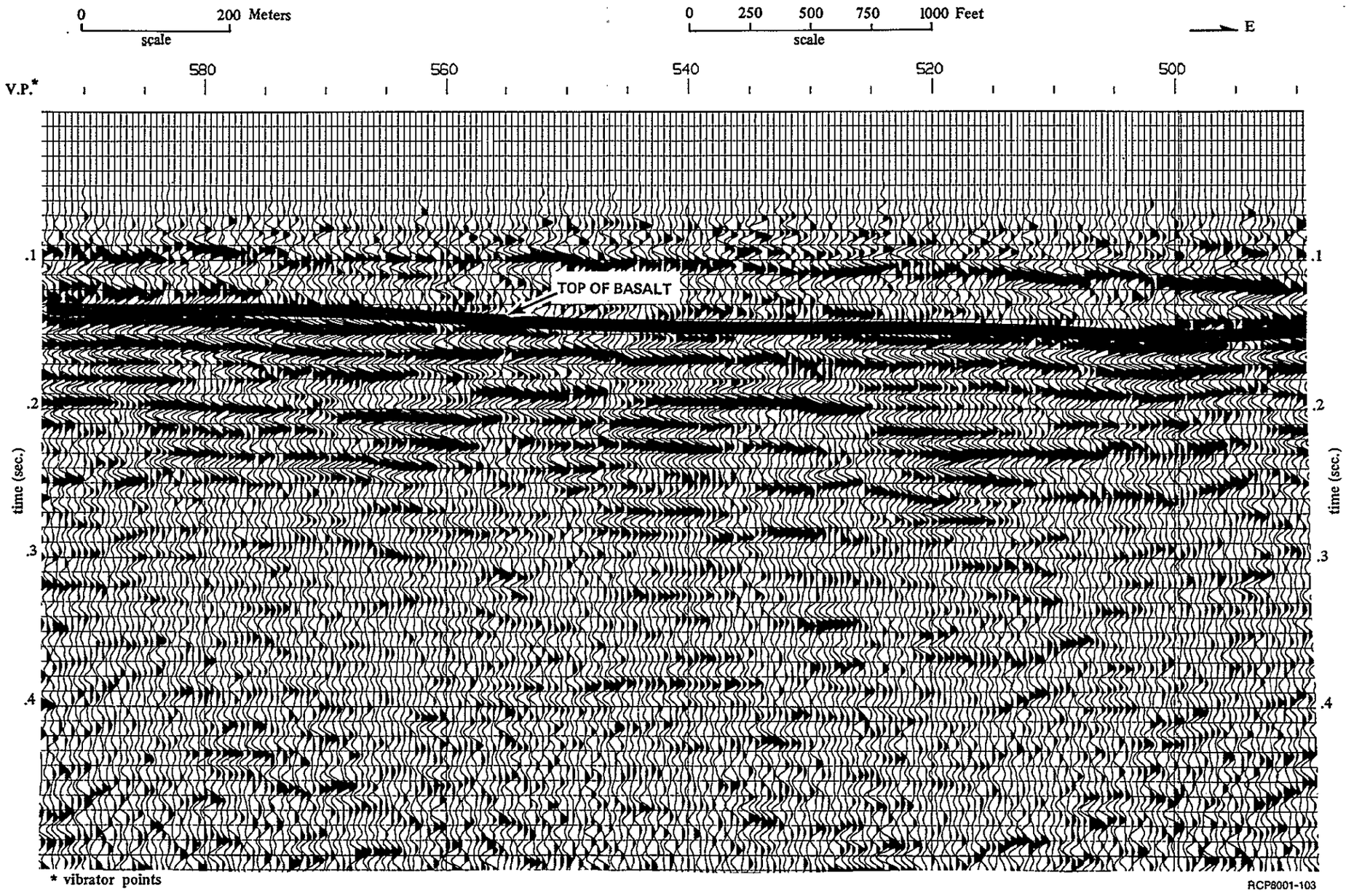

Figure D-8 (continued)

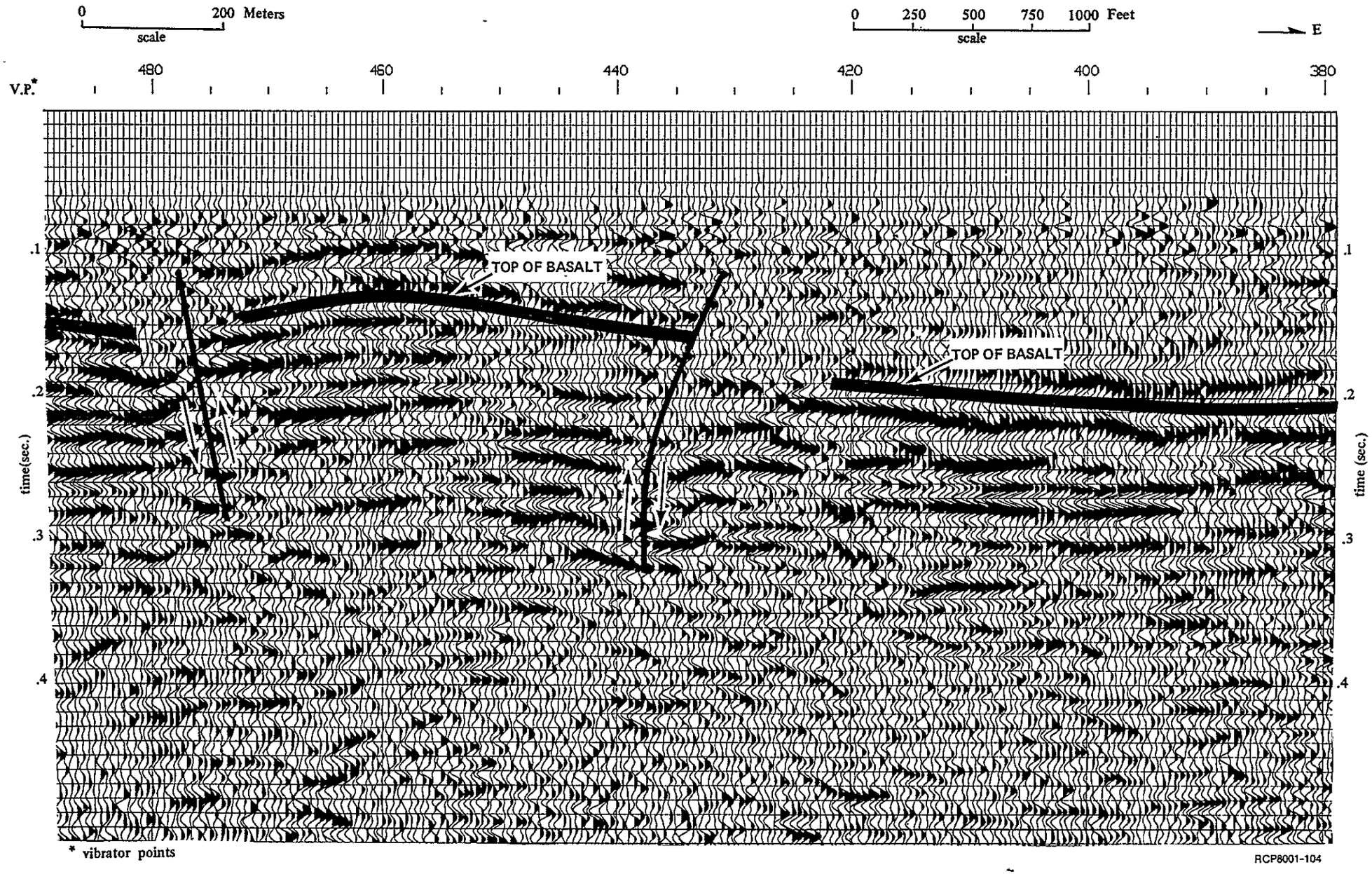

Figure D-8 (continued)

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APPENDIX E

MAGNETOTELLURIC SURVEY

9 2 1 2 2 9 1 1 3 2 3

APPENDIX E

MAGNETOTELLURIC SURVEY

The magnetotelluric method provided the capability to determine the subsurface electrical conductivity distribution by measuring the naturally varying electromagnetic field at the surface of the earth. These variations were recorded over a wide frequency range (0.001 to 20.0 hertz). Depth of penetration is inversely proportional to frequency and directly proportional to the resistivity of the section. Interpretation consists of matching measured apparent resistivity versus period plots against calculated model response.

Magnetotelluric surveys were made during fiscal years 1978 and 1979. The fiscal year 1978 survey (Czimer and Edwards, 1978) was a test of magnetotelluric techniques in the Pasco Basin which consisted of 4 tensor and 18 scalar stations. Results of the fiscal year 1978 survey were used to design the fiscal year 1979 survey. The fiscal year 1979 magnetotelluric survey utilized 26 tensor stations and a 6 x 6 mile (9.7 x 9.7 kilometer) grid.

METHODOLOGY

Tensor theory explicitly takes into account directional characteristics (anistropy) and gives a mathematical foundation for interpreting the data in complicated situations. The tensor system used to acquire these data utilized a cryogenic magnetometer and orthogonal telluric lines with dipole lengths of 1,000 feet (∿300 meters) to simultaneously record 5 components of the electromagnetic field (Hx, Hy, Hz, Ex, and Ey). Electrical strike, predicted coherency, dimensionality parameters, and true resistivity with respect to depth were calculated through impedance tensor analysis and modeling the E-parallel apparent resistivity.

Scalar data were obtained using continuously recording (24-hour) systems designed to record the 0.01 hertz to 20.0 hertz telluric spectrum. Mobile units were tied via radio station WWV time code to a fixed base station. Telluric dipole orientation was based on electrical strike previously determined by tensor analysis.

The 24-hour data tapes were stripped out and a time series (>3 hours and <10 hours) of the best data interval was spectrally analyzed. The spectra at each field station were normalized to the time-aligned telluric spectrum at the base station. Normalized power spectra estimates at each station were then multiplied by the tensor E-parallel base station sounding curve (Station 1-2) to calculate the earth's electromagnetic impedance at each station.

RESULTS

Tensor sounding curves (apparent resistivity versus period) from fiscal year 1978 are shown in Figures E-1a through E-1c. Data from the fiscal year 1979 survey are shown in Figures E-2a through E-2y. Next to each sounding curve is a model (4 to 5 layers) of true resistivity and

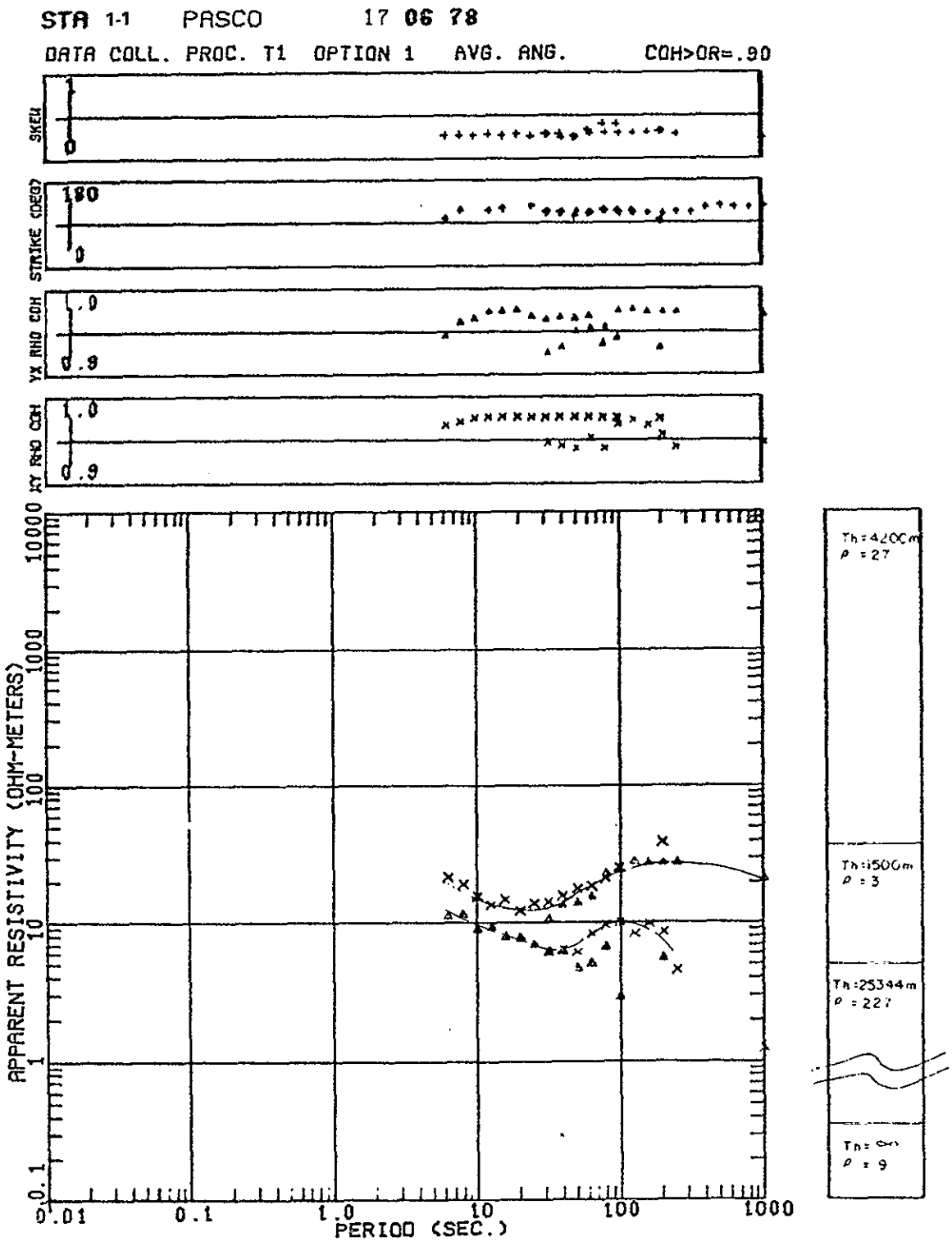

FIGURE E-1a. Tensor Sounding Curves-Fiscal Year 1978.

9 2 1 2 4 9 4 1 8 2 5

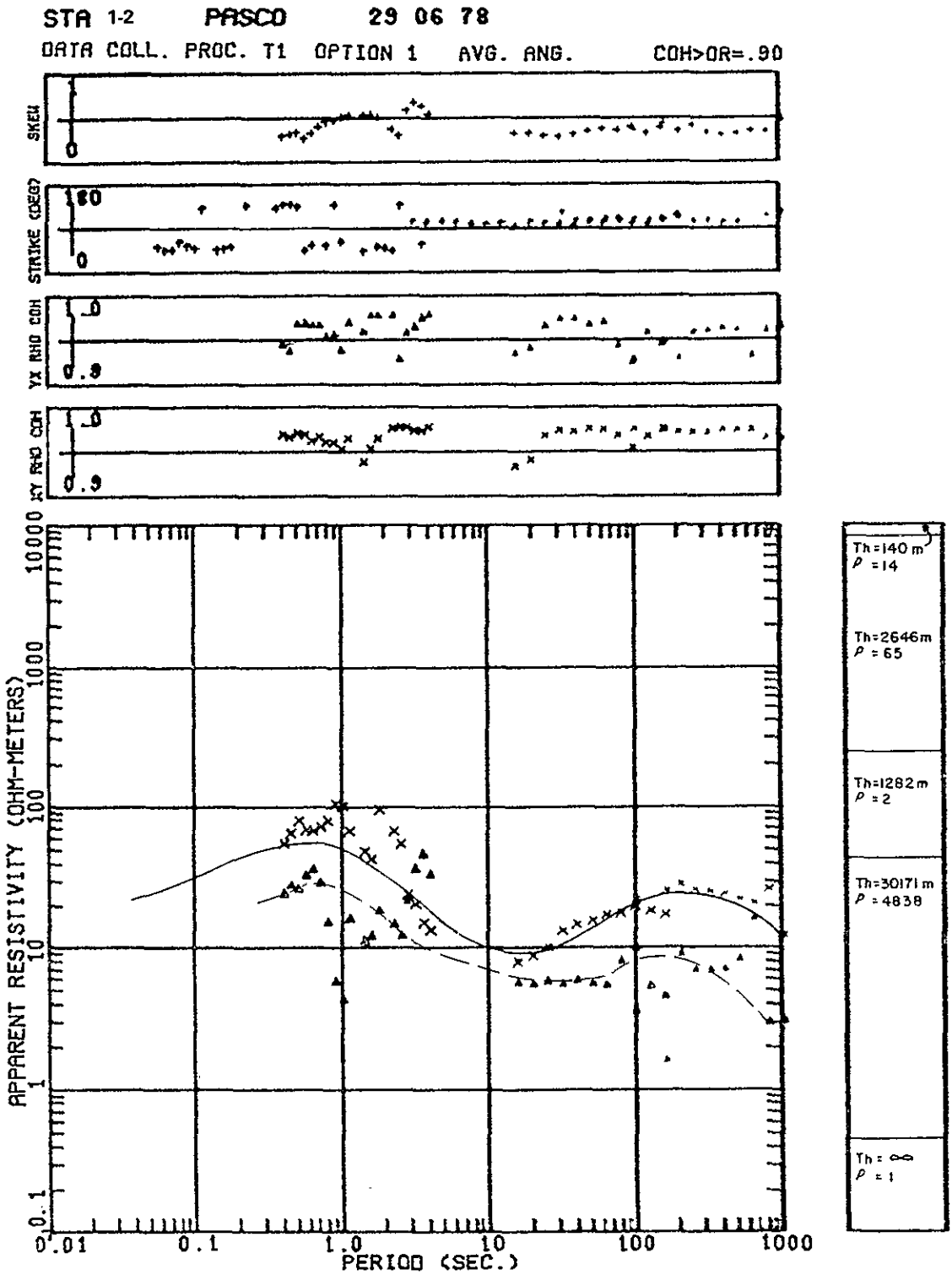

FIGURE E-1b. Tensor Sounding Curves-Fiscal Year 1978.

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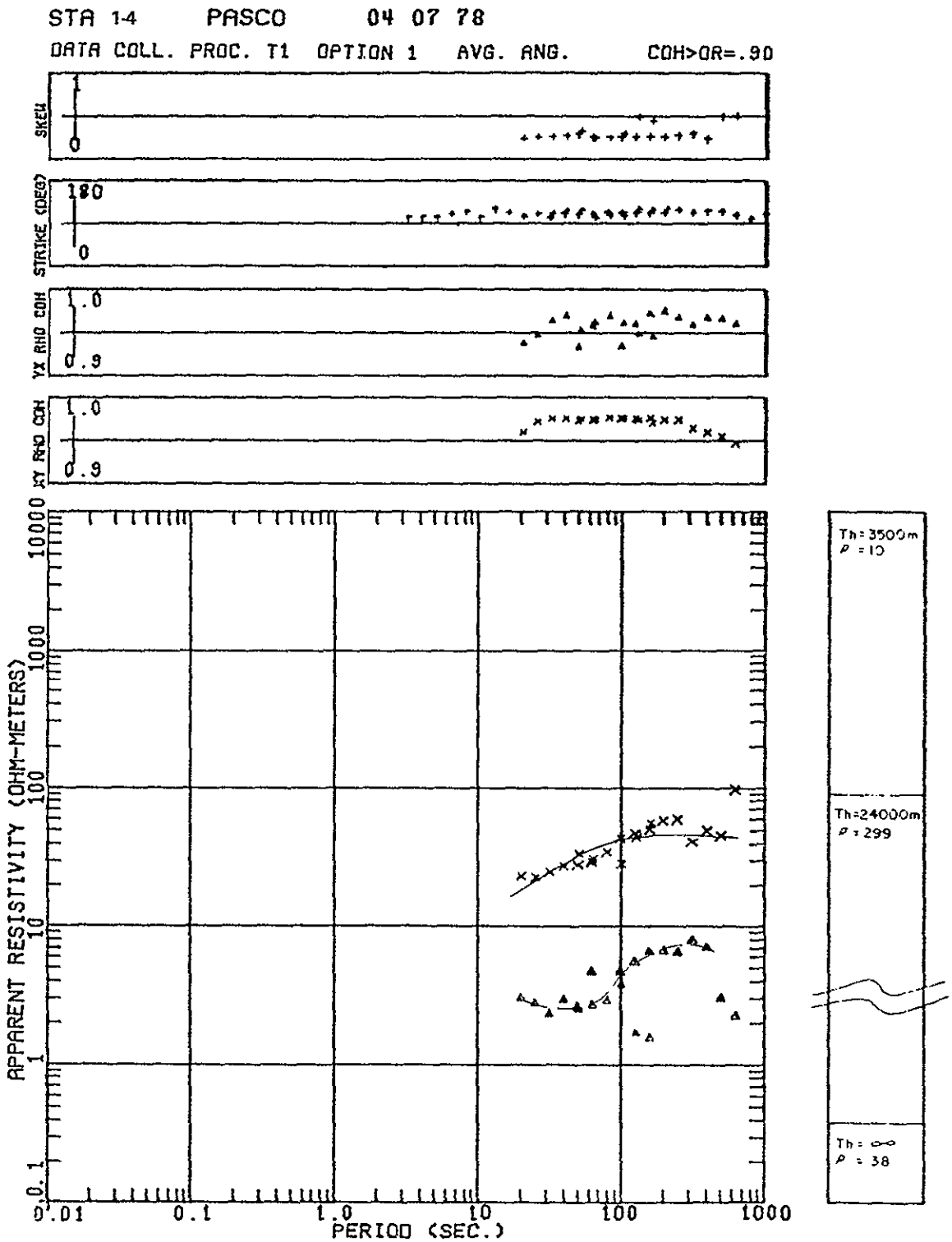

FIGURE E-1c. Tensor Sounding Curves-Fiscal Year 1978.

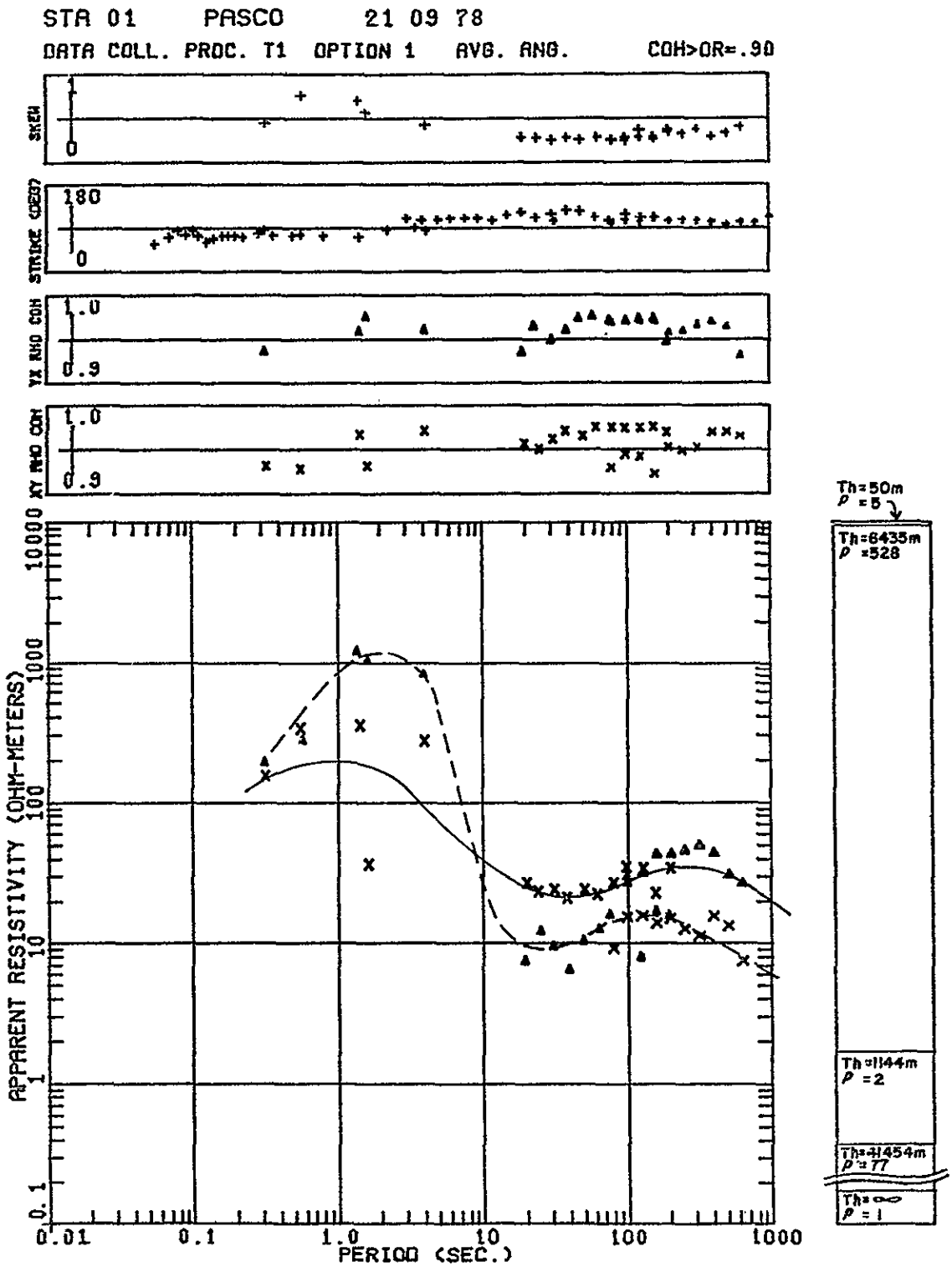

FIGURE E-2a. Tensor Sounding Curves-Fiscal Year 1979.

9 2 1 2 1 9 4 1 3 2 3

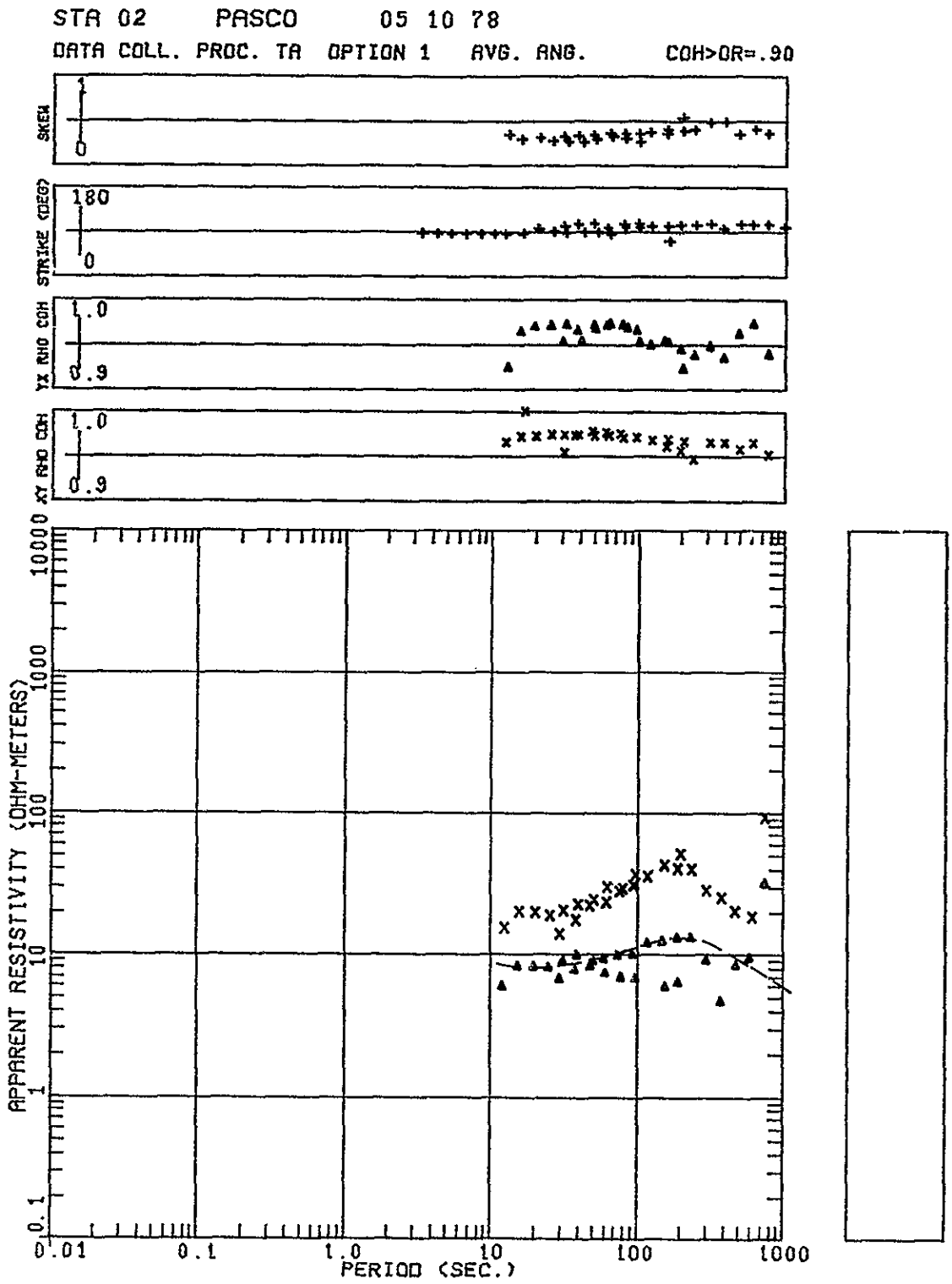

FIGURE E-2b. Tensor Sounding Curves-Fiscal Year 1979.

9 2 1 2 1 9 4 1 8 2 9

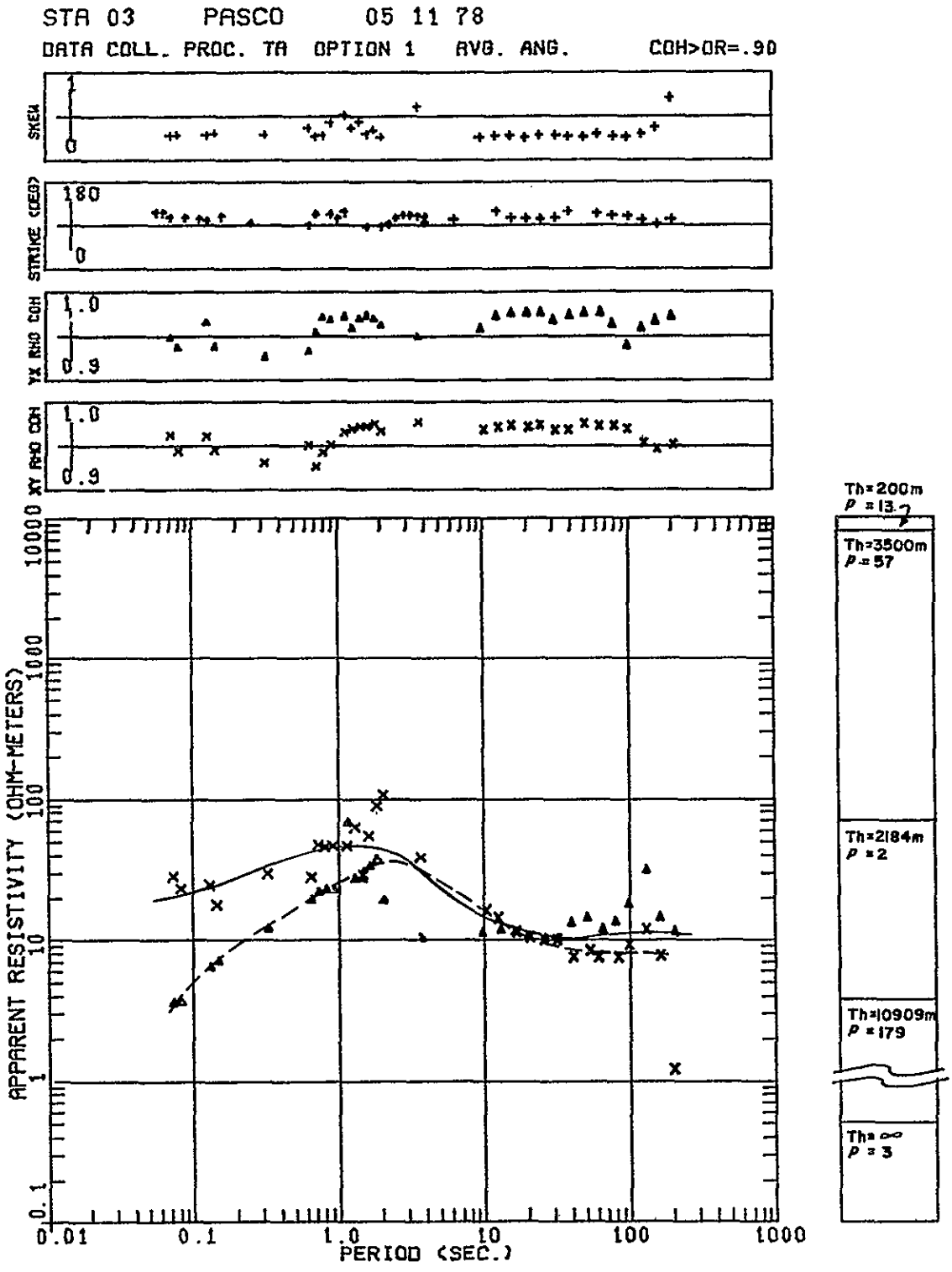

FIGURE E-2c. Tensor Sounding Curves-Fiscal Year 1979.

9 2 1 2 . 9 4 1 3 3 0

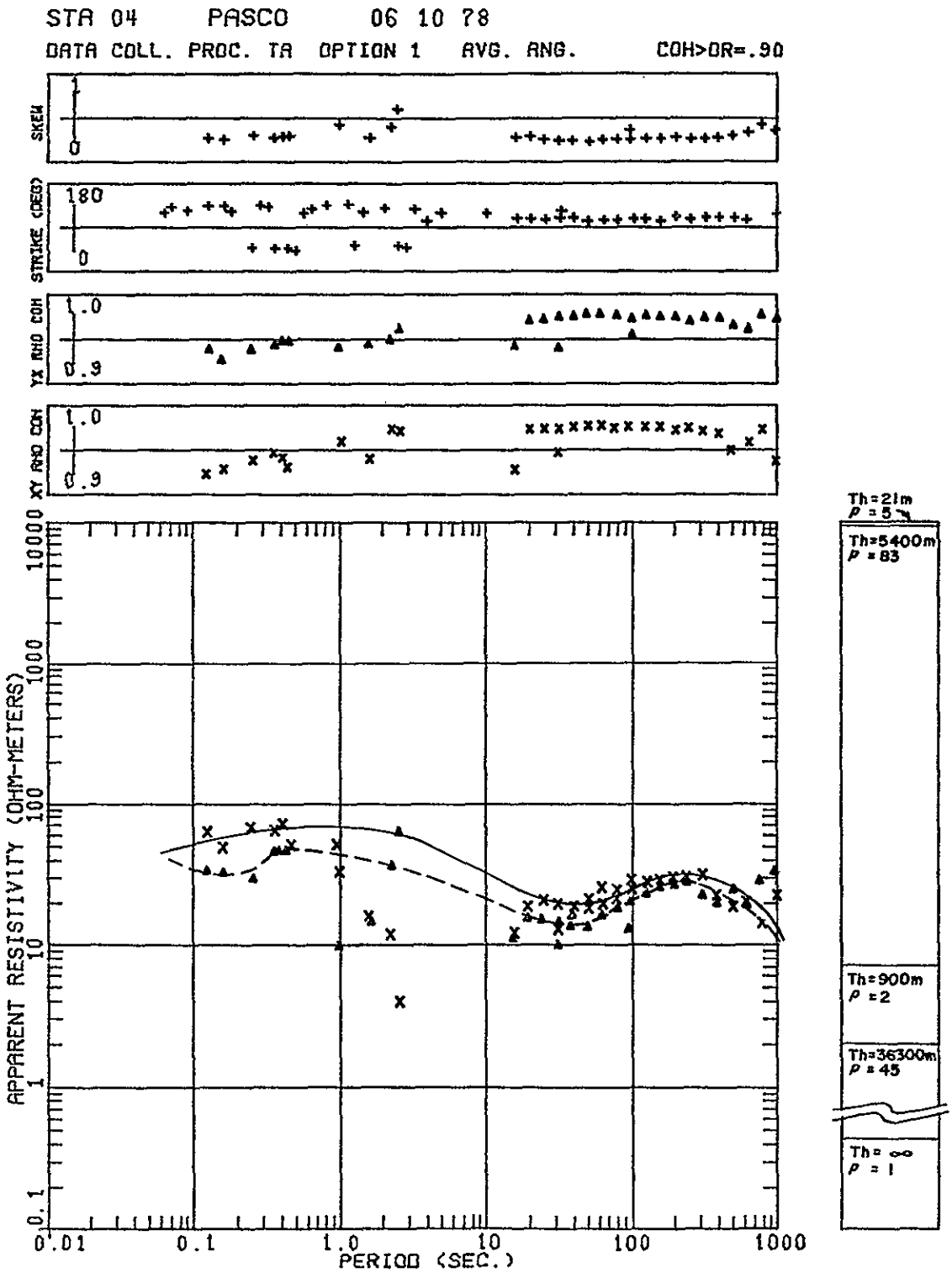

FIGURE E-2d. Tensor Sounding Curves-Fiscal Year 1979.

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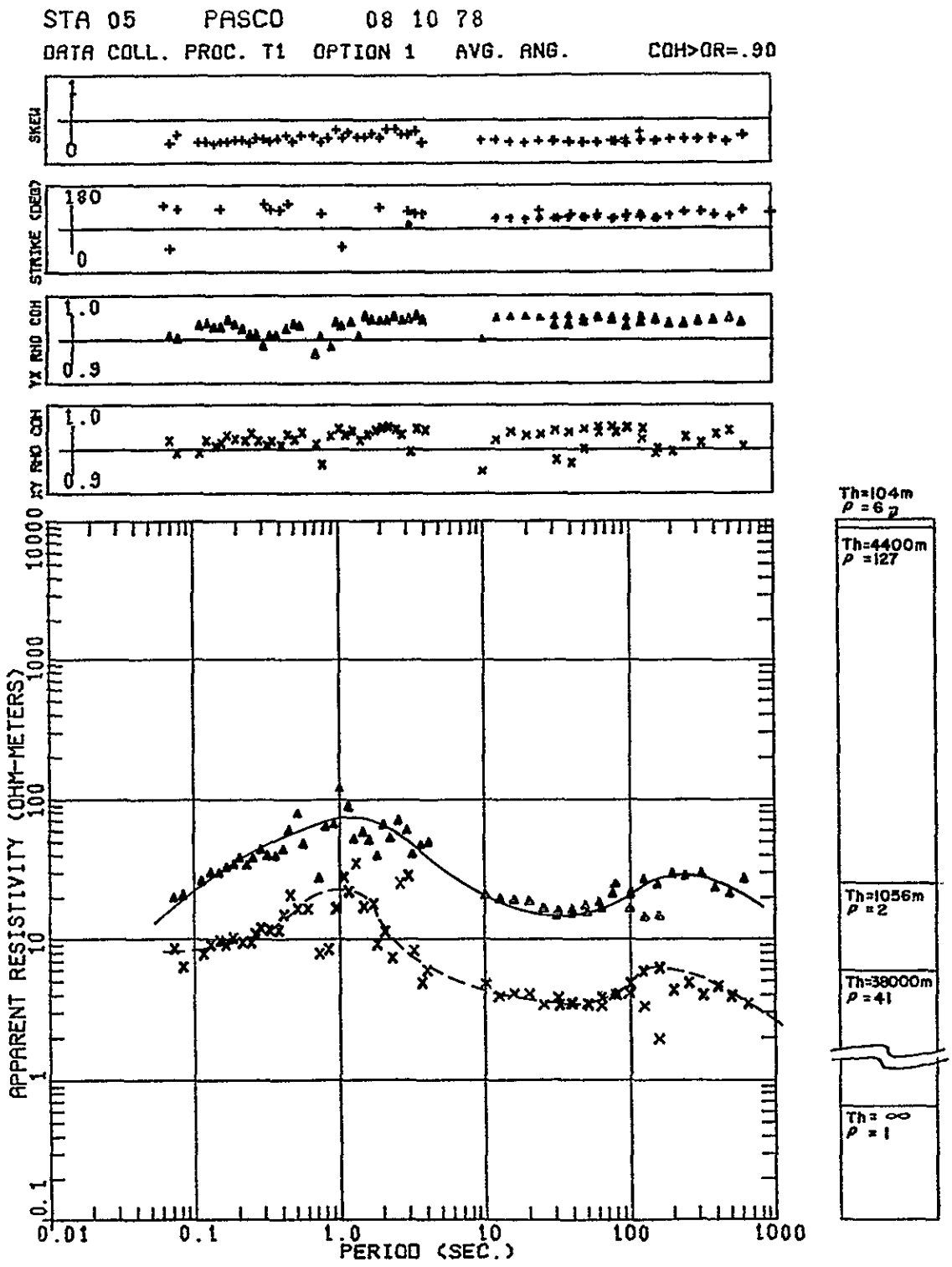

FIGURE E-2e. Tensor Sounding Curves-Fiscal Year 1979.

9 2 1 2 . 9 4 1 3 3 2

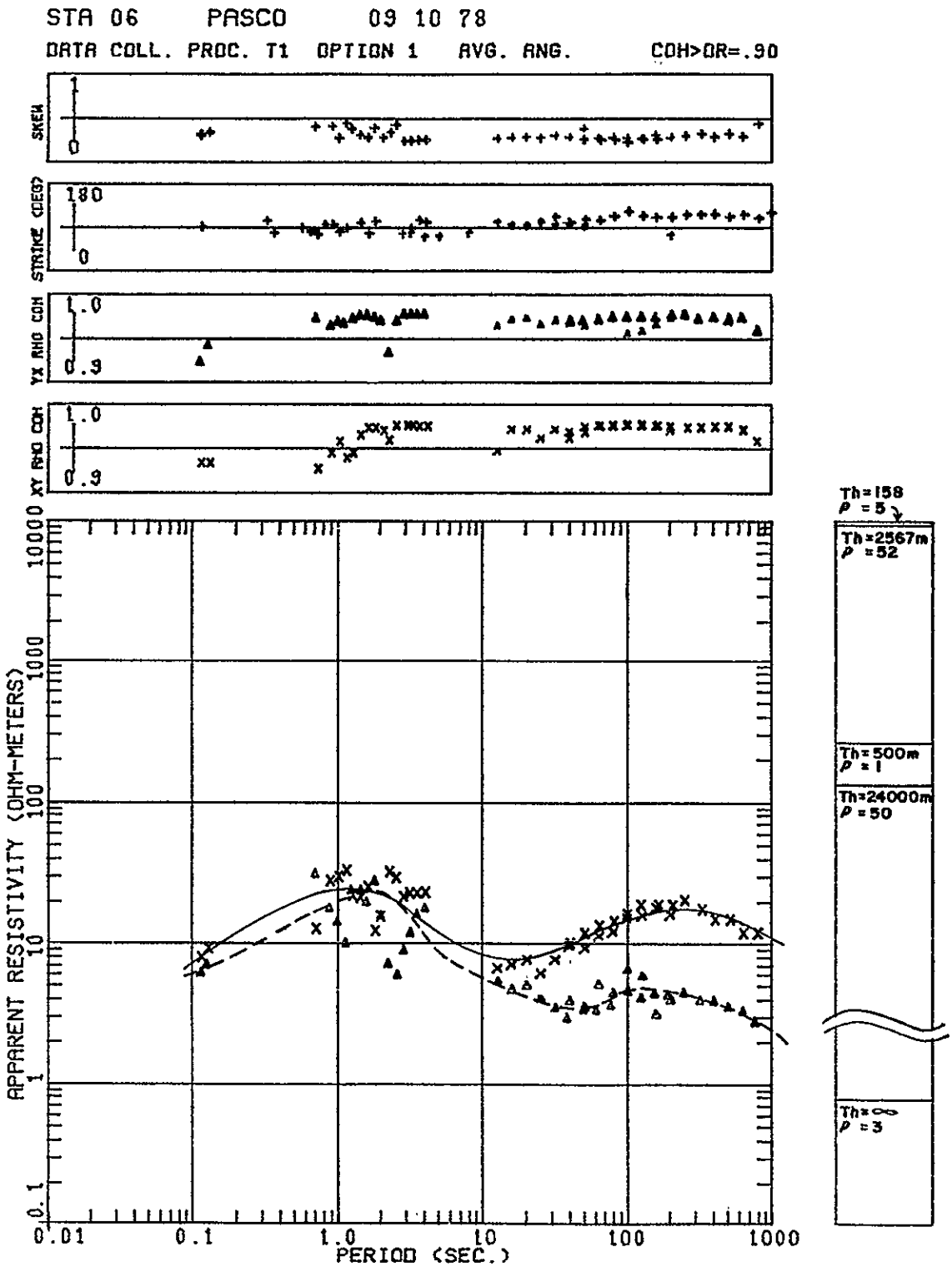

FIGURE E-2f. Tensor Sounding Curves-Fiscal Year 1979.

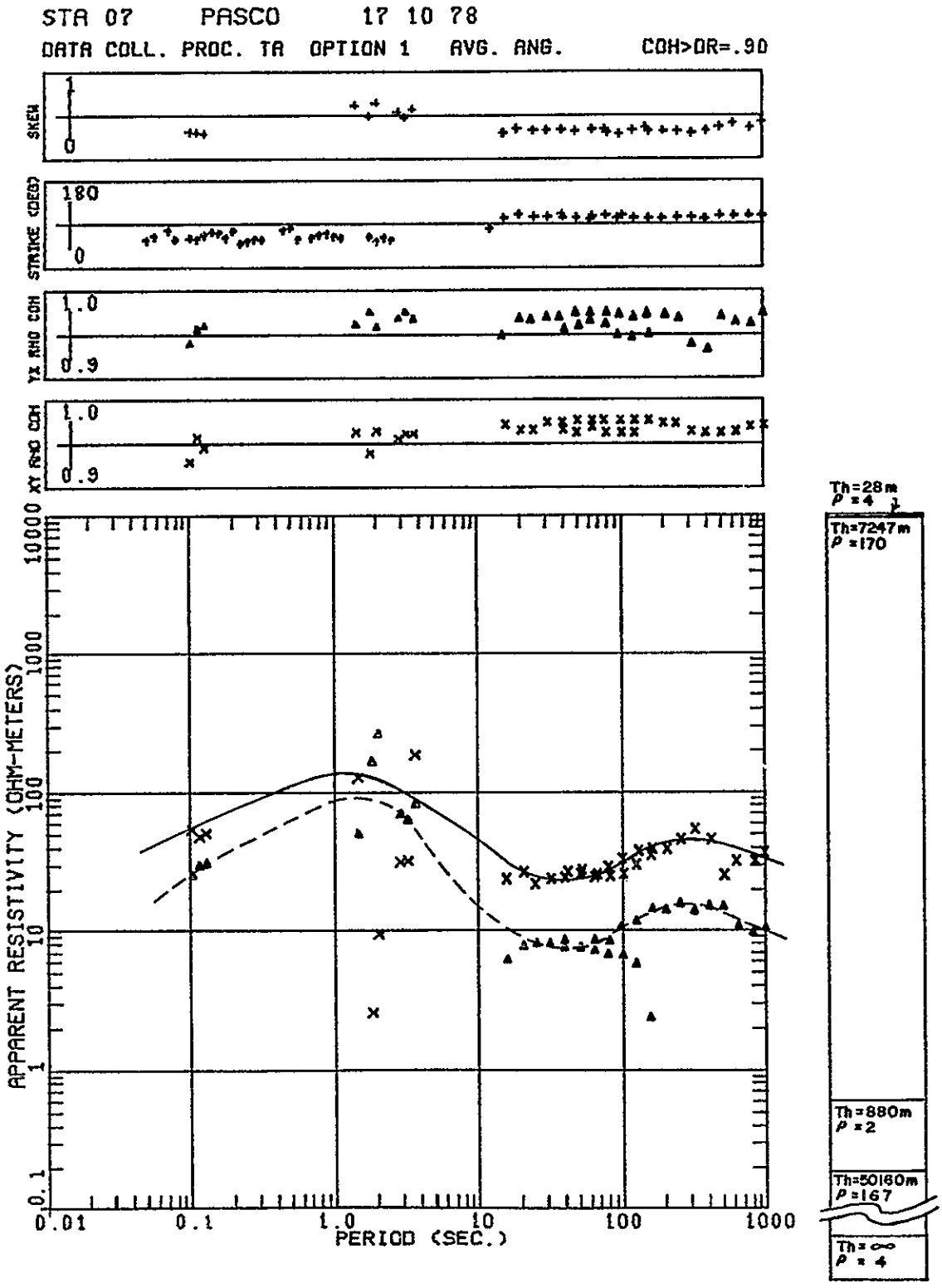

FIGURE E-2g. Tensor Sounding Curves-Fiscal Year 1979.

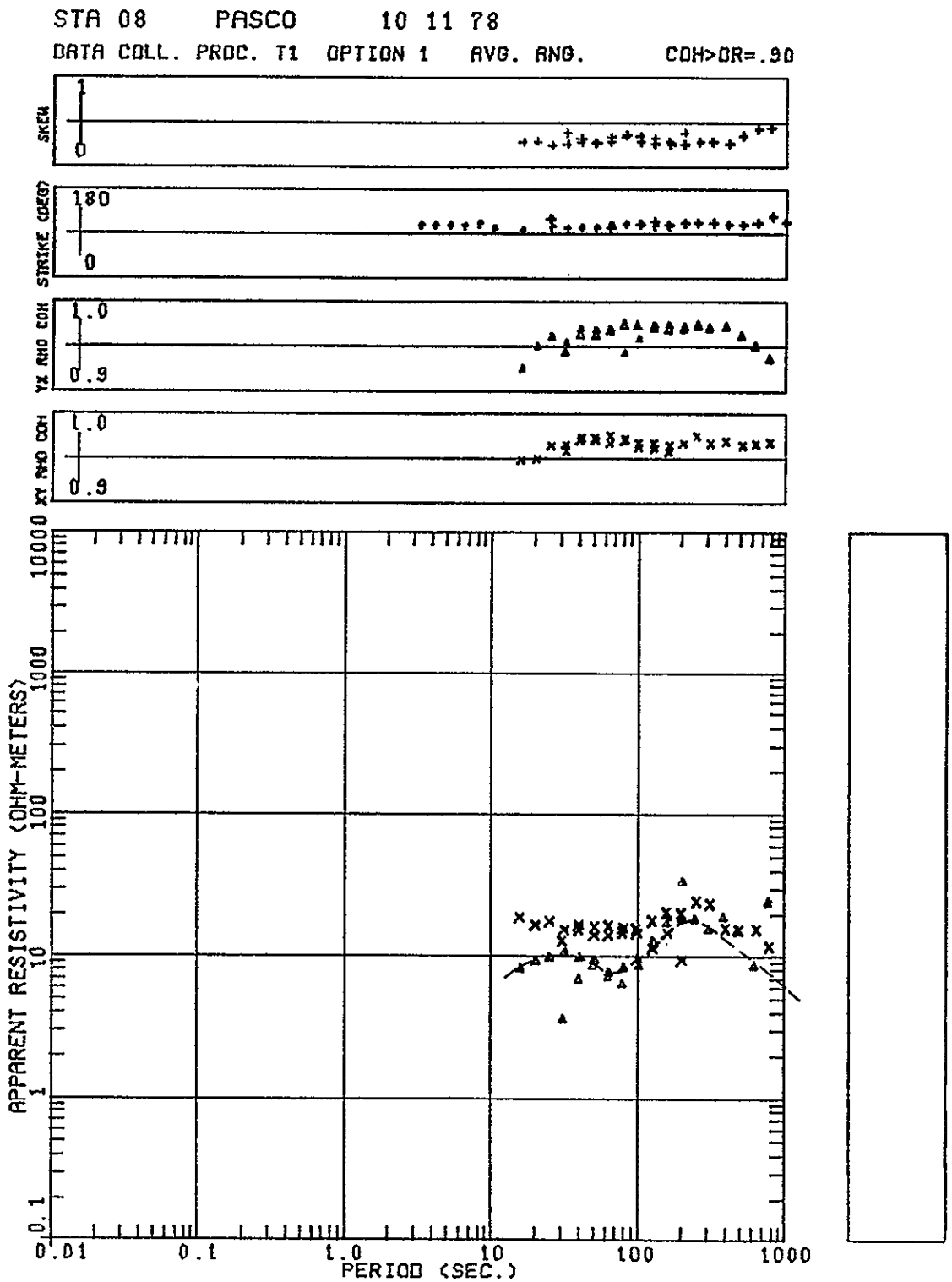

FIGURE E-2h. Tensor Sounding Curves-Fiscal Year 1979.

9 2 1 2 1 9 4 1 3 3 6

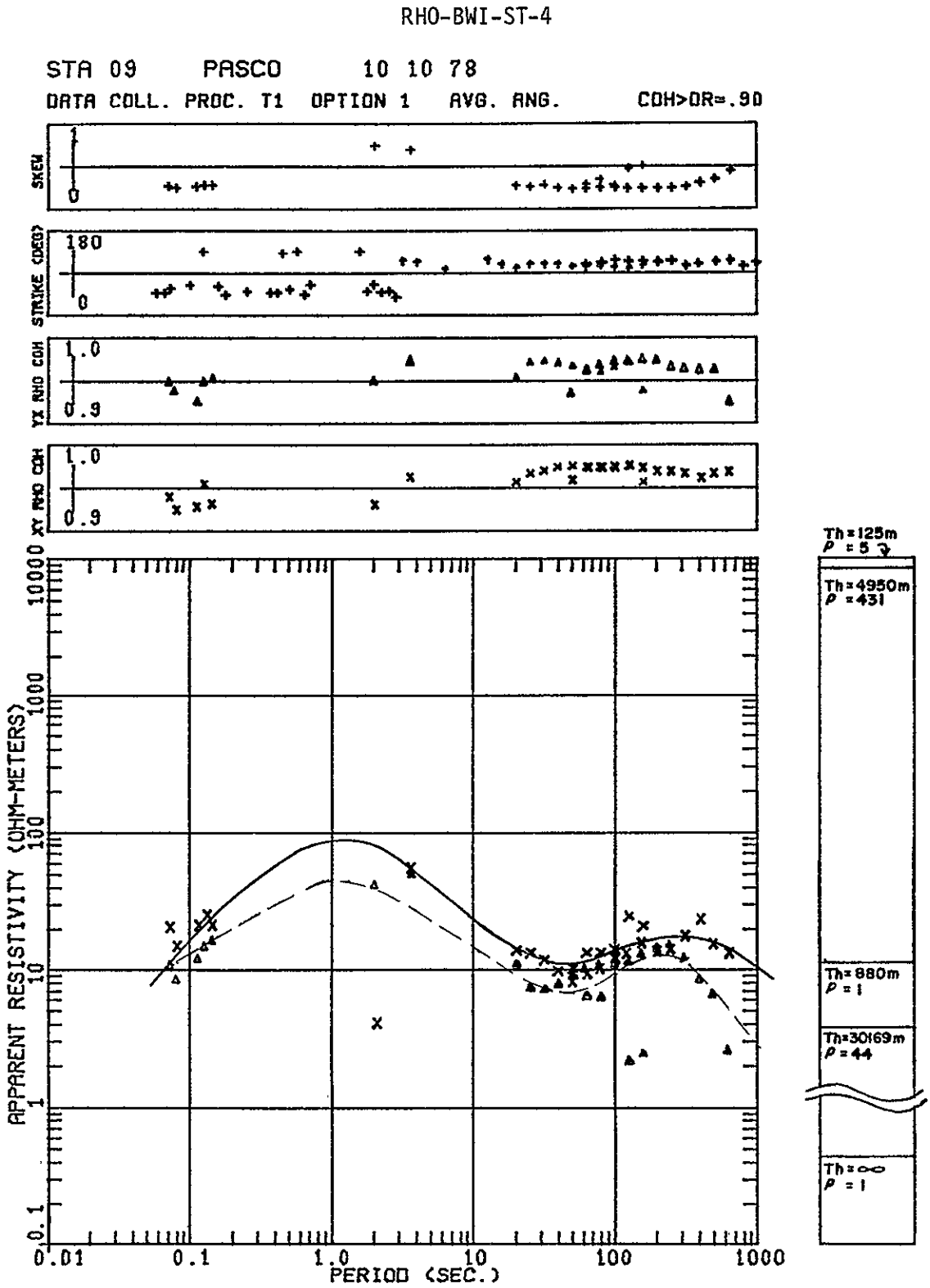

FIGURE E-2i. Tensor Sounding Curves-Fiscal Year 1979.

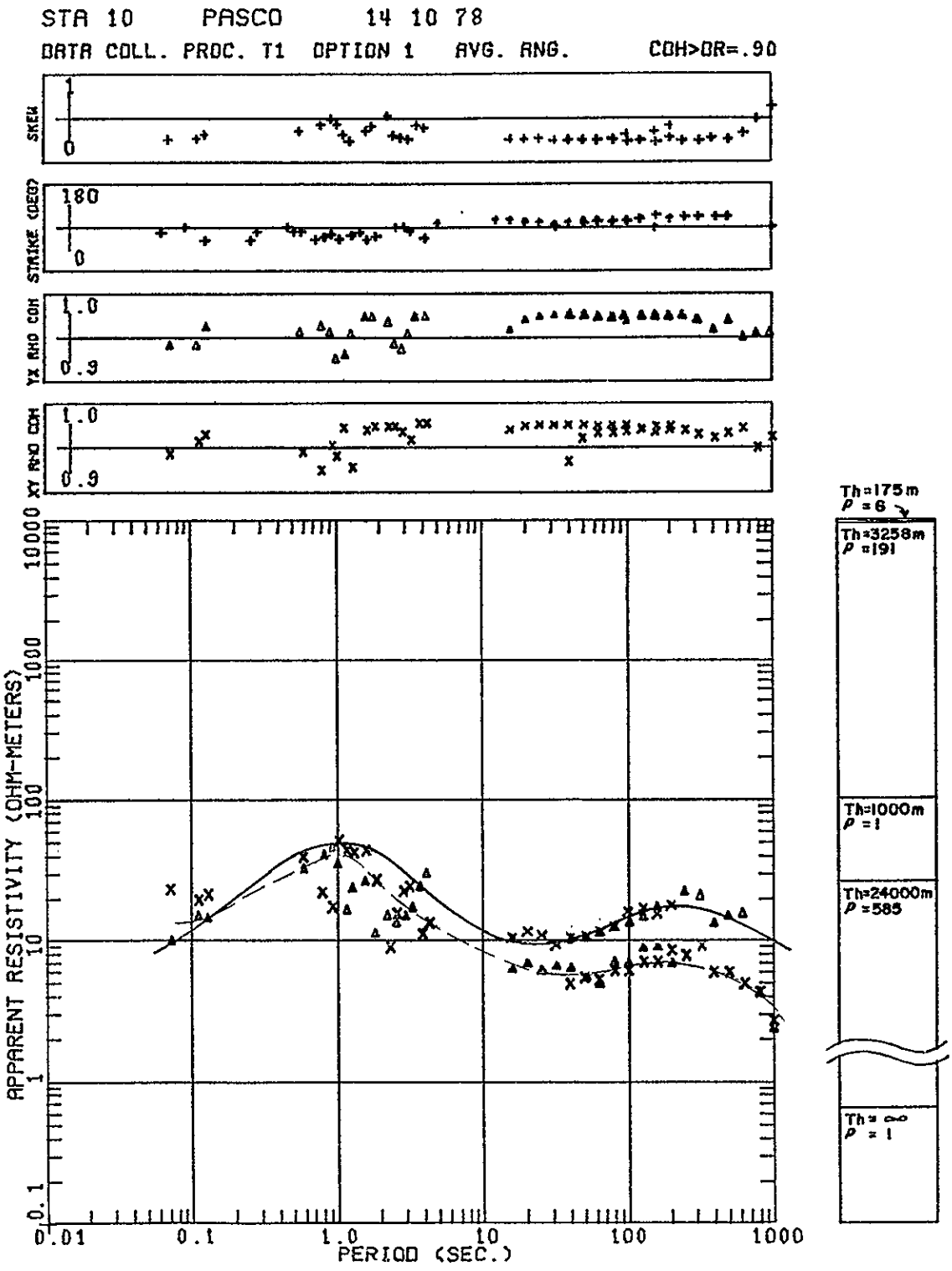

FIGURE E-2j. Tensor Sounding Curves-Fiscal Year 1979.

9 2 1 2 1 9 4 1 3 3 7

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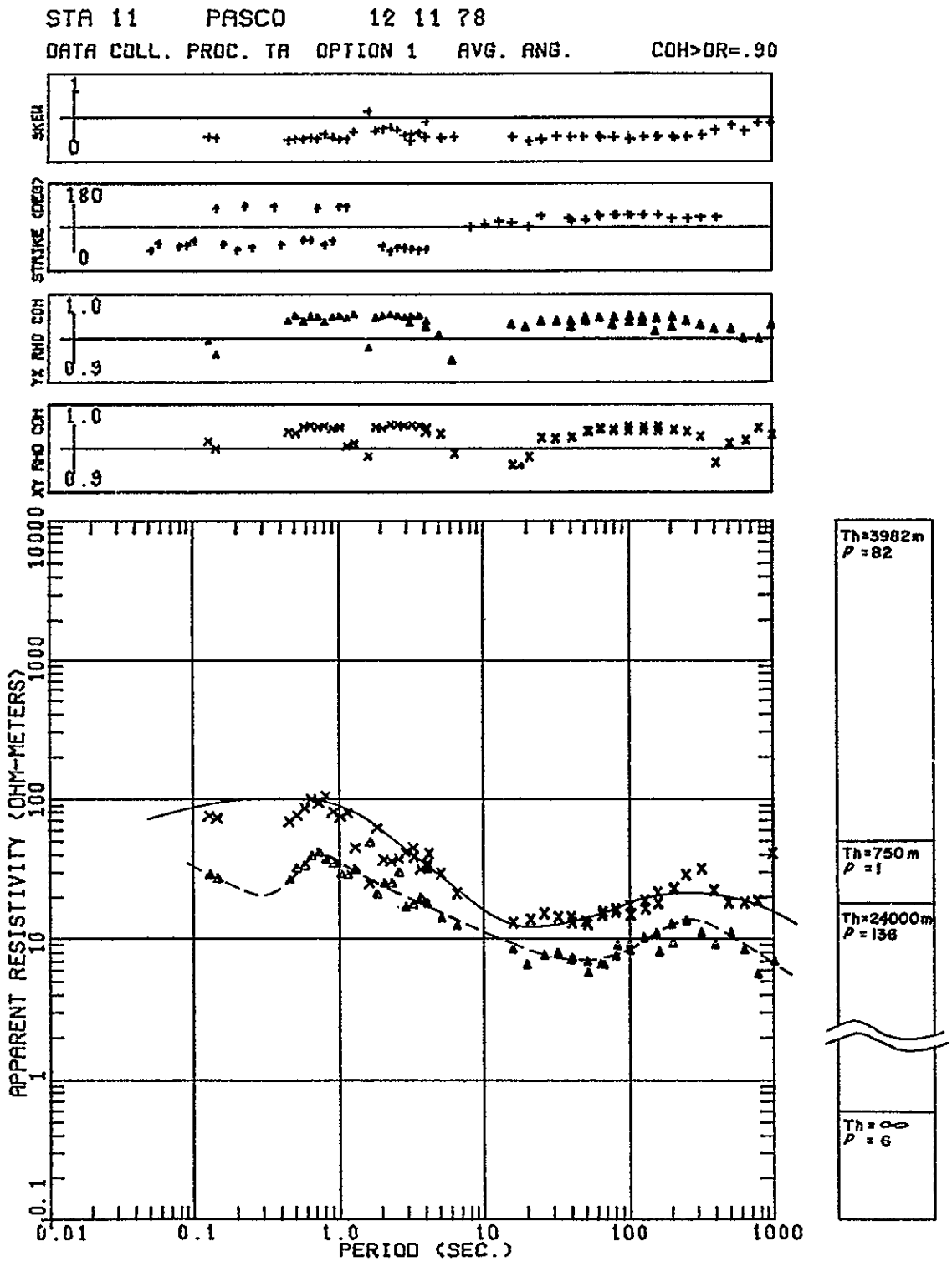

FIGURE E-2k. Tensor Sounding Curves-Fiscal Year 1979.

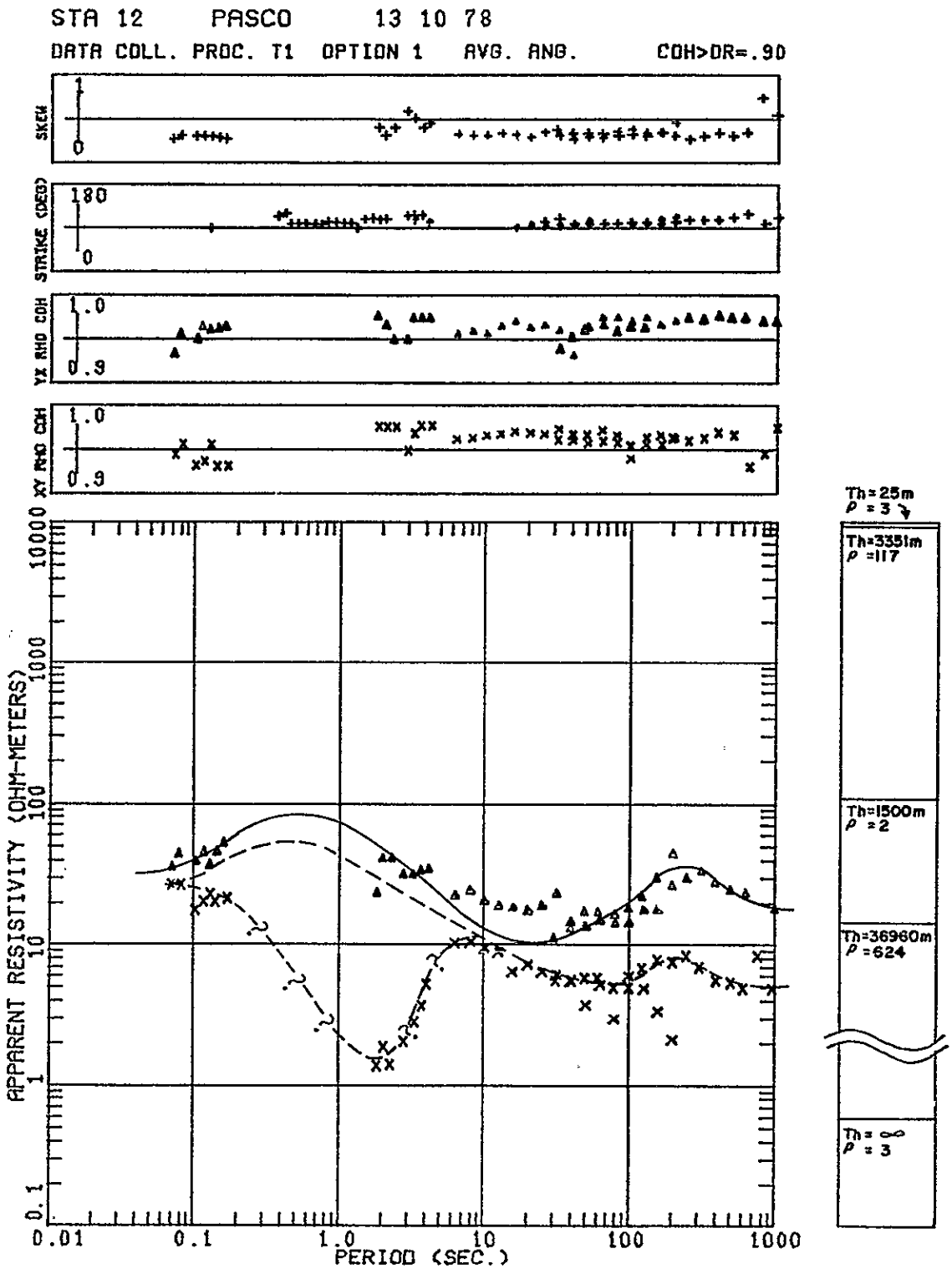

FIGURE E-21. Tensor Sounding Curves-Fiscal Year 1979.

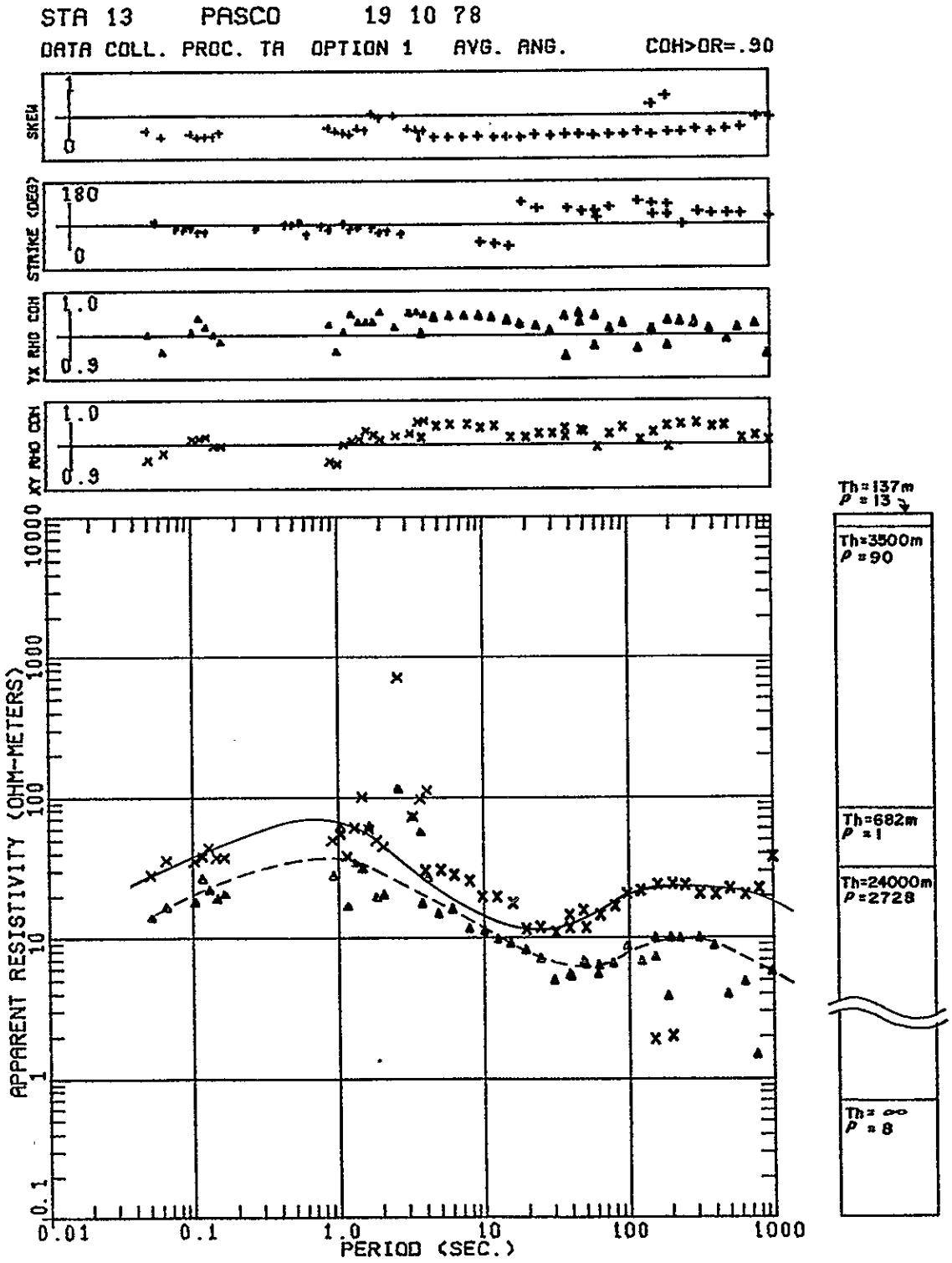

FIGURE E-2m. Tensor Sounding Curves-Fiscal Year 1979.

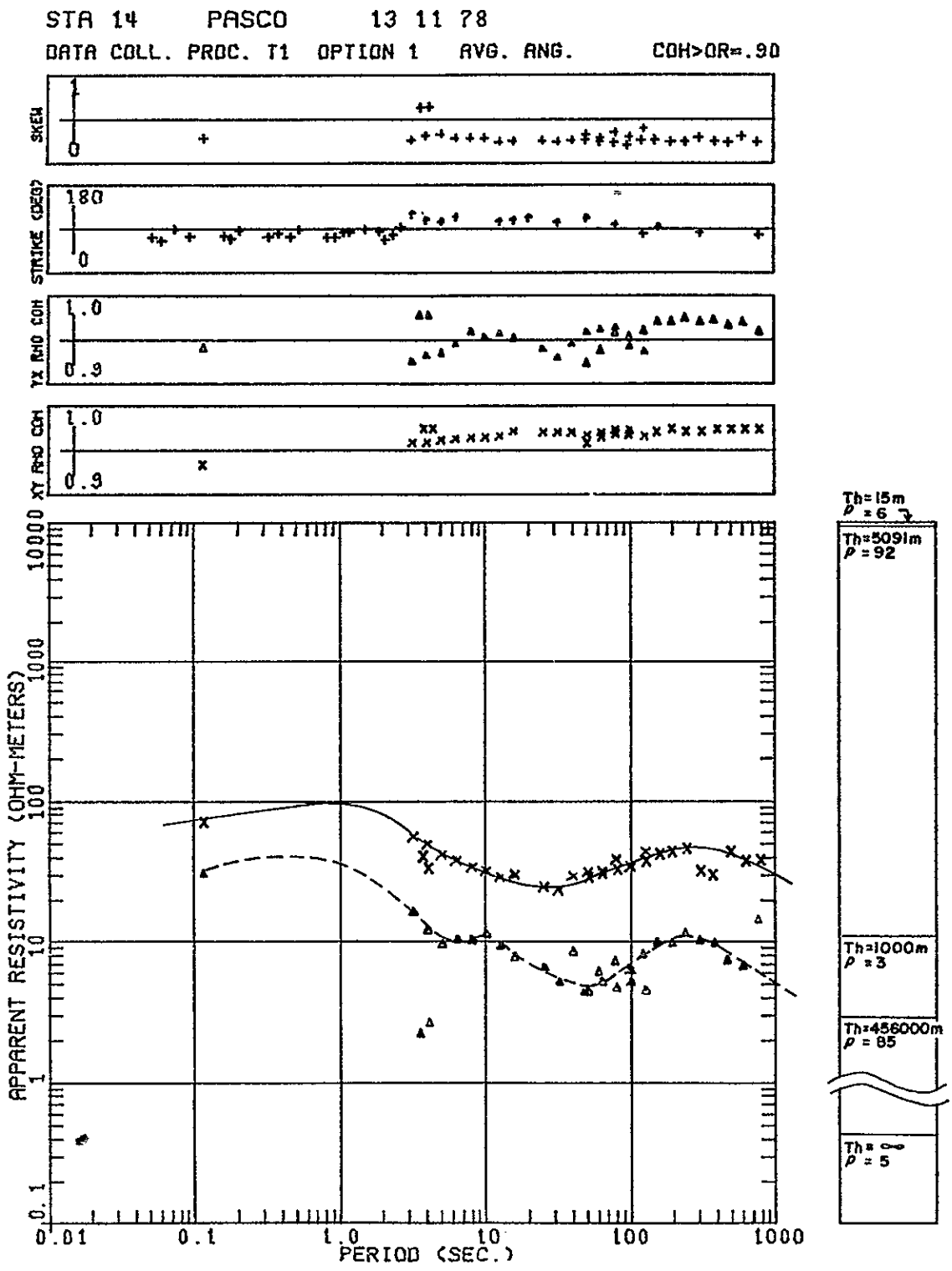

FIGURE E-2n. Tensor Sounding Curves-Fiscal Year 1979.

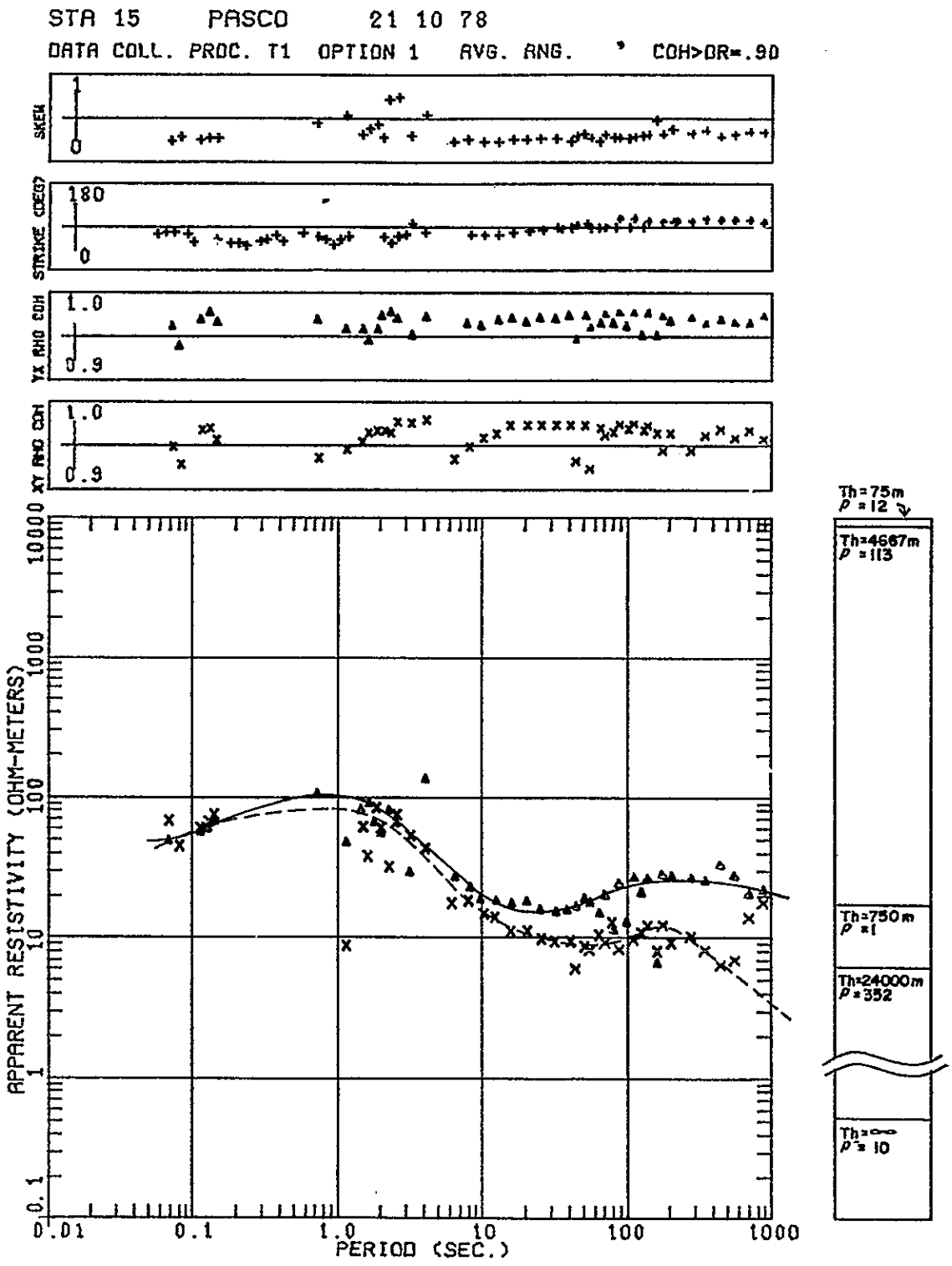

FIGURE E-2o. Tensor Sounding Curves-Fiscal Year 1979.

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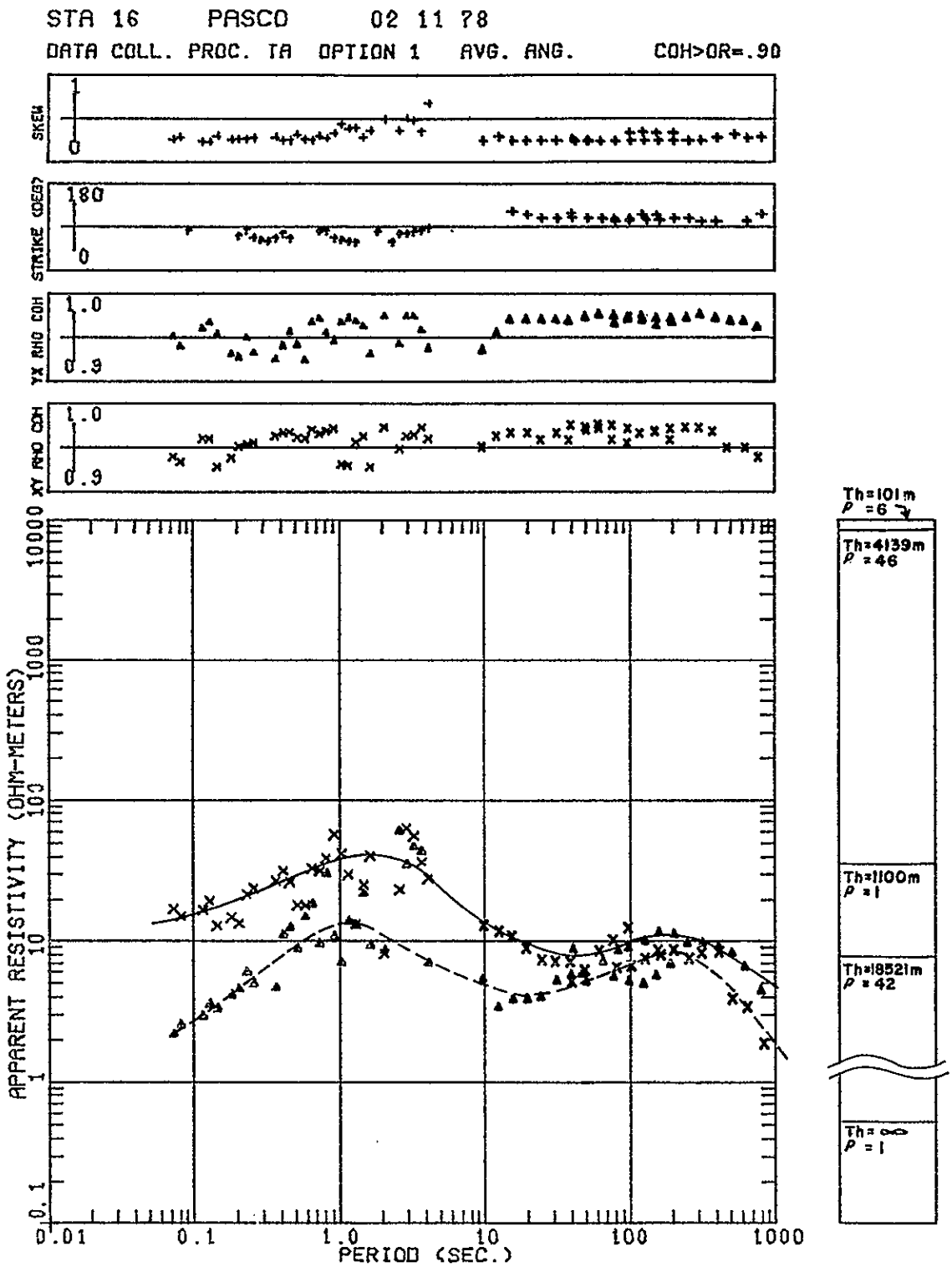

FIGURE E-2p. Tensor Sounding Curves-Fiscal Year 1979.

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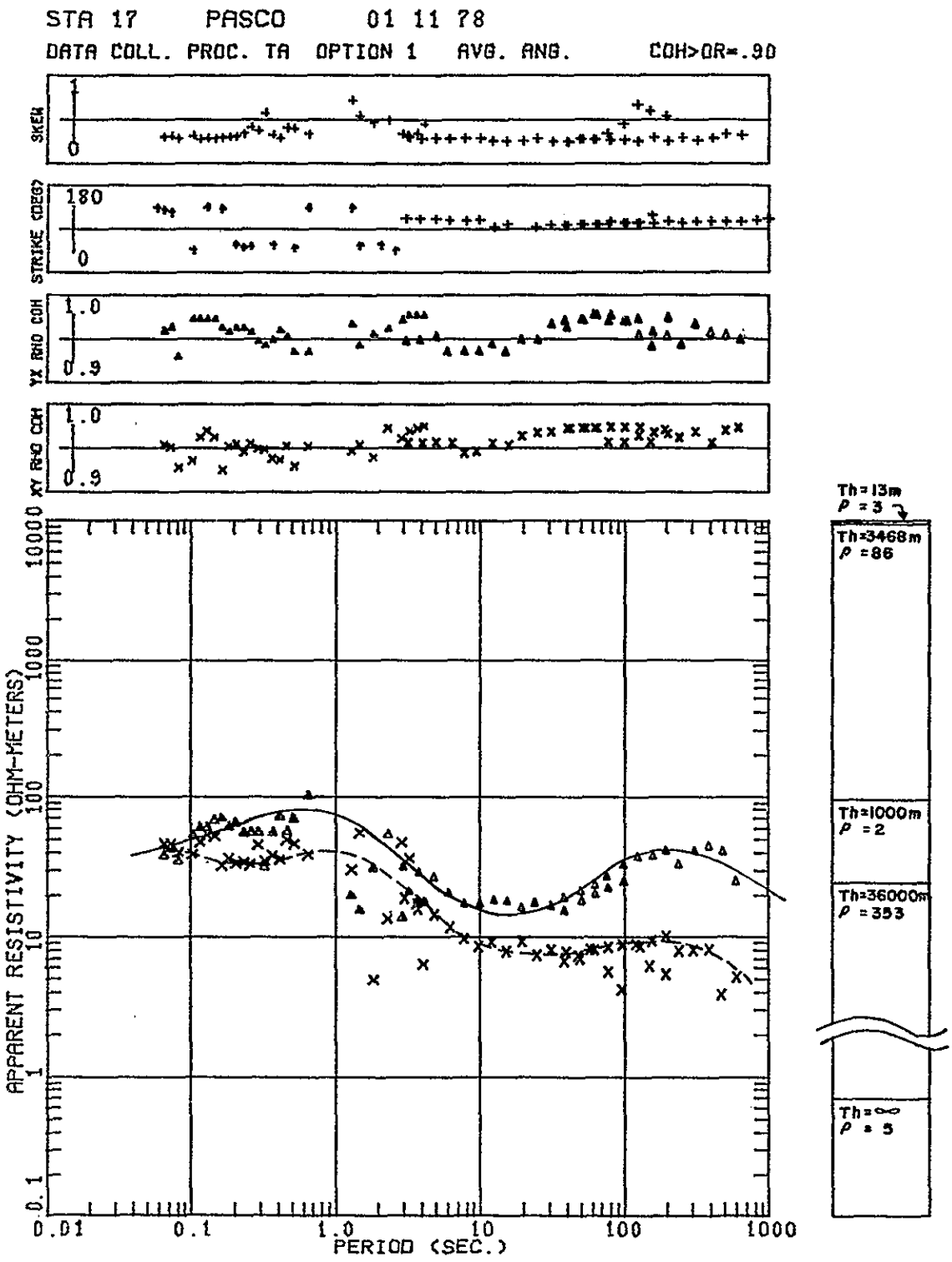

FIGURE E-2q. Tensor Sounding Curves-Fiscal Year 1979.

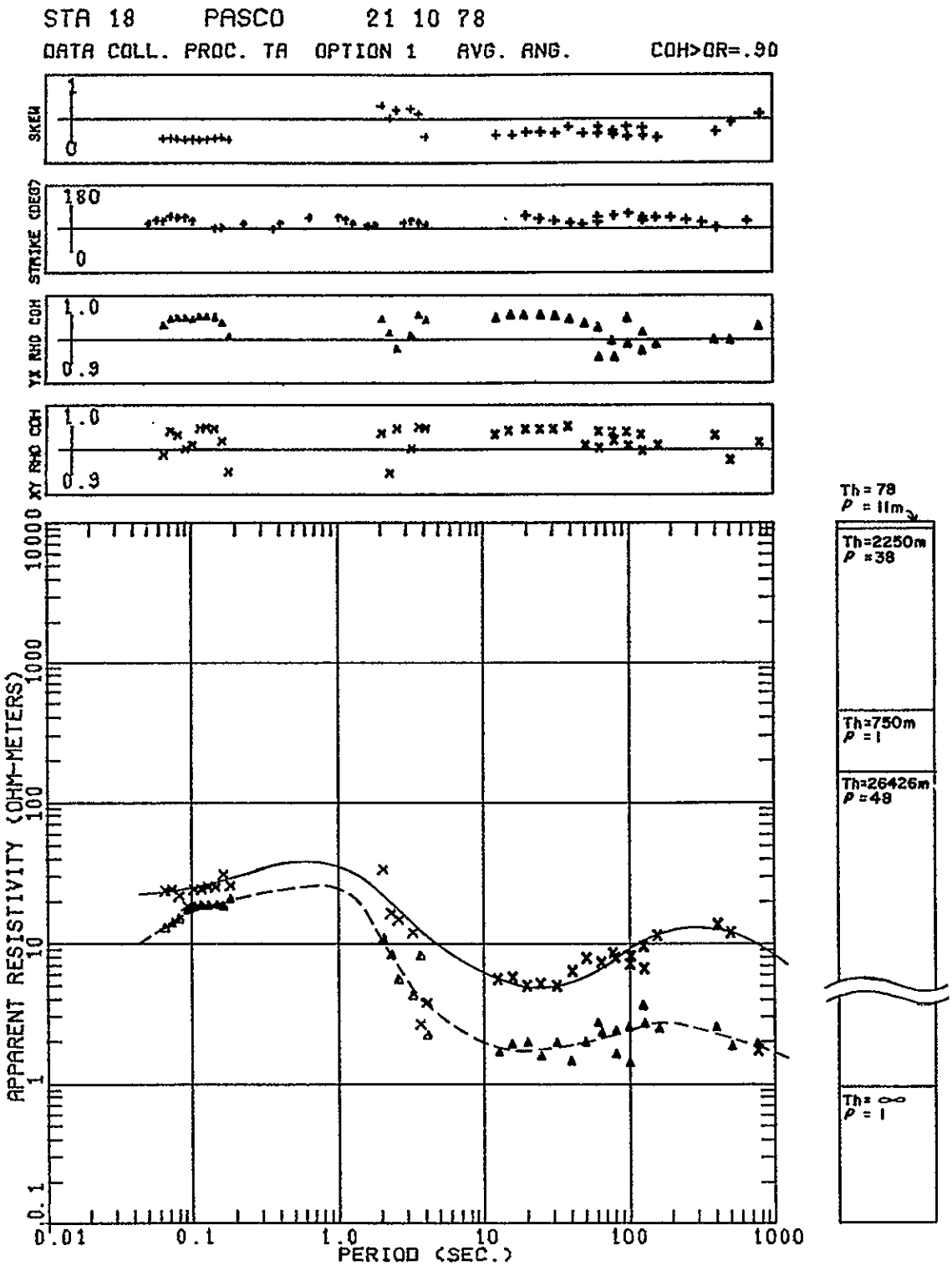

FIGURE E-2r. Tensor Sounding Curves-Fiscal Year 1979.

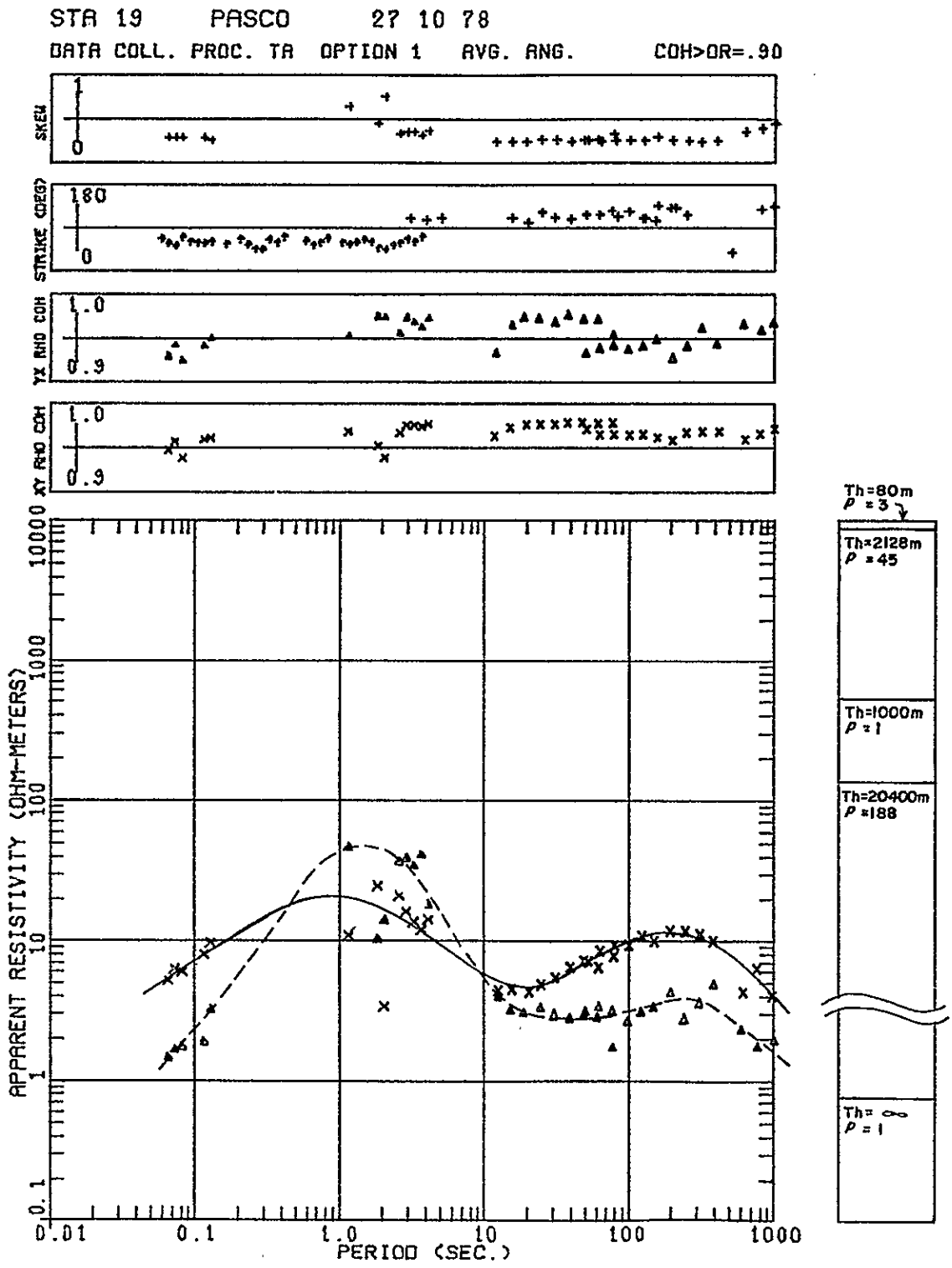

FIGURE E-2s. Tensor Sounding Curves-Fiscal Year 1979.

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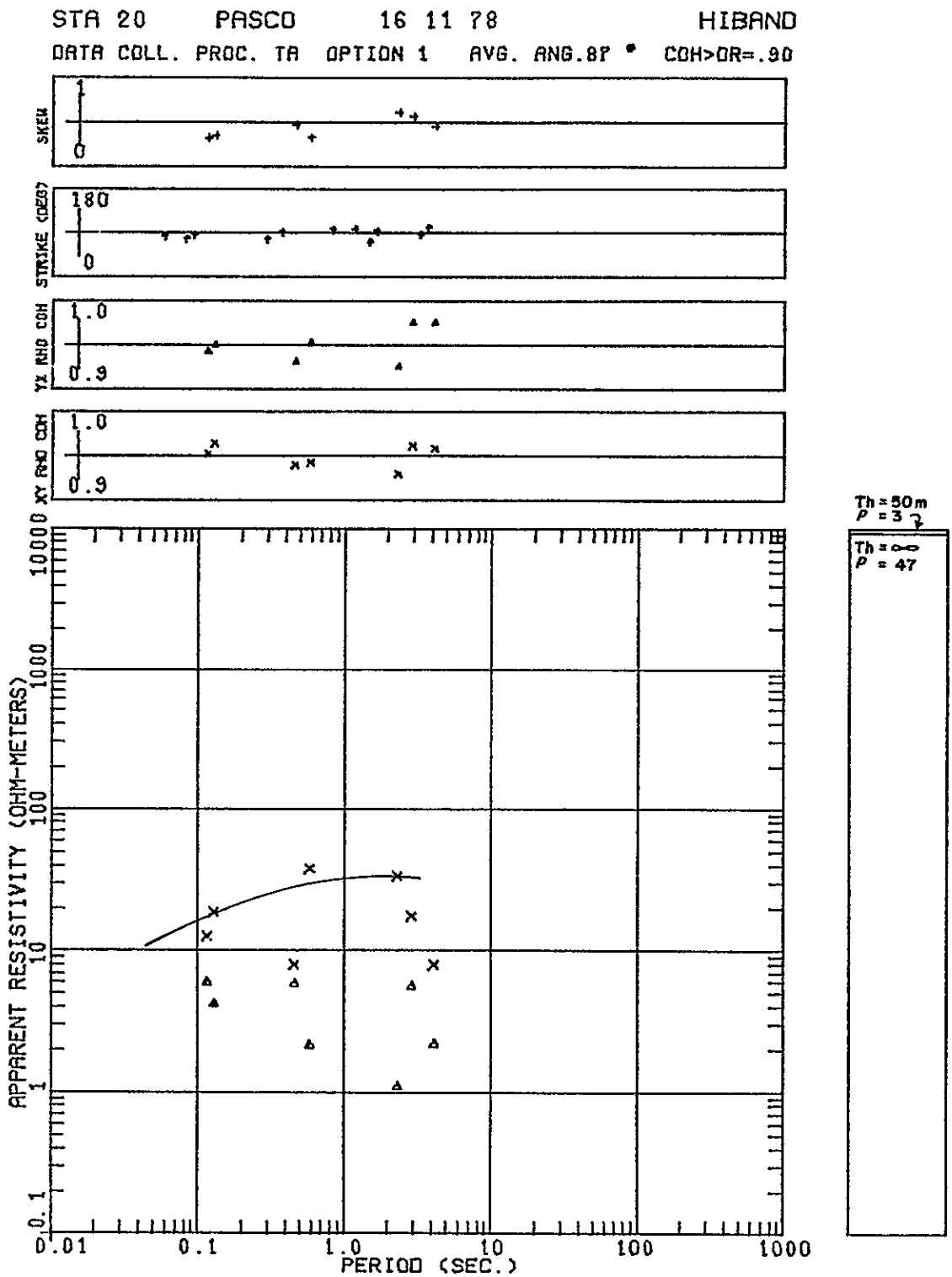

FIGURE E-2t. Tensor Sounding Curves-Fiscal Year 1979.

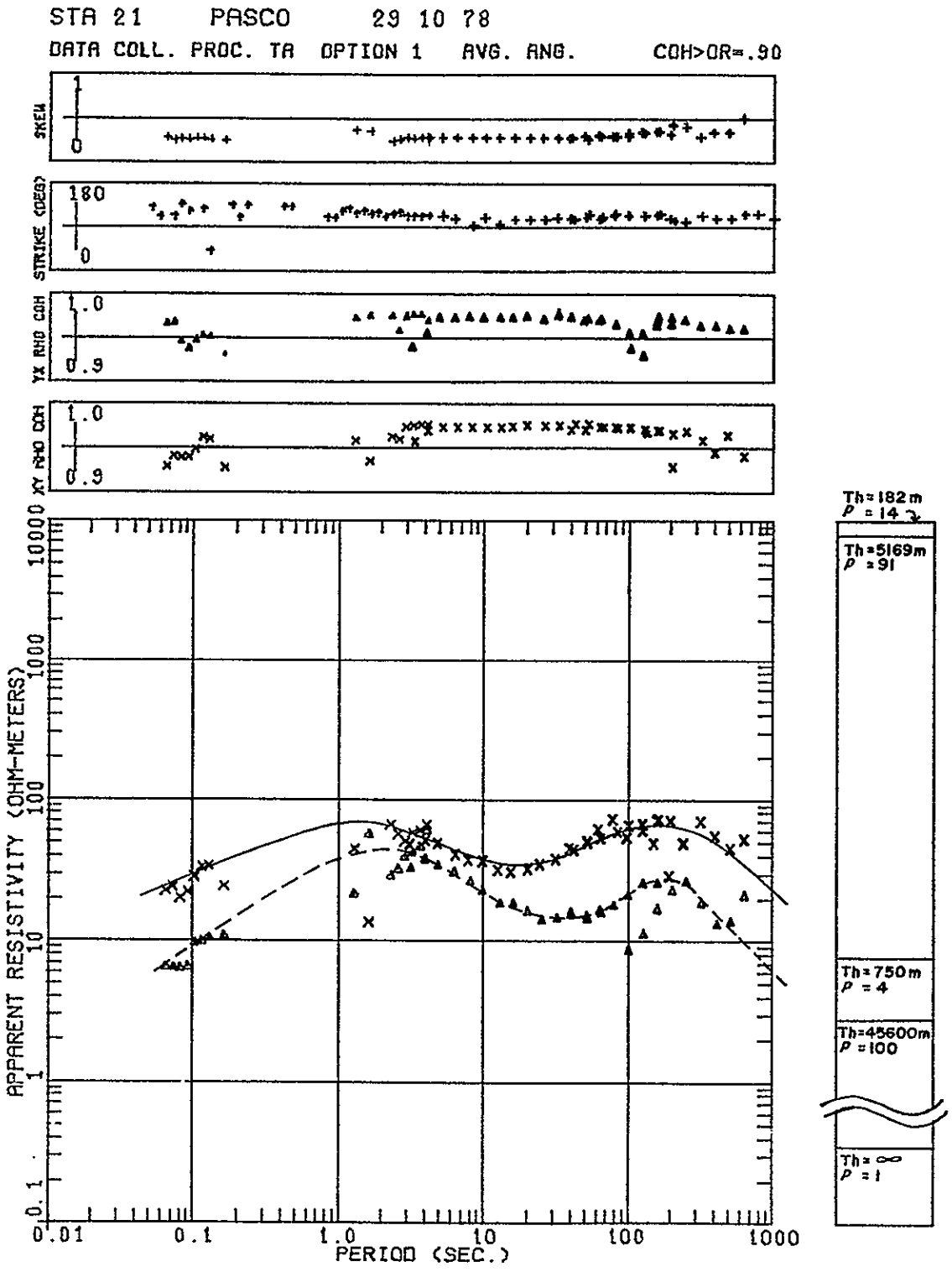

FIGURE E-2u. Tensor Sounding Curves-Fiscal Year 1979.

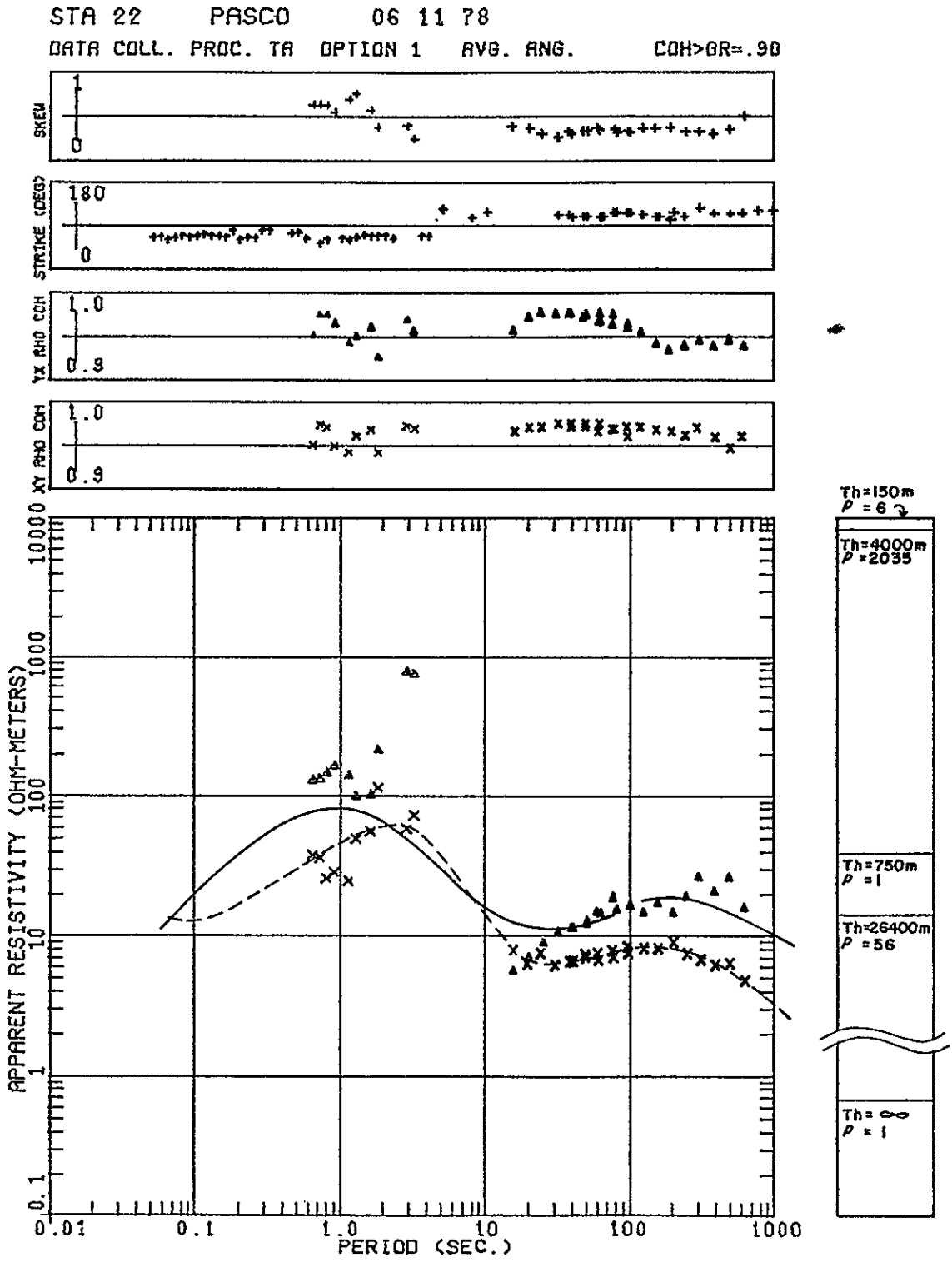

FIGURE E-2v. Tensor Sounding Curves Fiscal Year 1979.

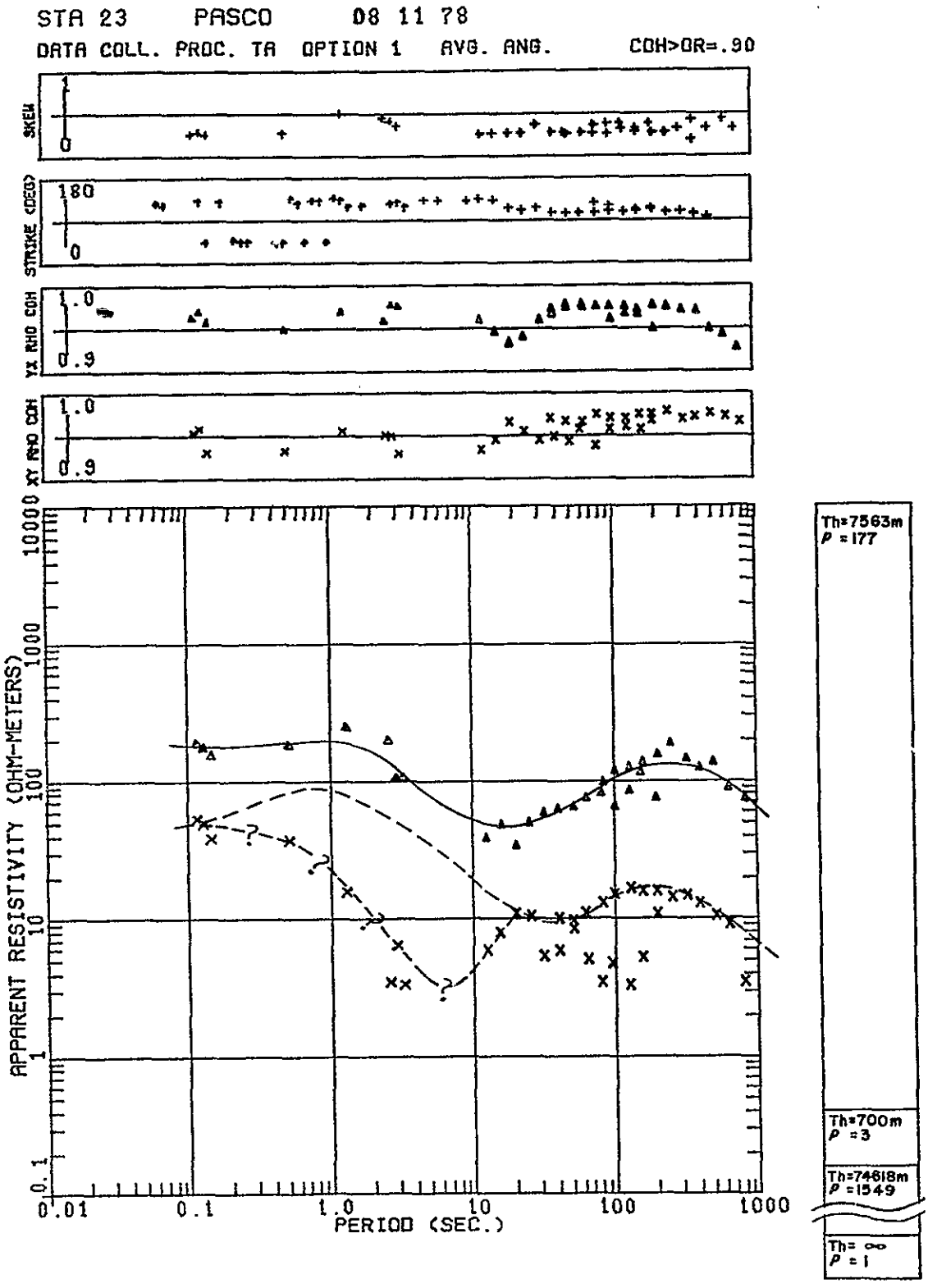

FIGURE E-2w. Tensor Sounding Curves-Fiscal Year 1979.

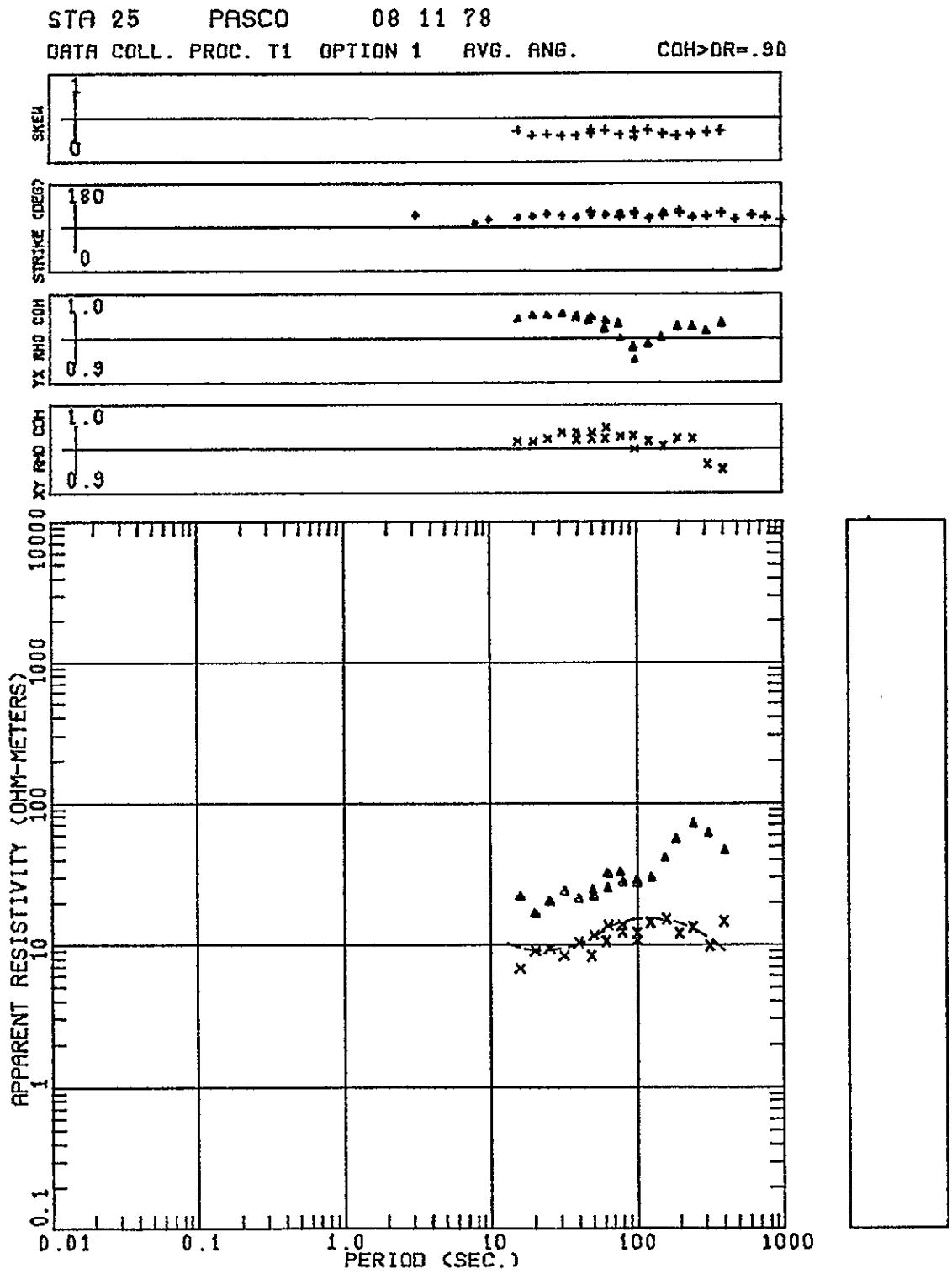

FIGURE E-2x. Tensor Sounding Curves-Fiscal Year 1979.

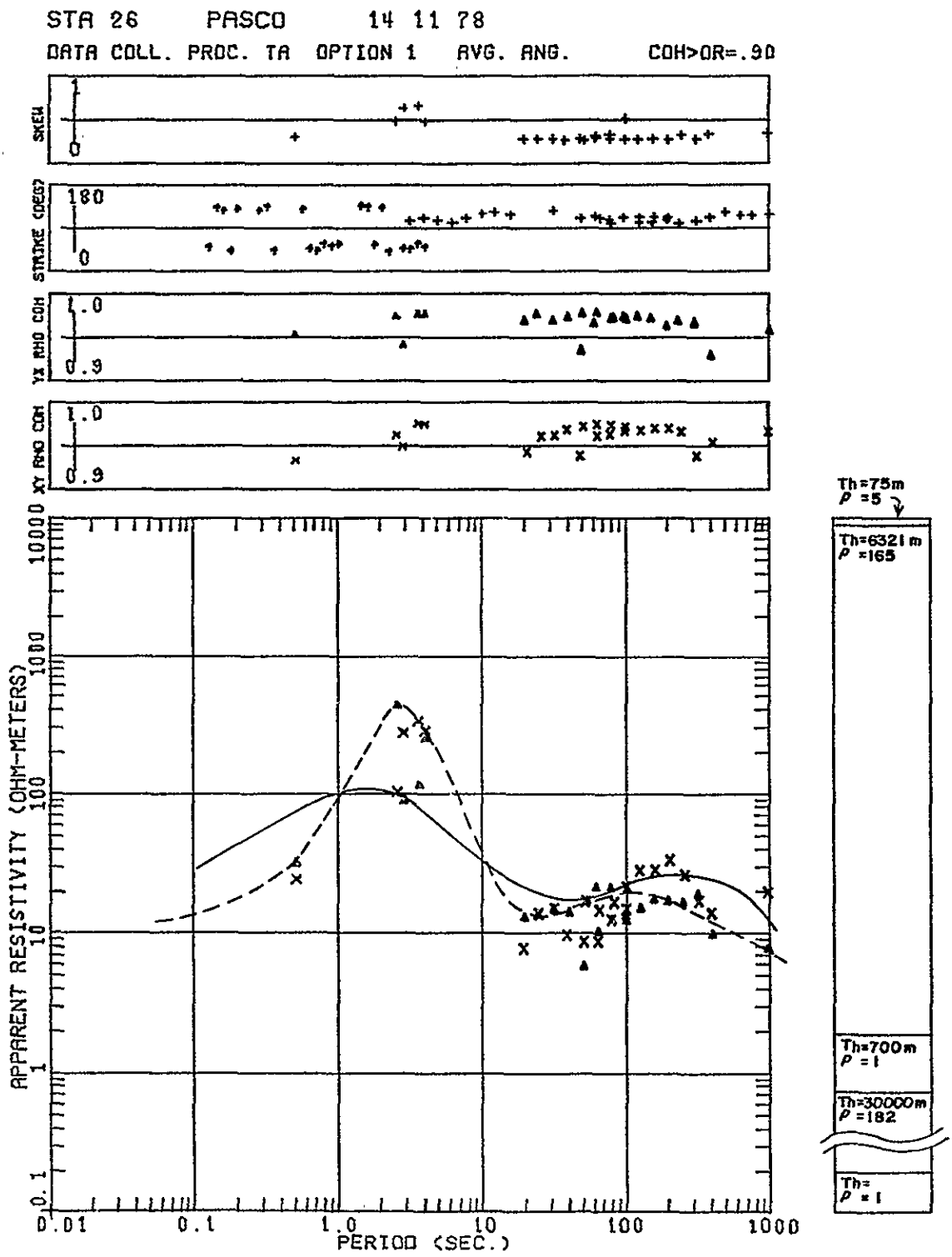

FIGURE E-2y. Tensor Sounding Curves-Fiscal Year 1979.

depth (resistivity in ohm-meters and thickness in meters). The theoretical model response is superimposed (solid line) on the E-parallel data. The dashed line indicates E-perpendicular data. Magnetotelluric measurements along electrical strike are a basic requirement for obtaining subsurface resistivity models which best approximate the stratigraphic section. The fiscal year 1978 survey consisted of data acquisition, processing, and interpretation at 3 tensor sites before scalar data acquisition (electrical strike cannot be calculated from scalar data). Scalar dipoles were then aligned northwest-southeast parallel to tensor-defined electrical strike (Stations 1-1, 1-2, and 1-4 [Figure E-3]) which correlated with major structures within the survey. The fiscal year 1979 tensor magnetotelluric survey indicated a very complex electrical strike pattern (Figure E-3); therefore, disproving the initial basic assumption of a uniform northwest-southeast electrical strike. Because of this known divergence within electrical strike, the fiscal year 1978 scalar data were utilized only as a gross subsurface indicator.

Figure E-4 shows contoured elevations on the top of geoelectric layer 2 (Table E-1). Contours were drawn using data from magnetotelluric survey stations as control points, and using known structural trends in the basalt. The importance of this map is the consistency of the magnetotelluric data with known trends.

Figure E-5 shows contoured elevations on the top of geoelectric layer 3 (Table E-1). The exact lithology forming this geoelectric layer is unknown because it has not been penetrated by deep drilling in the Pasco Basin, although it is postulated that it might be Mesozoic or early Tertiary sedimentary rock. Regardless of the exact lithology, the magnetotelluric data reveal a low-resistivity, high-conductivity layer beneath the high-resistivity, low-conductivity basalt, indicating a major lithologic change in rock type.

Figure E-6 shows contoured elevations on the top of geoelectric layer 4 (Table E-1). This layer is a highly resistive unit beneath layer 3. The lithology of this unit is unknown. It might be crystalline basement.

Figure E-7 shows contoured elevations on the top of geoelectric layer 5 (Table E-1). Recognition of geoelectric layer 5 is based on the pronounced change in resistivity observed in the long period (1,000-second), low-frequency data. These longest wavelength data are representative of the deepest units penetrated. Geoelectric layer 5 is probably within the mantle.

Figures E-8, E-9, and E-10 show thickness variations of geoelectric layer 2 (basalt), geoelectric layer 3 (sediment), and geoelectric layer 4 (crystalline basement), respectively. Comparison of Figures E-4, E-5, E-6, and E-7 with Figures E-8, E-9, and E-10 has led to the following preliminary interpretations.

a. Elevation highs in geoelectric layers 3, 4, and 5 trend northeast beneath the Pasco Basin. The elevation highs correspond spatially very close among the three layers.

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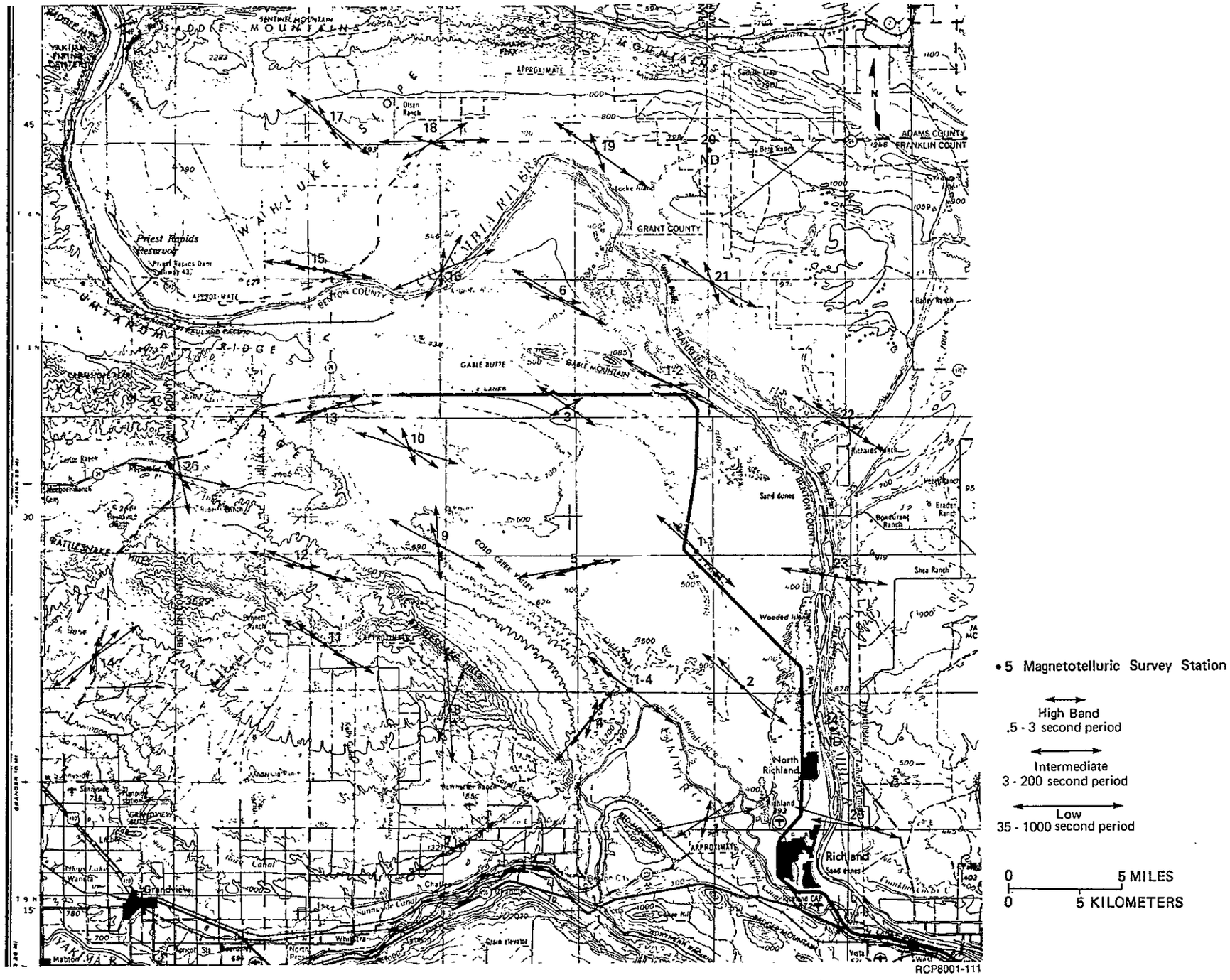

FIGURE E-3. Electrical Strike, Tensor Magnetotelluric Data.

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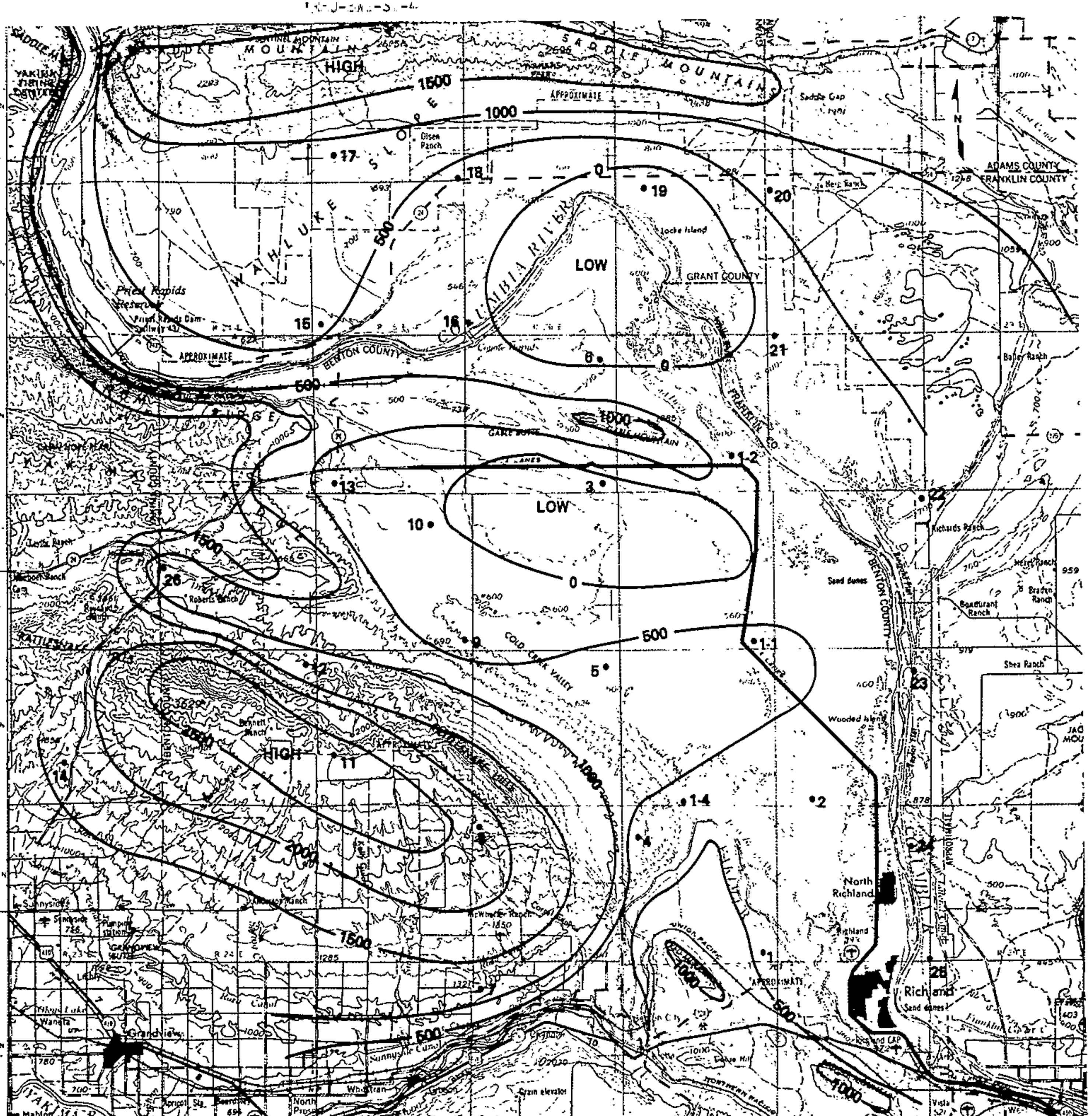
9 2 1 2 4 9 4 1 8 5 5

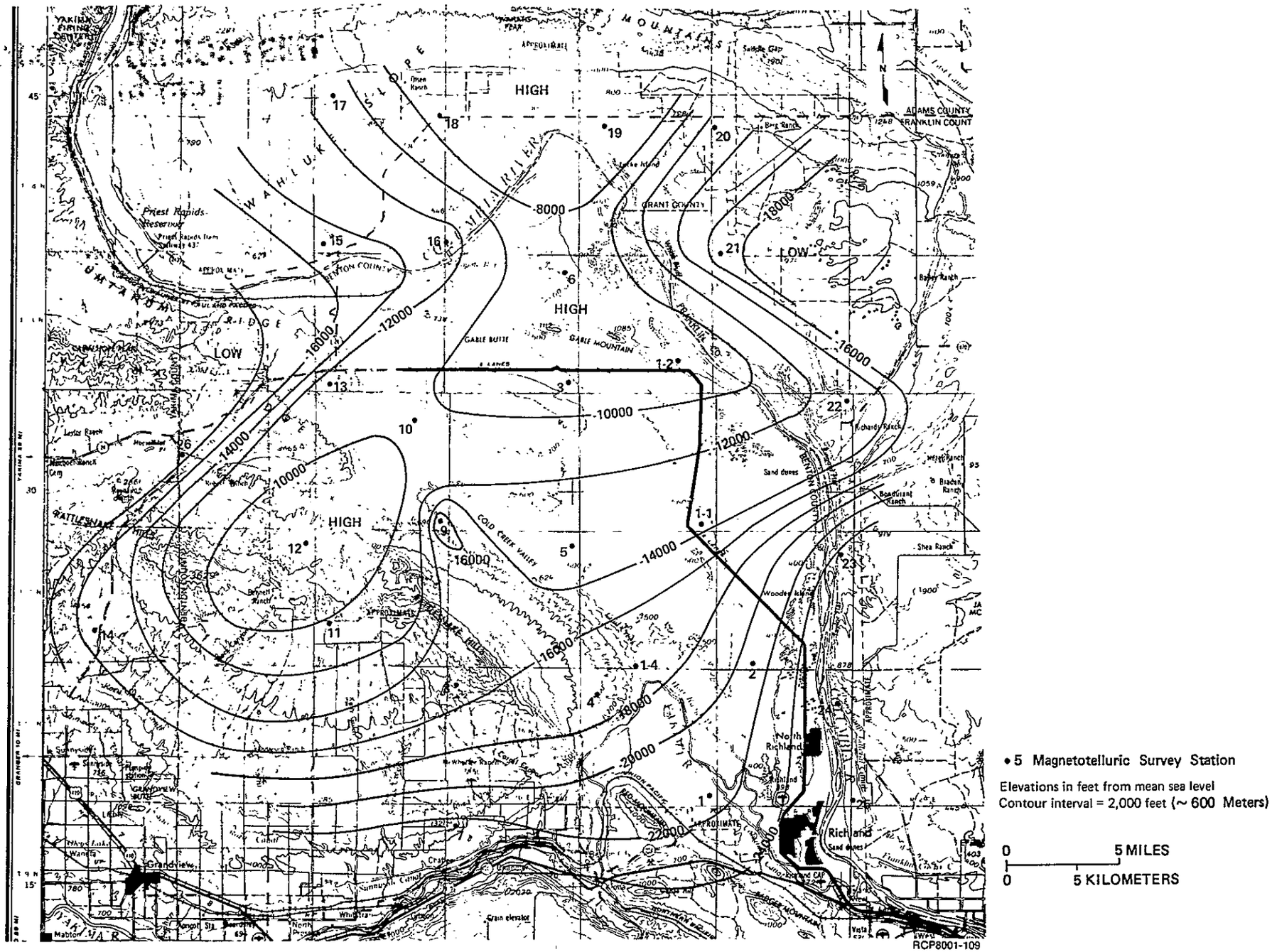


• 5 Magnetotelluric Survey Station

Elevations in feet from mean sea level
Contour interval = 500 feet (~150 Meters)

0 5 MILES
0 5 KILOMETERS

FIGURE E-4. Elevation Contours on the Top of Geoelectric Layer 2 (Basalt) Using Magnetotelluric Data.



• 5 Magnetotelluric Survey Station

Elevations in feet from mean sea level
Contour interval = 2,000 feet (~ 600 Meters)

0 5 MILES
0 5 KILOMETERS

FIGURE E-5. Elevation Contours on the Top of Geoelectric Layer 3 Using Magnetotelluric Data.

TABLE E-1. Geoelectric Layer and Interpreted Rock Type.

GEOELECTRIC LAYER	ROCK TYPE
1 (conductive)	Surficial Sediments
2 (resistive)	Basalt (includes Columbia River Basalt Group, interbeds, and pre-Columbia River Basalt Group volcanic rocks)
3 (conductive)	Unknown (probably a layer of Mesozoic or early Tertiary sedimentary rocks)
4 (high resistive)	Unknown (probably crystalline basement rocks)
5 (conductive)	Unknown (probably within subcrust or upper mantle)

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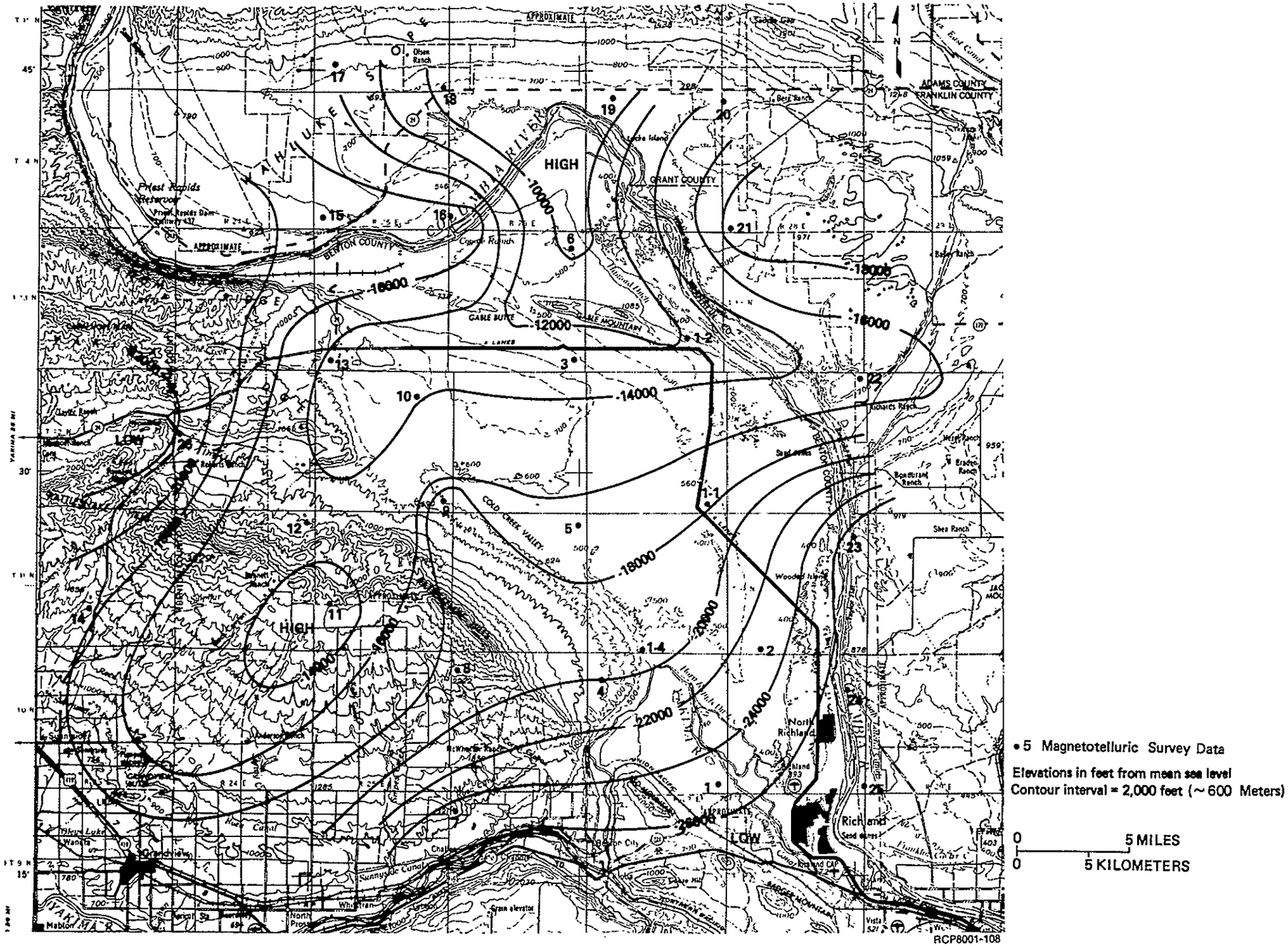

FIGURE E-6. Elevation Contours on the Top of Geoelectric Layer 4 Using Magnetotelluric Data.

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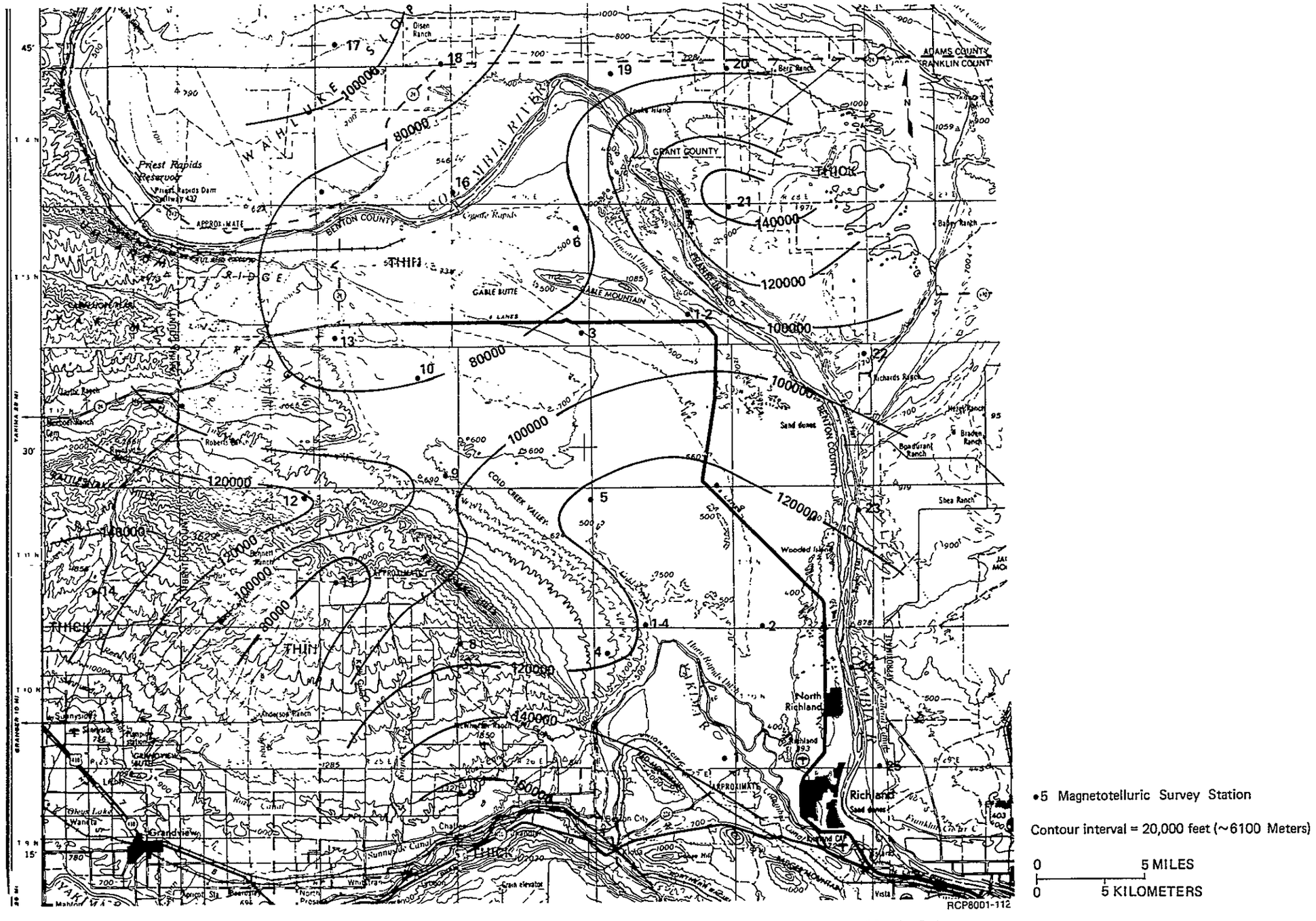
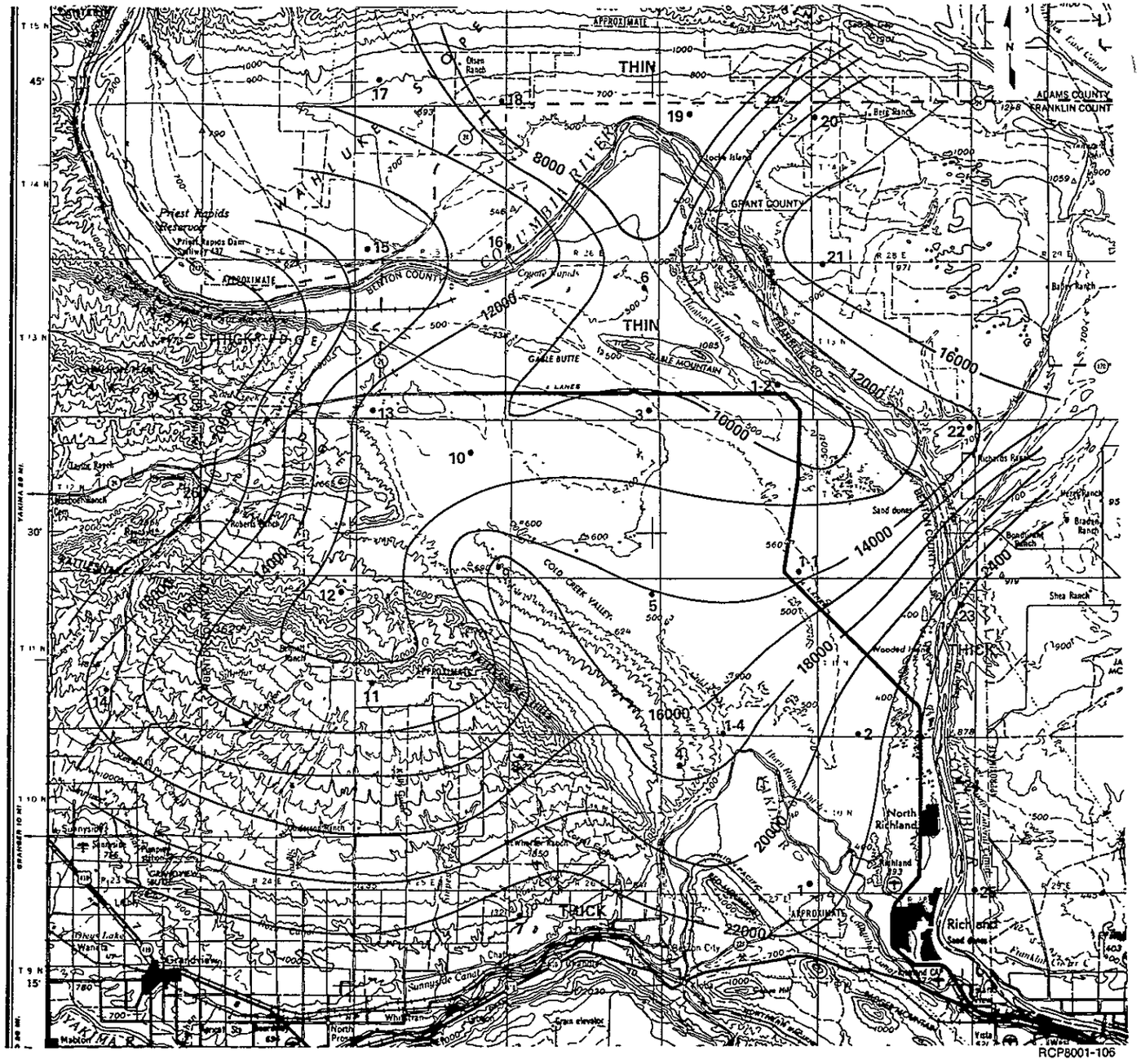


FIGURE E-7. Elevation Contours on the Top of Geoelectric Layer 5 Using Magnetotelluric Data.



•5 Magnetotelluric Survey Station

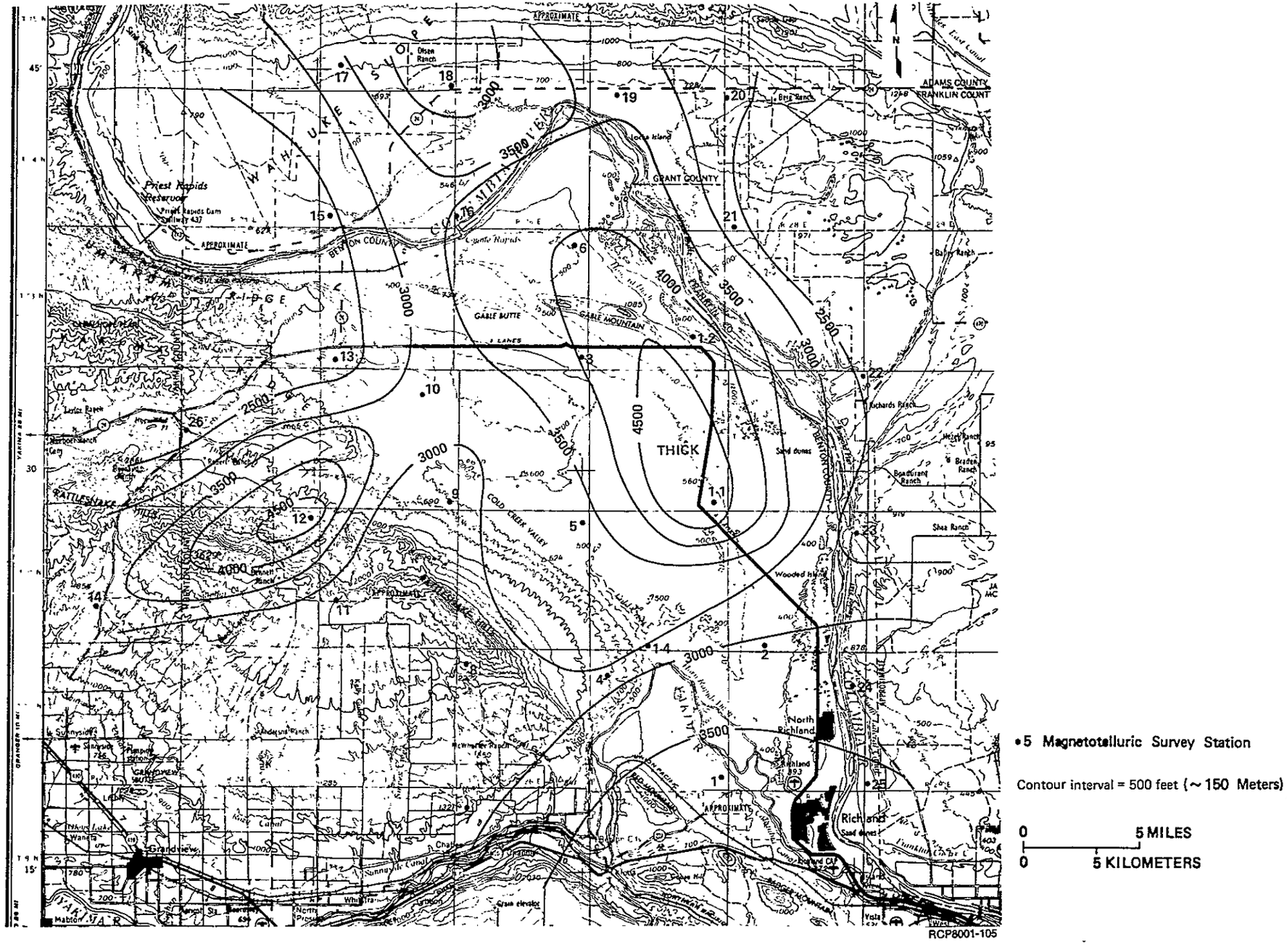
Contour interval = 2,000 feet (~ 600 Meters)

0 — 5 MILES

0 — 5 KILOMETERS

FIGURE E-8. Isopach Map, Geoelectric Layer 2.

9 2 1 2 1 9 4 1 8 5 0



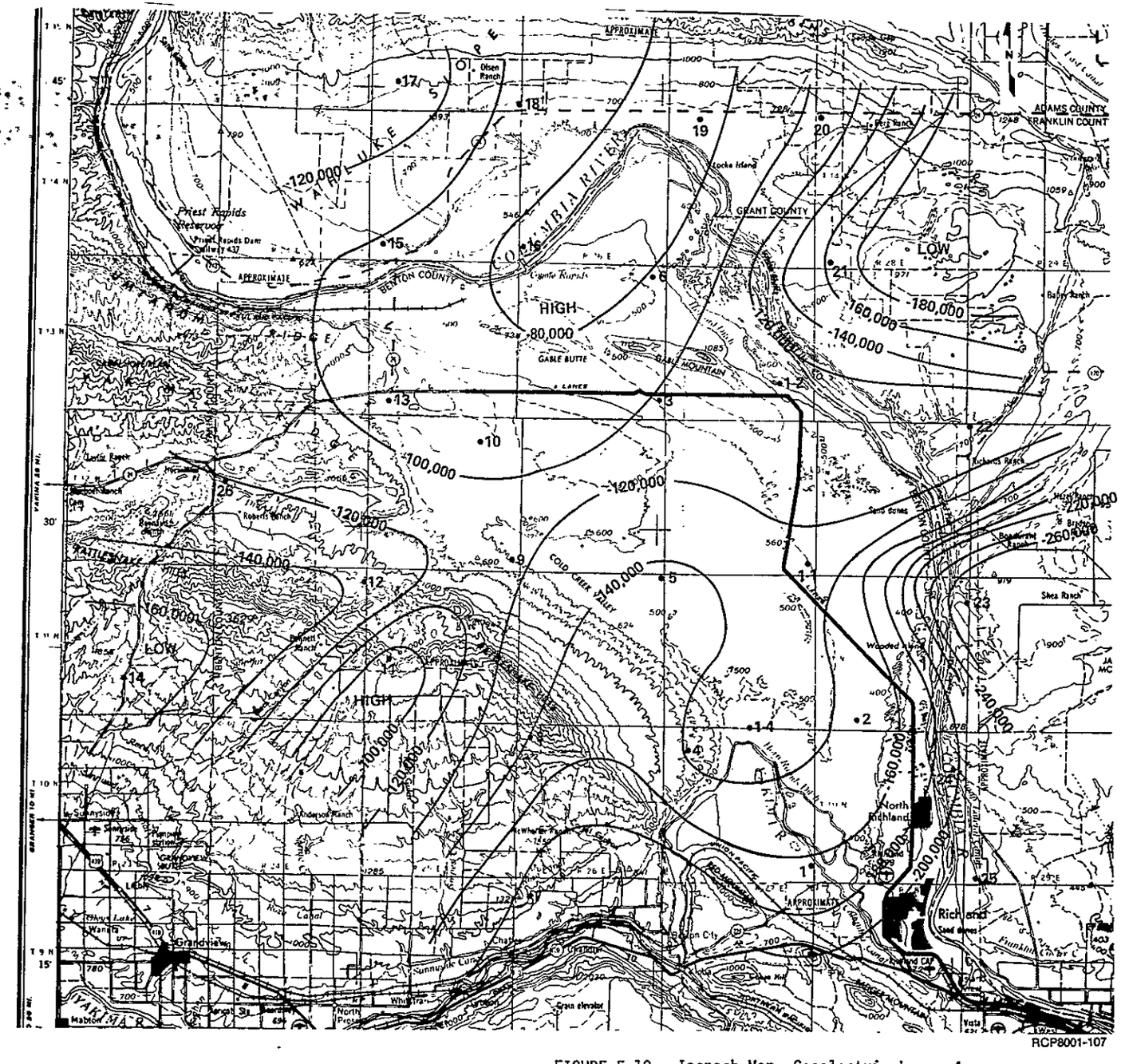
• 5 Magnetotelluric Survey Station

Contour interval = 500 feet (~ 150 Meters)

0 — 5 MILES

0 — 5 KILOMETERS

FIGURE E-9. Isopach Map, Geoelectric Layer 3.



• 5 Magnetotelluric Survey Station

Elevations in feet from mean sea level
Contour interval = 20,000 feet (~6100 Meters)

0 — 5 MILES
0 — 5 KILOMETERS

FIGURE E-10. Isopach Map, Geoelectric Layer 4.

b. Zones of thinning in geoelectric layers 2, 3, and 4 parallel and generally coincide with the elevation highs.

c. Assuming the elevation high in geoelectric layers 3, 4, and 5 represents a structural high, the northeast structural trends of the deep geoelectric layers contrast sharply with the northwest structural trends in the basalt.

d. A zone of crustal thinning appears to trend northeast beneath the Pasco Basin.

The northeast-trending zone of crustal thinning beneath the Pasco Basin is consistent with regional gravity trends (Deju and Richard, 1975) and with interpretations by Eaton in Smith (1978). Eaton concluded from an analysis of regional quarry blasts and a long refraction profile (Hill, 1972) that the crust thins to about 15 miles (25 kilometers) in thickness beneath the Pasco Basin.

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APPENDIX F

SUMMARY OF EARTHQUAKE RECORDS ON THE COLUMBIA PLATEAU

APPENDIX F

BRIEF HISTORY OF EARTHQUAKE RECORDS IN EASTERN WASHINGTON

Recorded history of earthquakes occurring or felt in eastern Washington is brief (Rasmussen, 1967; Berg and Baker, 1963). Earthquakes that occurred prior to the early 1900's were reported only in newspapers and journals published soon after the event. Speculations on locations of these events were highly dependent upon the distribution of population in eastern Washington (Weston Geophysical Research, 1977), which, in 1870, numbered less than 6,500 people (exclusive of Indians). With such a population distribution, it is likely that some events of small to moderate size were not felt, or at least were not noted in contemporary accounts. Sizes of events that were felt were reported in terms of damage or effect upon existing buildings or structures or to the terrain. Accounts describing these effects were often written days, weeks, or months after the events and, consequently, may well be exaggerated. Based upon available accounts, intensities (generally Modified Mercalli) were assigned to these events at some later date. While it is unlikely that any large earthquake events went unreported, accuracies of locations and estimates of sizes are highly subjective, permitting inferences only as to size, frequency, and location. Attempts to locate or assign intensity values to these earthquakes often meet with difficulty (Coombs and Others, 1976).

The period of instrumental records of earthquakes in eastern Washington began on June 30, 1909, with installation of a Wiechert seismograph in the Jesuit Seminary at Gonzaga, near Spokane. Similar to other contemporary instruments in Victoria, British Columbia (a Milne horizontal seismograph was installed in 1899) and Seattle, Washington (a Bosch-Omori seismograph began operating in 1906), this instrument had relatively low magnification and low-frequency response, making it better suited to recording teleseisms rather than local events. Station SPO at Gonzaga, which operated until September 1970, was the only instrument operating in eastern Washington until 1945. It subsequently became part of the Jesuit Seismological Association network. In 1946, the Wiechert instrument was replaced by a Wood-Anderson seismograph that operated until 1970. Station SPO operated intermittently as a function of availability of trained clergy at the seminary, but the station did record the 1918 Corfu and the 1936 Milton-Freewater earthquakes. Records from station SPO are on file at Pacific Northwest Laboratory, Richland, Washington. Other stations have operated for periods of a few years at Grand Coulee, Washington and Nordman, Idaho. Installation by the U.S. Geological Survey of a battery of instruments at Newport, Washington in 1966 afforded the ability to record three components of short- and long-period earthquake ground motion from moderate to large earthquakes in eastern Washington.

Concern about seismicity in the area of the Hanford Site in the mid-1960's led to establishment by the U.S. Geological Survey of a microearthquake recording network in 1969. Various reviews of seismicity and tectonics related to development of seismic design criteria for the

Fast Flux Test Facility and proposed nuclear generating stations of the Washington Public Power Supply System, Inc. demonstrated a need for more detailed knowledge of seismicity in the Hanford vicinity (Jones and Deacon, 1966; Jahns, 1967; Housner 1966; Waldron and Bonilla, 1968). Seven short-period, single-component, vertical seismographs were installed by the U.S. Geological Survey in cooperation with the U.S. Atomic Energy Commission in the vicinity of the Hanford Site in 1969. This telemetered (to Menlo Park, California) network permitted significant reduction in threshold magnitude of earthquakes that could be detected and located in southeastern Washington. The Hanford array was expanded to 16 stations in 1970 and to 24 stations by 1971. (Figure F-1) In 1972 and 1973, minor changes were made in station locations to improve the quality of data. When operational responsibility for the network shifted from the U.S. Geological Survey to the University of Washington in 1975, 15 stations were located on and along the periphery of the Hanford Site (Malone, 1977) and 9 other stations were present in southern Washington and northern Oregon (Figure F-1).

Since assuming responsibility for the network, the University of Washington has expanded the eastern Washington array to a 36-station regional monitoring system. Several stations have been added in the northern part of the Columbia Plateau and its margins to provide a more uniform earthquake detection capability. These 36 stations enable detection and location of earthquakes in eastern Washington to a minimum uniform threshold of magnitude 2.0, with thresholds of magnitude 1.5 around Hanford and in the Columbia Plateau to the north. Events as small as magnitude 0 can be detected, but only some of these are recorded by enough stations to permit accurate location of hypocenters. Some stations have been relocated to the Lake Chelan area in order to obtain more data on that area of relatively frequent seismic activity. Four stations in the University of Washington microearthquake array are located in Oregon, thus permitting accurate location of events in southern Washington. Five additional stations have recently been installed in the foothills of the Cascade Range.

Earthquake data processing techniques have changed during the course of earthquake monitoring in eastern Washington (Weston Geophysical Research, 1977). Locations were initially determined by the U.S Geological Survey using the HYPOLAYR program, but use of the HYPO71 model was initiated in 1971. Velocity models were also changed as more information became available. The U.S. Geological Survey used a 5-layer velocity model throughout eastern Washington; the University of Washington currently uses a 4-layer model north of 47 degrees north latitude and a 6-layer model south of 47 degrees north. Magnitudes were initially determined by the U.S. Geological Survey from trace amplitudes, but later were changed to a combination trace amplitude--coda length magnitude. The University of Washington currently uses a coda length magnitude relationship that was calibrated against Wood-Anderson magnitude. The currently used equation for coda length magnitude gives results that agree well with Wood-Anderson magnitudes, but is substantially different from coda length magnitude relationships in California. These differences in data processing gave rise to a non-uniform earthquake data set; however, conversion to a uniform data set has been completed recently (Malone, 1979).

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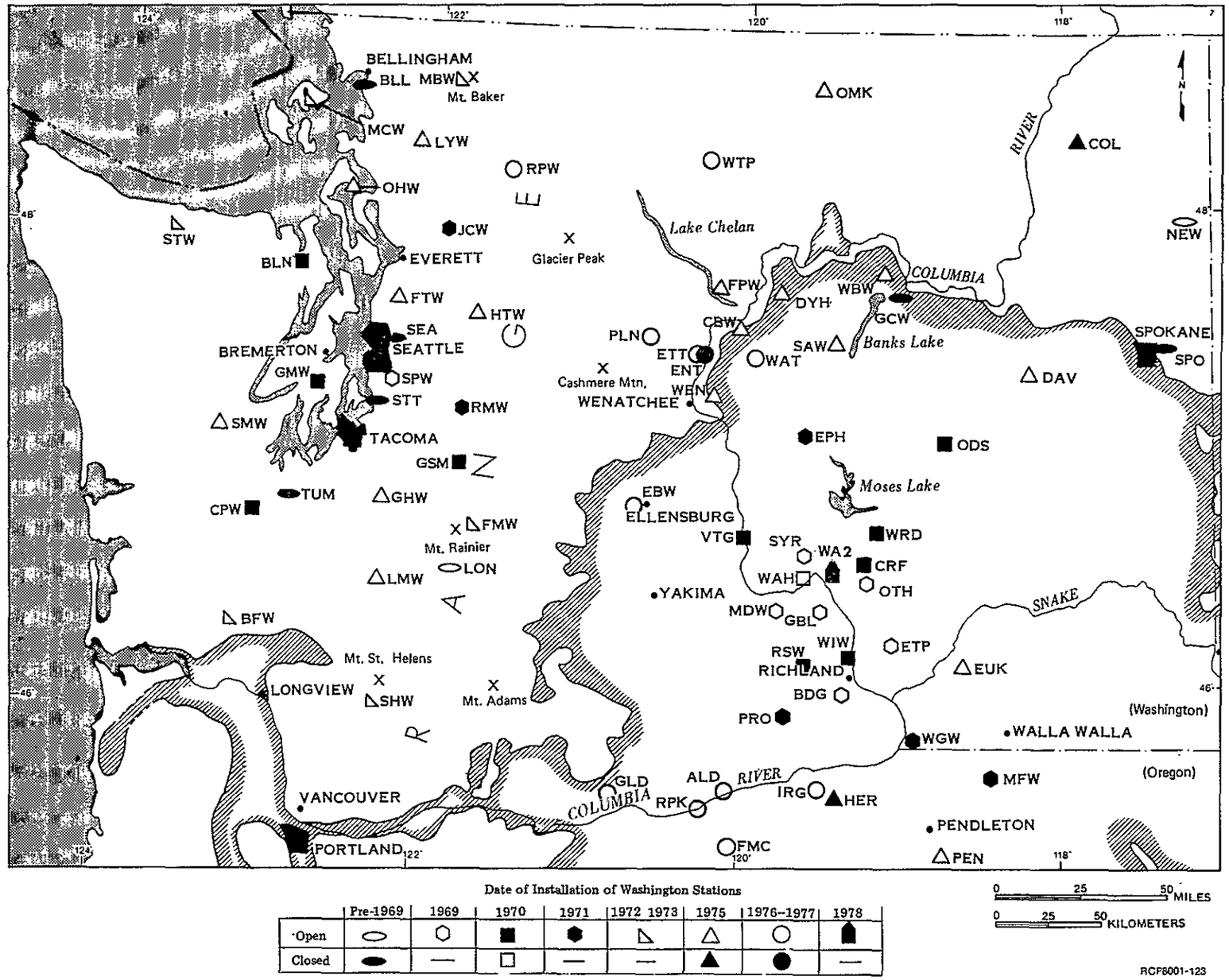

Date of Installation of Washington Stations

	Pre-1969	1969	1970	1971	1972 1973	1975	1976–1977	1978
Open	⬭	⬡	■	⬢	◺	△	○	⬟
Closed	⬬	—	□	—	—	▲	●	—

FIGURE F-1. Washington State Seismic Stations.

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Several small seismic detection arrays have operated for brief periods of time in eastern Washington. Most of these portable arrays were operated by the University of Washington and were designed to monitor activity in very limited areas. The objective of these arrays was to gather as much detailed information as possible regarding size, frequency, location, and possible source parameters and structures in small areas known to be affected by earthquake activity. Seismic activity detection arrays operated by University of Washington personnel have monitored microseismic swarm activity near Wooded Island (Rothe, 1978), as well as at Eltopia, Wahluke Slope, and Royal City, Washington (Malone and Others, 1975). Woodward-Clyde Consultants operated several small arrays for the Washington Public Power System, Inc. during the summer and autumn of 1978. These arrays consisted of six to eight stations, were operational for a few weeks at any one locality, and were moved to new localities in the area of Milton-Freewater, Oregon, and the Ross Lake-Methow graben and Ellensburg, Washington (Withers and Others, 1978).

BRIEF HISTORY OF EARTHQUAKE RECORDS IN WESTERN WASHINGTON

Most earthquakes recorded in Washington before the turn of the century occurred in, or were felt, in western Washington (Rasmussen, 1967). All of these events are reported to have occurred at the largest center of population affected by the earthquake, but, in reality, the events may have occurred as far as several tens of miles (kilometers) distant from the reported epicenter. The size of each event has been stated as an intensity which was assigned after the event, based on maximum effects that were recorded within the felt area. Considering distribution of population and the fact that there were no instruments to record earthquakes, assessment of seismicity from these data is limited. Many events less than Modified Mercalli intensity V were probably not reported and the reported size of other events is probably less than the maximum, due to the absence of people reporting from the area (Rasmussen, 1967). Stepp (1973) considers earthquake data for the Puget Sound region to be adequate to reasonably assess seismicity from about 1930 to the present for events greater than Modified Mercalli intensity V.

The first seismograph in Washington commenced operation in 1906 when a Bosch Omori instrument was installed at the University of Washington in Seattle (Table F-1). This instrument had a relatively short period, low magnification, and measured two orthogonal components of horizontal ground motion. The instrument operated from 1906 until 1949, when it was replaced by Sprengnether instruments which measured three components of ground motion (two horizontal and one vertical). Station SEA closed on November 1, 1970. Records from 1931 to the closing of station SEA are available at the University of Washington.

Station SEA was the only seismograph operating in western Washington until the late 1950s when the Longmire (LON) and Tumwater (TUM) stations opened. Station LON began in August 1957 with three short-period, non-calibrated seismometers designed to study local earthquakes. In 1962, the station was briefly closed while being upgraded to conform with

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TABLE F-1. Seismograph Stations in Washington, Oregon, Idaho, and Montana.

EASTERN WASHINGTON

STATION CODE	STATION LOCATION	COORDINATES NORTH DEG.	NORTH MIN.	NORTH SEC.	WEST DEG.	WEST MIN	WEST SEC.	ELEVATION (M)	TIMING	INSTRUMENTATION COMPONENTS (2)	TYPE	INSTALLED BY	DATE OF OPERATION	CURRENTLY OPERATED BY	NETWORK AFFILIATION	RECORDS LOCATION	DATA SOURCE	COMMENTS
MDW	MIDWAY	46	36	48	119	45	39	330	CRYSTAL CLOCK (1) WWV	SPV	MARK IV - LC	USGS (3)	3/69	UW	EASTERN WASH.	UW	MALONE (1978)	
SYR	SMYRNA	46	51	46.8	119	37	04.2	260				USGS	3/69					
OTH	OTHELLO	46	44	20.4	119	12	59.4	260					3/69					
WA2 (8)	WAHLUKE	46	45	24	119	33	45.6	230				UW	5/78					
CRF	CORFU	46	49	30.6	119	23	05.4	260				USGS	8/70					
GBL	GABLE MT.	46	35	51.6	119	27	35.4	360					3/69					
ETP	ELTOPIA	46	27	53.4	119	03	32.4	250					3/69					
BDG	BADGER MT.	46	14	04.8	119	19	03.0	410					3/69					
EUK	EUREKA	46	23	45	118	33	43.2	400				UW	7/75					
PRO	PROSSER	46	12	45.6	119	41	09	600				USGS	10/71					
RSW	RATTLESNAKE HILLS	46	23	28.2	119	35	19.2	1130					8/70					
PEN	PENDLETON, ORE.	45	36	43.2	118	45	46.2	460				UW	7/75					
WGW	WALLULA GAP	46	02	40.8	118	55	57.6	160				USGS	10/71					
WIW	WOODED ISLAND	46	25	55.8	119	17	17.4	130					8/70					
IRG	IRRIGON, ORE.	45	53	09	119	29	55.2	200				UW	11/77					
MFW	MILTON-FREEWATER, ORE	45	54	10.8	118	24	21	430				USGS	10/71					
OMK	OMAK	48	28	49.2	119	33	39	450				UW	7/75					
DYH	DYER HILL	47	57	37.8	119	46	09.6	900					7/75					
WBW	WILSON BUTTE	48	01	04.2	119	08	13.8	910					7/75					
SAW	ST. ANDREWS	47	42	06	119	24	03.6	800					7/75					
CBW	CHELAN BUTTE	47	48	25.2	120	01	57.6	1,290		(5)			7/75					
FPW	FIELDS POINT	47	58	00	120	12	46.2	360					7/75					
PLN	PLAIN	47	47	04.8	120	37	58.2	670					6/77					
ETT	ENTIAT	47	39	18	120	17	36	930					6/77					
WEN	WENATCHEE	47	31	46.2	120	11	39	1,140					7/75					
EPH	EPHRATA	47	21	07.8	119	35	46.2	500				USGS	10/71					
ODS	ODESSA	47	18	24	118	44	42	610		(5)			8/70					
DAV	DAVENPORT	47	38	20	118	13	33.6	780				UW	7/75					
WRD	WARDEN	46	58	11.4	119	08	36	410				USGS	7/70					
WAT	WATERVILLE	47	41	55.2	119	57	15	900				UW	11/76					
VTG	VANTAGE	47	57	28.8	119	59	14.4	210		(5)		USGS	7/70					

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Table F-1 (continued)

EASTERN WASHINGTON CONTINUED

STATION CODE	STATION LOCATION	COORDINATES NORTH DEG.	NORTH MIN	NORTH SEC	WEST DEG.	WEST MIN.	WEST SEC	ELEVATION (M)	TIMING	INSTRUMENTATION COMPONENTS (2)	INSTRUMENTATION TYPE	INSTALLED BY	DATE OF OPERATION	CURRENTLY OPERATED BY	NETWORK AFFILIATION	RECORDS LOCATION	DATA SOURCE	COMMENTS
NEW	NEWPORT	48	15	49.8	117	07	13.2	830	CRYSTAL CLOCK (1) WWV	SPV, SP-NS, EW LPV, LP-NS, EW	BENIOFF (SP) SPRENGNETHER (LP) WOOD ANDERSON	USGS	1966	UW	USGS-NEIS (4)	BOULDER, COLO., UW	GLOVER (1977)	FOOTNOTE (10)
FMC	FOUR MILE CANYON, ORE.	45	37	28.2	120	01	42	300		SPV	MARK IV - LC	PG& E	1/77	TERA CORP. FOR PORTLAND GAS & ELECTRIC	EASTERN WASHINGTON	UW		FOOTNOTE (11)
RPK	ROOSEVELT	45	45	42	120	13	49.8	330					1/77				MALONE (1978)	
ALD	ALTER RIDGE	45	49	10.2	120	04	00	290					1/77					
GLD	GOLDENDALE	45	50	20	120	48	51	700				UW	11/77	UW				
EBW	ELLENSBURG	47	00	15	120	40	28.2	830					12/77					
WTP	WINTHROP	48	28	16.2	120	14	52.2	760					6/77					
WAH	WAHLUKE	46	45	24	119	34	40.8	230				USGS	7/70-5/78	CLOSED				FOOTNOTE (12)
HER	HERMISTON	45	50	08.4	119	22	51	190				UW	7/75-11/77					FOOTNOTE (13)
ENT	ENTIAT	47	40	43.8	120	13	48	860					11/75-6/77					FOOTNOTE (14)
COL	COLVILLE	48	35	36	117	52	55.2	810					7/75-4/77					FOOTNOTE (15)
RPW	ROCKPORT	48	26	54	121	30	49.2	850					8/77	UW				
SPO	SPOKANE	47	43	48	117	20	32	713	UNKNOWN	SPH	WIECHERT WOOD ANDERSON	GONZAGA JESUIT SEMINARY	6/09-9/70	CLOSED	JESUIT SEISMOLOGICAL ASSN.	BATTELLE RICHLAND, WA.	WPPSS AMEND 23	FOOTNOTE (16)
GCW	GRAND COULEE	47	56	29	118	58	48	462		SPV, SP-NS, EW	BENIOFF	USC GS FOR U.S. BUR. RECLAMATION	1941-1949		NONE	NOAA - NGSDC BOULDER	POPPE, ET AL (1978) POPPE (1979)	
(49) TK-WA	TONASKET	48	47	38	119	35	16	549	WWV	SPV, SP-NS, EW	BENIOFF SPRENGNETHER	TELEDYNE GEOTECH (GARLAND, TEX.)	8/21/63 5/17/64		LASM (6)	TELEDYNE GEOTECH (7)		

WESTERN WASHINGTON

STATION CODE	STATION LOCATION	COORDINATES NORTH DEG.	NORTH MIN	NORTH SEC	WEST DEG	WEST MIN.	WEST SEC	ELEVATION (M)	TIMING	INSTRUMENTATION COMPONENTS	INSTRUMENTATION TYPE	INSTALLED BY	DATE OF OPERATION	CURRENTLY OPERATED BY	NETWORK AFFILIATION	RECORDS LOCATION	DATA SOURCE	COMMENTS
SPW	SEWARD PARK (SEATTLE)	47	33	13.3	122	14	45.1	80	WWV	SPV		UW	9/69	UW	WESTERN WASHINGTON	UW	CROSSON (1972)	
GMW	GOLD MT.	47	32	52.5	122	47	10.8	505					2/70					
GSM	GRASS MT.	47	12	11.4	121	47	40.2	1,305					6/70					
BLN	BLYN MT.	48	00	26.5	122	58	18.6	585					7/70					
CPW	CAPITOL PEAK	46	58	25.8	123	08	10.8	792					7/70					
RMW	RATTLESNAKE MT.	47	27	35.0	121	48	19.1	1,024					7/71					
LON	LONGMIRE	46	45	00.0	121	48	35.0	854	WWSSN	SPV N-S, EW LPV N-S, EW	BENIOFF SPRENGNETHER		8/57, 9/62		WWSSN (9)		GLOVER (1977)	FOOTNOTE (17)
JCW	JIM CREEK	48	11	36.50	121	55	46.20	616	WWV	SPV			2/71		WESTERN WASHINGTON		CROSSON (1974)	
FMW	MT. FREMONT	46	55	54.00	121	40	19.20	1,890					9/72					
BFW	BAW FAW MT.	46	29	12.00	123	12	53.40	902					10/72					
SHW	MT. ST. HELENS	46	11	33.00	122	14	12.00	1,423					10/72					
MBW	MT. BAKER	48	47	02.40	121	53	58.80	1,676					11/72					

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Table F-1 (continued)

WESTERN WASHINGTON CONTINUED

STATION CODE	STATION LOCATION	COORDINATES NORTH DEG	NORTH MIN.	NORTH SEC.	WEST DEG.	WEST MIN	WEST SEC.	ELEVATION (M)	TIMING	INSTRUMENTATION COMPONENTS	INSTRUMENTATION TYPE	INSTALLED BY	DATE OF OPERATION	CURRENTLY OPERATED BY	NETWORK AFFILIATION	RECORDS LOCATION	DATA SOURCE	COMMENTS
MCW	MT. CONSTITUTION	48	40	46.80	122	49	56.4	693	WWV	SPV		UW	11/72	UW	WESTERN WASHINGTON	UW	CROSSON (1974)	
STW	STRIPED PEAK *	48	09	0.75	123	40	12.00	309					6/73					
LYW	LYMAN	48	32	0.72	122	06	06.0	107					4/16/75				POPPE (ET AL. 1978)	
OHW	OAK HARBOR	48	19	24	122	31	54.6	54					5/16/75					
FTW	FAIRMONT	47	52	36	122	12	05.0	147					9/24/75					
HTW	HAYSTACK	47	48	12.5	121	46	08.7	829					6/11/75					
SMW	SOUTH MOUNTAIN	47	19	10.2	123	20	30.0	840					3/24/75					
GHW	GARRISON HILL	47	02	30 0	122	16	21.0	268					9/24/75					
LMW	LADD MOUNTAIN	46	40	04.8	122	17	28.8	1.195					6/30/75					
BLL	BELLINGHAM	48	44	20.0	122	29	05.0	96		SPV, SP-NS, EW		WWSC (3)	12/61-7/69	CLOSED	NONE			
SEA	SEATTLE	47	39	18.0	122	18	30.0	30	WWVB	LP-NS, EW SPV, SP-NS, EW	BOSCH-OMORI ('09-'49) SPRENGNETHER ('49-'70)	UW	1909-11/70		NONE	UW (1931-1970)		
STT	SEATTLE-MARSHALL	47	25	22	122	18	49.2	–	WWV DAILY CHECK	LPN-NS	GALLITZIN	J. MARSHALL	4/64-4/76		NONE			
TUM	TUMWATER	47	00	54.0	122	54	30.0	20	WWV	SPV, NS, EW LPV, NS, EW	GEOTECH S-13 GEOTECH SL 210.220	UW	5/58-07/70			UW		

FOOTNOTE:

(1) EARTHQUAKES GIVEN IN UNIVERSAL TIME. WITH TIMING BY CRYSTAL CLOCK COORDINATED WITH WWV.
(2) COMPONENT ABBREVIATION AS FOLLOWS:
SPV SHORT PERIOD VERTICAL
LPV LONG PERIOD VERTICAL
SP-NS, EW SHORT PERIOD HORIZONTAL IN NORTH-SOUTH AND EAST-WEST DIRECTIONS
LP-NS, EW LONG PERIOD HORIZONTAL IN NORTH-SOUTH AND EAST-WEST DIRECTIONS
SPH SHORT PERIOD HORIZONTAL WITH AZIMUTH UNSPECIFIED
(3) USGS UNITED STATES GEOLOGICAL SURVEY
UW UNIVERSITY OF WASHINGTON
PGE PORTLAND GAS AND ELECTRIC
WWSC WESTERN WASHINGTON STATE COLLEGE
(4) NEIS NATIONAL EARTHQUAKE INFORMATION SERVICE
(5) MONITORED VERTICAL AND TWO HORIZONTAL COMPONENTS OF SHORT PERIOD GROUND MOTION FROM 7/75 TO 6/77
(6) LRSM LONG RANGE SEISMIC MEASUREMENTS
(7) TELEDYNE GEOTECH - SEISMIC DATA ANALYSIS CENTER, 314 MONTGOMERY ST., ALEXANDRIA, VA
(8) WA2 - STATION RELOCATED FROM WAH - LOCAL STATION CODE
(9) WWSSN WORLD WIDE STANDARD SEISMOGRAPH NETWORK
(10) PART OF TSUNAMI WARNING NETWORK WASHINGTON EARTHQUAKE DATA ARE SHARED WITH THE UNIV. WASHINGTON
(11) STATIONS ALD, FMC, & RPK ARE THE NETWORK FOR PEBBLE SPRINGS NUCLEAR GENERATING STATION DATA ARE MAILED MONTHLY TO U.W.
(12) STATION MOVED TO WA2 BECAUSE OF NOISE
(13) STATION MOVED TO IRG
(14) TEMPORARY STATION, MOVED TO ETT FOR PERMANENT LOCATION
(15) STATION CLOSED BECAUSE OF TELECOMMUNICATION PROBLEMS AREA SEISMICALLY QUIET
(16) WIECHERT REPLACED BY WOOD-ANDERSON IN 1946.
(17) OPENED 8/57 WITH 3 SHORT PERIOD VERTICAL SEISMOMETERS ADDED 3 LONG PERIOD INSTRUMENTS IN 9/62 TO CONFORM WITH W.W.S.S.N. SPECIFICATIONS.

Table F-1 (continued)

OREGON

STATION CODE	STATION LOCATION	COORDINATES NORTH DEG.	NORTH MIN.	NORTH SEC	WEST DEG	WEST MIN	WEST SEC.	ELEVATION (M)	TIMING	INSTRUMENTATION COMPONENTS (19)	INSTRUMENTATION TYPE	INSTALLED BY	DATES OF OPERATION	CURRENTLY OPERATED BY	NETWORK AFFILIATION	RECORDS LOCATION	DATA SOURCE	COMMENTS
COR	CORVALLIS	44	35	08	123	18	11	122	WWSSN	SPV, SP-NS, EW LPV, LP-NS, EW SPV SPV	BENIOFF SPRENGNETHER GEOTECH S-13 WOOD ANDERSON SCHLICHTER	OSU (20) OSU OSU/UCAL (23)	1962 1946-1949 1949-1962	OSU CLOSED	WWSSN (21)	NOAA-NGSDC (22) & OSU 1949-1961 UCAL ARCHIVES	GLOVER, (1977) COUCH & LOWELL (1971)	FOOTNOTE (33)
PTD	PORTLAND	45	30	30	122	42	59	208	POOR HIGH DRIFT	SPV	WILSON-LAMISON	OMSI (24)	5/54	OMSI	NONE	OSU	POPPE, ET AL, (1978) POPPE (1979) COUCH, PERS. COM.	FOOTNOTE (34)
KFO	KLAMATH FALLS	42	16	0.0	121	44	42.0	1439	WWV	SPV	BENIOFF	OTI (25)	/62- /78	CLOSED	OREGON (26)	OSU		FOOTNOTE (35)
PMT	PINE MOUNTAIN	43	47	27.2	120	56	41.7	1924	GEOTECH TG-110	SPV, SP-NS, EW		NASA-MSC (27)	9/69-1978		OREGON (26)	UNKNOWN		FOOTNOTE (36)
BMO	BLUE MOUNTAIN OBSERVATORY	44	50	56	117	18	20	1189	WWV	15 SPV 3 IPV-NS, EW 3 LPV-NS, EW	JOHNSON-MATHISON ELECTRO-TECH GEOTECH	AFCRL-ARPA (28)	9/62-5/75		BLUE MTN. ARRAY		COUCH & LOWELL (1971)	FOOTNOTE (37)
HMO	HAROLD MASON	45	32	17	122	34	19	64	~WWV	SPV	HOMEMADE	HAROLD MASON	1975	HAROLD MASON	NONE		POPPE, ET AL. (1978) POPPE (1979) COUCH, PERS. COM.	

IDAHO

STATION CODE	STATION LOCATION	COORDINATES NORTH DEG	NORTH MIN	NORTH SEC.	WEST DEG.	WEST MIN.	WEST SEC.	ELEVATION (M)	TIMING	INSTRUMENTATION COMPONENTS (19)	INSTRUMENTATION TYPE	INSTALLED BY	DATES OF OPERATION	CURRENTLY OPERATED BY	NETWORK AFFILIATION	RECORDS LOCATION	DATA SOURCE	COMMENTS
BSE	BOISE	43	39	0.0	116	05	30.0		WWV	SPV	SPRENGNETHER	BSU (29)	5 75	BSU	BOISE STATE	BSU	VINCENT & APPLEGATE (1978)	FOOTNOTE (38)
KGI	KELLOG	47	29	18	116	04	54.0	1400	CRYSTAL CLOCK	SPV-NS, EW	SPRENGNETHER S-6000	USBM-SMRC (30) (31)	1970	USBM	NONE	USBM-SMRC	POPPE ET AL (1978) MC LAUGHLIN, ET AL (1976)	FOOTNOTE (39)
MUL	MULLAN	47	27	42	115	46	54	1300			GEOTECH S-13 & SP		1968					FOOTNOTE (40)
WAL	WALLACE	47	27	36	115	57	54	1200			SPR. S-6000		1965					FOOTNOTE (41)
NTI	NORDMAN	48	37	48	116	57	48	823	USGS-NEIS (32)	SPV	GEOTECH 18 300	USGS	8/67-12/75	CLOSED		NEWPORT GEOPHYSICAL OBSERVATORY		FOOTNOTE (42)
BHI	BERTHA HILL	46	45	50.4	115	47	31.2	1652	WWVB		MARK IV	UNIV. OF MONTANA	10/71-1/76		DWORSHAK DAM ARRAY	EARTHQUAKE RESEARCH LAB GEOLOGY DEPT. UNIV. OF MONT.	POPPE (1979)	FOOTNOTE (43)
DEI	DENT	46	38	24	116	11	57	960					10/71-7/74					
ERI	EUREKA RIDGE	46	32	04.8	116	16	29.4	862					10/71-7/74					
GHI	GILBERT HILL	46	28	12.6	116	19	08.4	920					10/71-1/76					
HHI	HARMONY HEIGHTS	46	28	32.4	116	08	47.4	636					10/71-7/74					
LGM	LITTLE GREEN MOUNTAIN	46	43	58.8	116	05	34.8	1455					10/71-7/74					
MAS	MASON BUTTE	46	37	57.6	116	21	28.2	1141					10/71-1/76					
WBI	WHISKEY BUTTE	46	34	57.2	115	58	43.5	1341					10/71-1/76					

Table F-1 (continued)

MONTANA

STATION CODE	STATION LOCATION	COORDINATES NORTH DEG.	NORTH MIN.	NORTH SEC	WEST DEG	WEST MIN	WEST SEC.	ELEVATION (M)	TIMING	INSTRUMENTATION COMPONENTS	INSTRUMENTATION TYPE	INSTALLED BY	DATES OF OPERATION	CURRENTLY OPERATED BY	NETWORK AFFILIATION	RECORDS LOCATION	DATA SOURCE	COMMENTS
LDM	LIBBY DAM	48	27	14	115	19	02	638	WWV	SPV (44)	BENIOFF 4681A	USGS (45)	2/70	U.S. ARMY CORPS. ENGINEERS SEATTLE	LIBBY DAM ARRAY	PRE 1976 ERL-UM 1976-CORPS. ENG. SEATTLE	POPPE. ET AL. 1978 POPPE. 1979 CORPS. ENG.	FOOTNOTE (48)
RXF	REXFORD	48	51	53	115	07	27	4040			GEOTECH RANGER SS 1	CORPS. (47)	10/76	CORPS.			PERS. COMMUN. 1979	
YKM	YAAK	48	51	43	115	42	42	4950					10/76					
BBM	BIG BEND	48	22	35	115	19	39	719			MARK LIV	USGS	2/71-7/74	CLOSED		ERL-UM (46)		
BCB	BIG CREEK BALDY	48	38	06.5	115	32	43.4	1524					7/72-10/76					
BLK	BLACK BUTTE	48	51	16.8	115	07	02.6	969					2/71-10/76					
CFM	CLIFFSIDE	48	12	29	115	27	30.0	898					2/71-7/74					
PNK	PINKHAM CREEK	48	46	03.6	115	05	16.8	1350					2/71-7/74					
TEE	TEEPLES RANCH	48	22	46.3	115	35	17.1	805					2/71-10/76					
WCM	WARLAND CREEK	48	27	30.0	115	06	10.0	1704					2/71-7/74					

FOOTNOTES:

(19) SPV SHORT PERIOD VERTICAL
LPV LONG PERIOD VERTICAL
SP-NS. EW SHORT PERIOD HORIZONTAL -- NORTH-SOUTH AND EAST-WEST COMPONENTS
LP-NS. EW LONG PERIOD HORIZONTAL -- NORTH-SOUTH AND EAST-WEST COMPONENTS
IPV-NS. EW INTERMEDIATE PERIOD HORIZONTAL -- NORTH-SOUTH AND EAST-WEST COMPONENTS
(20) OSU OREGON STATE UNIVERSITY: CORVALLIS
(21) WWSSN WORLD WIDE STANDARD SEISMOGRAPH NETWORK
(22) NOAA-NGSDC NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION. NATIONAL GEOPHYSICAL AND SOLAR DATA CENTER
(23) UCAL UNIVERSITY OF CALIFORNIA AT BERKLEY
(24) OMSI OREGON MUSEUM OF SCIENCE AND INDUSTRY. PORTLAND
(25) OTI OREGON TECHNICAL INSTITUTE. KLAMATH FALLS
(26) A SEISMOGRAPH STATION NETWORK IS CURRENTLY BEING ESTABLISHED IN OREGON BY PROF. R.W. COUCH OF OREGON STATE UNIVERSITY IN CORVALLIS. AS PRESENTLY CONCIEVED. IT WILL CONSIST OF SIX SEISMOMETERS THAT MEASURE THE SHORT PERIOD VERTICAL COMPONENT OF GROUND MOTION. DATA WILL TELEMETERED TO CORVALLIS WHERE TIMING AND RECORDING WILL TAKE PLACE. INSTALLATION IS ANTICIPATED IN 1979
(27) NASA-MSC NATIONAL AERONAUTICS AND SPACE ADMINISTRATION. MANNED SPACECRAFT CENTER
(28) AFCRL-ARPA AIR FORCE CAMBRIDGE RESEARCH LABORATORY-ADVANCED RESEARCH PROJECTS AGENCY
(29) BSU BOISE STATE UNIVERSITY
(30) USBM-SMRC U.S. BUREAU OF MINES-SPOKANE MINING RESEARCH CENTER
(31) FOUR SEISMOMETERS OWNED BY THE BUREAU OF MINING ARE ON LOAN TO MINING COMPANIES THAT OPERATE STATIONS AND SEND RECORDS WEEKLY TO USBM-SMRC. THE INTENT OF THESE AND OTHER DETECTION ARRAYS OPERATING IN THE MINES. IS TO MONITOR STRESS CHANGES IN AN EFFORT TO PREDICT ROCKBURSTS. LOCATING EARTHQUAKES IS A SECONDARY OBJECTIVE.
(32) USGS-NEIS U.S. GEOLOGICAL SURVEY. NATIONAL EARTHQUAKE INFORMATION SERVICE
(33) WWSSN STATION OPERATED BY PROF. R.W. COUCH OF SCHOOL OF OCEANOGRAPHY INSTALLED BY DR. H.R. VINYARD. OSC DEPT. PHYSICS INSTALLED IN HILLSIDE VAULT NEAR OSU CAMPUS
(34) INSTRUMENT LOANED TO OMSIBY USGS-NEIS AND IS STRICTLY FOR DISPLAY OF EARTHQUAKE DETECTION & RECORDING INSTRUMENTS. DATA GENERALLY NOT USEFUL FOR LOCATING EARTHQUAKES
(35) STATION CLOSED IN 1978 AND MOVED TO BEND. OREGON TO BECOME PART OF OSU ARRAY
(36) STATION INOPERATIVE DURING PERIOD 1972-1976
(37) STATION OPERATION SHIFTED TO U.S. COAST AND GEODETIC SURVEY IN 1/66
(38) ONE OF THREE STATIONS IN BOISE FOOTHILLS FUNDED BY U.S.D.O.E.
(39) INSTRUMENTS IN SUNSHINE MINE
STATION CLOSED FOR SIX MONTHS IN 1975
(40) INSTRUMENTS IN LUCKY FRIDAY MINE
(41) INSTRUMENTS IN GALENA MINE
(42) DATA TELEMETERED TO NEWPORT AND TIMED WITH N.E.I.S. STATION NEW
(43) BEGUN BY USGS. BUT LATER OPERATED BY U.S. CORPS OF ENGINEERS-SEATTLE ARRAY INTENDED TO CHECK FOR INDUCED SEISMICITY
(44) SPV - SHORT PERIOD VERTICAL COMPONENT OF GROUND MOTION
(45) USGS U.S.GEOLOGICAL SURVEY
(46) ERL-UM - EARTHQUAKE RESEARCH LAB. DEPT. GEOLOGY. UNIV. MONTANA. MISSOULA
(47) CORPS. U.S. ARMY CORPS. OF ENGINEERS. SEATTLE DISTRICT
(48) THE LIBBY DAM ARRAY WAS INSTALLED BY THE USGS TO MONITOR RESERVOIR INDUCED SEISMICITY. AFTER BRIEF OPERATION BY U.S.G.S.. ARRAY WAS OPERATED BY UNIVERSITY OF MONTANA WITH FUNDING BY U.S. ARMY CORPS. OF ENGINEERS. SEATTLE. CORPS. ASSUMED OPERATION OF ARRAY IN 1976 AND REDUCED NETWORK TO THREE STATIONS. TWO ADDITIONAL STATIONS AT 48 12' N. 115 43 W. AND 48° 27' N. 115 19' W ARE BEING ADDED TO THE ARRAY IN THE SUMMER OF 1979. TIMING AND TELEMETERY HAVE OFTEN BEEN A PROBLEM IN THIS ARRAY LEADING TO FREQUENT PERIODS OF INOPERATION. DATA PRESENTLY TELEMETERED FROM FIELD LOCATIONS TO DAM. TIMED AND RECORDED ON PAPER WHICH IS FORWARDED TO SEATTLE CORPS. OFFICE.
(49) TK-WA IS ONE OF NUMEROUS LRSM STATIONS THAT OPERATED FOR BRIEF PERIODS OF TIME.

Benioff short-period and Sprengnether long-period seismometers that are standard for World-Wide Standard Seismograph Network (WWSSN) stations. Records are kept at the University of Washington (Geophysics Program) which operates the station (Glover, 1977). Station TUM was operated by the University of Washington from May 1958 until mid-1970, when it closed. Three components of short-period and long-period ground motion were recorded. Records from station TUM are at the University of Washington. Station BLL at Western Washington University in Bellingham operated two horizontal component Sprengnethers and a vertical component Wilson-Lamison seismometer from December 1961 until 1969. The precision of the timing clock at this station was poor, but reasonably good records (especially vertical) were obtained and are now at the University of Washington. Station STT was privately operated from May 1958 until its closing in mid-1970, when the Seattle-Tacoma International Airport was enlarged. A Galitzin long-period seismometer measured the horizontal component of motion at station STT.

A telemetered seismograph array began operating in mid-1970 in the Puget Sound Basin and has subsequently been expanded to cover most of the area west of the Cascade Range. Five short-period seismometers that measure vertical components of ground motion began detecting earthquakes in the summer of 1970. A sixth station was added in 1971, and seven more were added in mid-1971 and 1972. In 1975, nine more stations were added to the network. Details of location of these instruments are given in Table F-1 and on Figure F-1.

Each station is mounted on bedrock and transmits its signal via radio or telephone to the University of Washington where the data are timed, recorded, processed, and analyzed by R. S. Crosson, who supervises the network. Expansion is planned for this network, which, at present, can detect and locate events to magnitude 2.0. Recording is presently by magnetic tape and develocorder, but digital recording is being initiated in 1979. Further detail of the network and analysis procedures may be found in Crosson (1972, 1974).

Temporary earthquake detection arrays have operated in western Washington at Mount Baker, Mount Rainier, Mount St. Helens, and along the Skagit River. All these arrays were operated by the University of Washington and monitored short-period vertical component of ground motion. An additional five-station array was operated by the U.S. Geological Survey at Mount Rainier in the summer of 1968 (Unger and Decker, 1970).

PRESENT STATUS OF EARTHQUAKE MONITORING IN THE COLUMBIA PLATEAU AND REGION

Eastern Washington

Earthquake activity in eastern Washington is currently monitored by a network of 37 seismographs that are operated by the Geophysics Program of the University of Washington, directed by S. D. Malone. This network is subcontracted by the U.S. Department of Energy with the University of Washington. Data from stations in Washington and four stations in

northeasternmost Oregon are telemetered via telephone to the University of Washington where they are recorded on develocorders. The system of recording is being changed in 1979 so that data will be recorded digitally on a computer, thus providing a better format for data reduction and analysis. Each station consists of a single short-period Mark 4 LC seismometer that measures vertical component of ground motion. The location of each station is shown on Figure F-1; coordinates and elevations are given in Table F-1. An additional station at Newport, Washington (NEW) which is operated and maintained by the U.S. Geological Survey as part of the NEIS network records both short- and long-period motion and operates on a 24-hour basis as part of the Tsunami Warning System. The Newport Observatory operates a Teledyne Geotech S-13 short-period vertical seismograph and three Sprengnether S-5100 seismometers that monitor two horizontal and one vertical component of motion. The Newport Observatory also operates two modified Wood-Anderson torsion seismographs, largely for calibration purposes. The Newport Observatory exchanges data with the University of Washington.

Five additional stations are being added along the eastern flank of the Cascade Range in the spring of 1979 to give more complete coverage of seismicity in eastern Washington. A short-period, single-component, vertical seismograph will operate at each of these new stations.

The eastern Washington regional array presently is capable of detecting and locating all events of magnitude 2.0 or larger between the Cascade Range and the Idaho border. The network has its greatest density of stations on and along the margins of the Hanford Site where it can detect and locate all events of magnitude 1.5 or larger. Some events of smaller magnitude can be detected, but only those occurring sufficiently close to three or more stations can be located.

Western Washington

Seismic activity in western Washington is presently monitored by the University of Washington with a 21-station telemetered network that operates independently of the eastern Washington array. The western Washington network was started as a 5-station array in 1970 by R. S. Crosson (University of Washington, Geophysics Program), who still directs the array (Crosson, 1972, 1974). Timing and recording on develocorders and magnetic tape occur at the university. Each of the 21 stations consists of a single-component seismometer that detects the vertical component of vibratory ground motion. Locations and elevations of these stations are given in Table F-1 and Figure F-1. The station at Longmire is not part of the western Washington array, but, rather, is a part of the WWSSN operated by the University of Washington. Data from Longmire are regularly reported with data from the 21 western Washington stations.

As with the eastern Washington array, limits and accuracy of earthquake detection and location vary with spacing and distribution of stations and quality of records. Within the network, earthquakes of magnitude 2.0 and higher are generally recorded. Some smaller events may be detected and possibly located. Location quality varies, but for events within the network recorded by 3 or more stations, error in

epicenter location is usually less than 1.2 miles (2 kilometers). Hypocenter errors are generally less than 3 miles (5 kilometers) (Crosson, 1974). Focal depths are difficult to define precisely, and are best determined for events located within 18 miles (30 kilometers) of a station.

Oregon

Compared with Washington, monitoring of earthquakes in Oregon is just beginning. A number of stations have operated in Oregon, but few are operational at present and quality of data recorded by several operating stations is minimal (Table F-1). Three of 10 stations in Oregon are operated and maintained as part of the eastern Washington array by the University of Washington and are located in northernmost Oregon (Poppe and Others, 1978; Malone, 1977) (Figure F-2). The stations at Pine Mountain (PMT) and Klamath Falls, Oregon (KFO) have recently been closed. Station KFO, which began operating in 1962, is currently being moved to Bend, Oregon where the Benioff short-period vertical seismometer will be operated by Oregon State University as part of their developing network. This instrument is presently operating at a temporary location until telemetry can be installed. The station at Pine Mountain (PMT) that began operating in September 1969 with National Aeronautics and Space Administration support has recently closed and operation is currently being shifted from the University of Oregon to Oregon State University. Station PMT, which was also closed between 1972 and 1976, recorded three orthogonal short-period components of ground motion on Geotech S-13 seismometers. An antiquated Wilson-Lamison short-period vertical seismometer is located at station PTD (Portland), where it is operated by the Oregon Museum of Science and Industry. This instrument, which began operation in 1964, is on loan from the U.S. Geological Survey (National Earthquake Information Service) and is used strictly for display of earthquake detection and recording equipment. As with several other Oregon stations, the reliability of the timing system at station PTD is questionable (timing is not coordinated with Radio Station WWV). A home-made, short-period seismometer was put into operation in 1975 by Harold Mason (station HMO) near Portland State University (which holds the records). Portland State University also has records from a Sprengnether long-period horizontal seismometer and a privately operated short-period Sprengnether instrument. Timing for both instruments is manually checked daily against Radio Station WWV.

The most complete and reliable earthquake recording station in Oregon is at Corvallis and is operated by Oregon State University. Station COR is a WWSSN station that operates under the direction of R. W. Couch, Department of Geophysics, School of Oceanography, Oregon State University. This station was started in 1946 by H. Vinyard of the Physics Department at Oregon State College with two Wood-Anderson seismographs that operated until 1949 (Couch and Lowell, 1971). Three Schlicter seismographs were added nearby in 1949 and replaced the Wood-Anderson instruments. Station COR was upgraded to conform with WWSSN standard equipment in 1962. Station COR records three orthogonal components of short- and long-period ground motion on WWSSN standard Benioff and Sprengnether instruments, respectively. A short-period vertical Geotech visual seismograph is also present at station COR.

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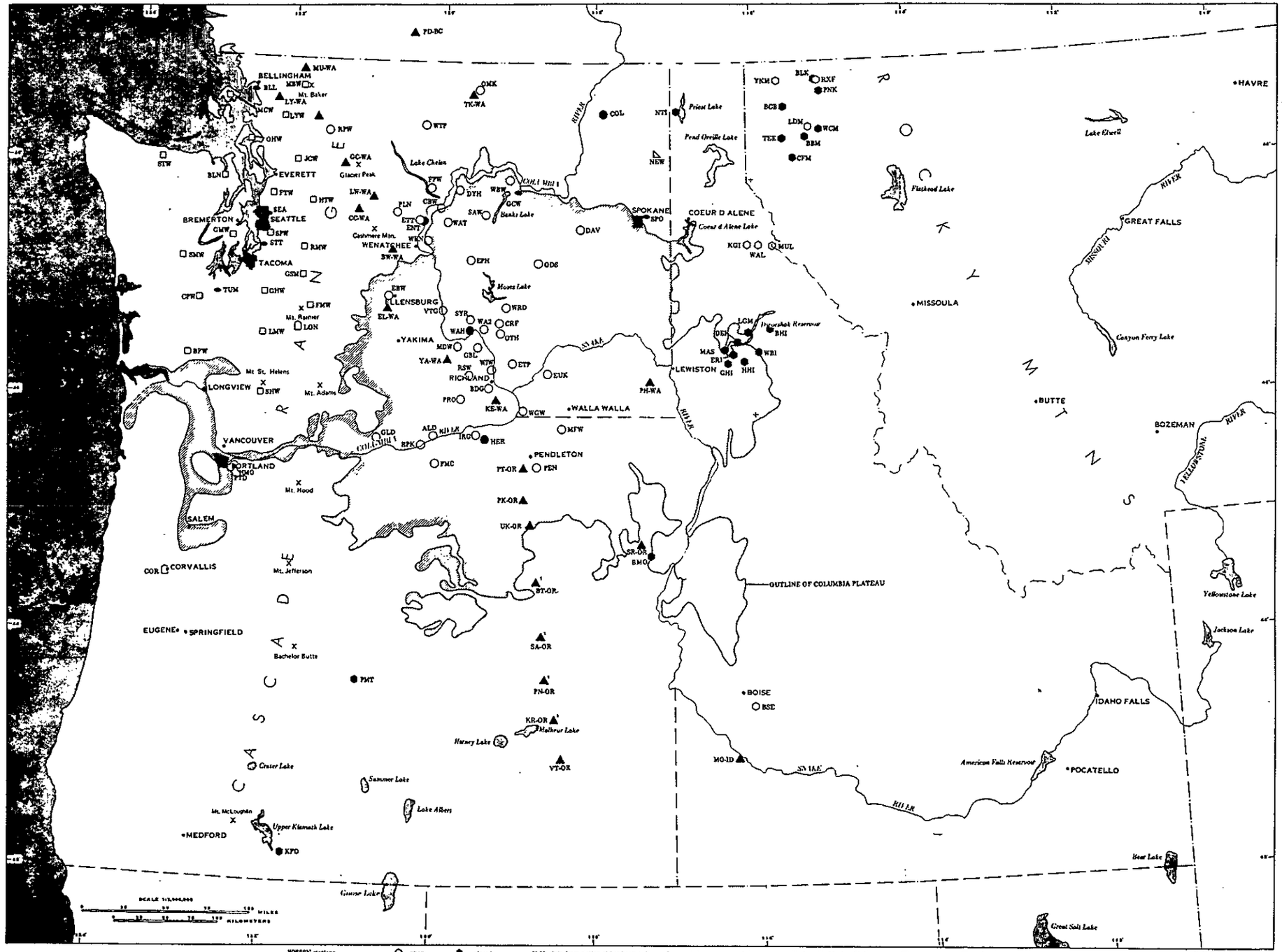

WWSSN stations	open	closed	
LRSM stations	open	closed	
Eastern Washington Station	open	closed	
U.S.G.S.-N.E.I.S.			
Western Washington Station	open	closed	
Oregon, Idaho, Mont. Stations	open	closed	
Independent	open	closed	

(1) No data from station either because it wasn't occupied, or was occupied very briefly (less than one day).

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F-14

FIGURE F-2. Regional Seismic Stations.

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A three-station network which is owned and operated by Tera Corporation for Portland General Electric Company has been in operation for several years in the vicinity of the proposed site for the Pebble Springs nuclear generating station near Arlington, Oregon. Records are changed by Portland General Electric personnel who forward copies of their data monthly to S. Smith of the University of Washington. Each of the three stations (ALD, FMC, and RPK) operates a single component, short-period, vertical seismometer.

The Blue Mountain Seismological Observatory was opened in 1962 by the Air Force Cambridge Research Laboratory at a site about 36 miles (60 kilometers) east of Baker, Oregon. Station operation was transferred to the U.S. Coast and Geodetic Survey in 1966 which operated the observatory until May 1975. Twenty-one seismometers were operated at the observatory and measured three components of short-, intermediate-, and long-period ground motion. Data were transmitted to Rockville, Maryland (Couch and Lowell, 1971).

A five-station, telemetered seismographic network in Oregon has begun operation. Instruments measuring the short-period vertical component of earthquake ground motion are operating in La Grande, Bend, Ashland, Portland, and an unknown site in southeastern Oregon. Data are telemetered via telephone line to Corvallis, Oregon where they are timed and recorded with the data from station COR. R. W. Couch of Oregon State University administers the network.

Idaho

Very little earthquake monitoring is currently being performed in Idaho west of the 115 degree west meridian, although a number of stations have operated in the past (Poppe and Others, 1978). Three-component, short-period instruments owned by the U.S. Bureau of Mines (Spokane, Washington) are operated by private mining companies in four mines in the Coeur d'Alene, Idaho district, but the intent of these stations is to detect rockbursts (McLaughlin and Others, 1976). A Sprengnether S-6000 seismometer began operating as a surface station at the Galena Mine near Wallace, Idaho (station WAL) in 1965. Similar instruments began operating at the Sunshine Mine near Kellogg, Idaho (station KGI) in 1970 and at the Lucky Friday Mine near Mullan, Idaho (station MUL) in 1968. Stations WAL and MUL also operate Geotech S-13 short-period seismometers. A Geotech short-period instrument began operation in 1975 at a depth of 2,000 feet (609 kilometers) in the Star Mine at Burke, Idaho. Each station in the Coeur d'Alene district is operated independently by mining personnel who forward data weekly to the U.S. Bureau of Mines (Spokane, Washington). Additional microearthquake detection equipment is temporarily deployed by mining companies in these mines with the intent of detecting changes in stress fields as a sign of impending rockbursts. Earthquakes are detected by these systems, but such detection is not the primary objective of the arrays.

Three short-period seismographs that measure the vertical component of ground motion were put into operation by Boise State University in 1975. The telemetered array is operated by J. Applegate of Boise State

University. Data are recorded by pen and ink and are stored at Boise State University. Timing is by crystal clock that is checked daily with Radio Station WWV (Vincent and Applegate, 1978). One of the three stations which is located in the Boise foothills is station BSE. Data from the Boise State University array is often combined with data from eastern Washington and Idaho Falls arrays to locate events occuring beyond the margins of the array.

During construction, filling, and early operation of the Dworshak Reservoir in north-central Idaho, an eight-station seismograph array was operated. Begun by the U.S. Geological Survey in 1971, the array was reduced to a four-station array in 1974 and subsequently closed in 1976 (Table F-1). Short-period, vertical seismometers were operated with the intent of measuring potential changes in seismicity associated with filling and operation of Dworshak Dam and Reservoir.

Montana

An array similar to the one at Dworshak Dam in Idaho was deployed in the vicinity of Libby Dam in northwestern Montana. Eight short-period, vertical seismometers were installed by the U.S. Geological Survey in 1971. Operation of the network then shifted to the University of Montana for the U.S. Army Corps of Engineers (Seattle District) for several years. In 1976, the U.S. Army Corps of Engineers assumed operation of the network and reduced it to a three-station array which expanded to a five-station array in 1979.

British Columbia

Seismograph stations in British Columbia provide data useful in locating events and in determining focal mechanism solutions in the Columbia Plateau. A station at Victoria, British Columbia (VIC) has been in operation at three closely spaced, but different, localities since 1898. The present location for station VIC was established in 1939. Since 1953, this station has recorded three orthogonal components of short- and long-period ground motion (Milne and Others, 1978). A few Wood-Anderson instruments were added in 1967. Stations measuring short-period ground motion are located at Alberni (ALB), Penticton (PNT), Haney (HYC), and Pender Island, British Columbia (PIB). These stations, as well as several that have operated in the past and now are closed, were operated by the Seismological Service of Canada (SSC). Table F-2 from Milne and Others (1978) lists SSC stations that have operated in southern British Columbia. Other stations that were operated temporarily, or by other agencies, are not shown. Portable arrays consisting of several short-period, vertical seismometers were deployed in the Hope, Chilliwack, and lower Fraser River areas during the summer of 1977 (Weston Geophysical Research, 1977). The intent of these surveys was to monitor activity in the suspected epicentral area of the December 14, 1872 earthquake.

TABLE F-2. Seismological Service of Canada Seismograph Stations in Southern British Columbia.

CODE	LOCATION	COORDINATES ' "N	COORDINATES ' "W	INSTRUMENTATION Components*	INSTRUMENTATION Type	DATES OF OPERATION	RECORDS LOCATION	DATA SOURCE	COMMENTS
VIC	Victoria	48 31 12	123 24 54	SPV, SP-NS, EW LPV, LP-NS, EW		1953-	Energy Mines & Resources-Earth Physics Branch	Milne and Others, 1978	
					Wood-Andersons	1967-			
		48 25 24	123 22 00		Milne	1898-1916	"	"	Moved in 1916.
		48 24 54	123 19 24		Milne	1916-1939	"	"	Instrument changed to Milne-Shaw 1922; moved in 1939.
ALB	Alberni	49 16 12	124 49 18	SP		8/51-	"		Closed 7/72-8/75.
PNT	Penticton	49 19 00	119 37 00	SP, LP		1/60	"	"	
HYC	Haney	49 15 54	124 34 36	SP		9/75-	"	"	Telemetered to VIC.
PIB	Pender Island	48 49 6	123 19 12	SP		1/76	"	"	"
HBC	Horseshoe Bay	49 22 42	123 16 36	SP		8/51-4/60	"	"	
LLL	Lillooet	50 41 42	121 55 0	SP		7/57-1/60	"	"	

*SPV = Short period vertical.
LPV = Long period vertical.
SP-NS, EW = Short period horizontal, north-south and east-west components.
LP-NS, EW = Long period horizontal, north-south and east-west components.

Summary of Seismic Monitoring in the Columbia Plateau and Region

Good quality earthquake records were generally not available for the Columbia Plateau and region until the 1960's. Prior to this time, few good instruments were deployed in the region; therefore, instrumental detection and location of earthquakes were limited to the few events that were sufficiently large (generally greater than magnitude 5.0) to have been recorded by the sparse network of stations. Most events sufficiently large to be recorded were also felt by people. Prior to the 1960's, most events were located from felt reports with resultant uncertainty as to epicentral location and an absence of focal depth information. With 60 stations operating in Washington and several more planned, the regional monitoring network in Washington is sufficiently dense to detect earthquakes of magnitude 2.0 or greater. The shallow depths of most events, particularly seismic swarms in the Columbia Plateau, will necessitate future deployment of closely spaced arrays in order to obtain good hypocenter locations and to determine whether relationships exist between these events and geologic structures.

The capability of earthquake detection and location in Oregon and Idaho is less sophisticated, resulting in higher magnitude thresholds for detection and location. A six-station network currently is being established in Oregon, but more stations will be needed to:

a. Determine the pattern of stress release across the entire Columbia Plateau;

b. Determine the magnitude, direction, and variation with geologic structure of in situ stress across the plateau;

c. Determine whether the pattern of stress release in the Columbia Plateau is different from that of the Basin and Range, and, if so, where this change occurs; and,

d. Obtain adequate azimuthal distribution of earthquake data in order to adequately constrain focal mechanism solutions for events in southern Washington; these data will be especially beneficial for determining stress release locations and patterns in the Milton-Freewater, Oregon-Walla Walla, Washington area.

A few stations in Idaho to help constrain focal mechanism solutions and to obtain a more complete pattern of stress release across the Columbia Plateau would be beneficial. Stations in Idaho in the Coeur d'Alene and Boise areas provide only minimal data relevant to the Columbia Plateau.

APPENDIX G

TECTONIC PROVINCES AND MAJOR REGIONAL STRUCTURES

APPENDIX G

TECTONIC PROVINCES AND MAJOR REGIONAL STRUCTURES

TECTONIC PROVINCES

A large region characterized by similar features or history and one that is distinct from surrounding regions is a province (Gray and Others, 1972). A tectonic province is a geologic region characterized by rocks of similar or related age and lithology and which displays structures of similar age and style. The area covered by Columbia River basalt is a tectonic province characterized by Miocene tholeiitic basalts that have been deformed. The area covered by Columbia River basalt is unique and readily distinguishable from surrounding tectonic provinces because of the age, rock types, and structures that characterize it compared with surrounding provinces such as the High Lava Plains, Idaho Batholith, and Cascade Range.

Columbia Plateau

Tholeiitic flood basalts of the Columbia River Basalt Group constitute the youngest known, moderate-sized, flood basalt province in the world. Basalt was erupted from north-northwest-trending dikes as highly fluid lava that subsequently flowed westward and northwestward along a gentle paleoslope. The basalt was erupted in the Miocene epoch and dates from about 6 to 16.5 million years before present (Baksi and Watkins, 1974). Most of the basalt was erupted between 13.5 and 16.5 million years ago at rates comparable with those for the Hawaiian Islands (Swanson and Others, 1975). The longer spans of time separating flows between about 6 and 13.5 million years ago are recorded by tuffaceous fluvial sandstones that separate and interfinger with the younger flows (Schminke, 1967b). Vertical and lateral relationships of flows suggest that deformation of the basalts had begun in middle to late Miocene time, at the time the Saddle Mountains Basalt was forming (Reidel, 1978a). Deformation continued into the Pliocene, but was apparently on the wane at the time of deposition of the fine-grained upper part of the Ringold Formation exposed at the White Bluffs.

The youngest exposed basalts in the northern and western parts of the Columbia Plateau exhibit mild deformation in the form of folds and faults (Newcomb, 1970; Grolier and Bingham, 1978). Three general trends of structures have been recognized; those with east-west, northeast, and northwest strike (Grolier and Bingham, 1978). East-west-trending structures east of 120 degrees west incude Pinto Ridge and Soap Lake anticlines, Frenchman Hills, Saddle Mountains, and Gable Mountain-Gable Butte. All these structures are asymmetrical anticlines with gently dipping southern flanks and more steeply dipping northern flanks, except for the Soap Lake anticline where the reverse is true.

Faults are known or strongly suspected along the steep northern flanks of Pinto Ridge, Frenchman Hills, and Saddle Mountains. These faults generally parallel the fold axes, are thrust or reverse faults, and probably developed synchronously with the folding (Grolier and

Bingham, 1978; Bingham and Others, 1970). The Saddle Mountains and Gable Mountain-Gable Butte area have been studied in detail recently by Reidel (1978a) and Fecht (1978). As these structures are within or along the flanks of the Pasco Basin, discussion is reserved for the section of this report dealing with the Pasco Basin.

Northwest, northeast, and east-west major structures are present over much of the Columbia Plateau (see the structure section of Chapter II), but major north-south structures appear to be restricted to the southeastern part of the plateau east of the Snake River. Folds in the basalt of the Yakima Basalt Subgroup (hereafter referred to as Yakima Folds) generally have an east-west to west-northwest orientation, are asymmetric in profile, and seem to differ in wavelength and amplitude from anticline to syncline. The ratio of wavelength to amplitude seems to be much less for anticlines than for synclines. Synclines are generally broad folds with gentle dips marginal to the axis giving them a cross-sectional shape similar to a broad trough. However, synclines are topographic lows, so that the trough of each fold is commonly covered by sediment, thereby masking whether undulations, or smaller, low-amplitude folds are superposed on larger synforms. Data from the Pasco Basin suggest that the trough of the broad Cold Creek syncline is not a catenary, but an undulating, surface that reflects topography which is probably structurally controlled.

East-west, northwest, and northeast trends are also present as joints and lineaments in north-central and northeastern Oregon where they have been related to the folding process (Lawrence, 1979). All of these features are generally compatible with a north-south-directed axis of compression that is nearly horizontal. Since this stress field is indicated by focal mechanism solutions of small earthquakes (Malone and Others, 1975; Malone, 1977; Rothe, 1978), it would appear as if much of the Columbia Plateau has been experiencing generally north-south-directed compression since some time in the late Miocene. Northwest-trending, right lateral, transcurrent faults in southern Washington are also compatible with such a stress field.

North-south-trending major structures are found in the Weiser embayment of the plateau and also as minor, secondary structures on some east-west-trending folds in the Pasco Basin. The north-south trend is a pronounced trend of normal and reverse faults in the Great Basin section of the Basin and Range province in southern Oregon and Nevada (Stewart, 1978; Walker, 1977). Extension of uncertain origin and amount has produced a block-faulted terrain of ridges and intervening basins in the Basin and Range province that began developing in the late Miocene.

Whether the faults of north-south trend in southwestern Idaho are extensional and compatible with the Basin and Range province structures in southern Oregon and Nevada are open questions. Lawrence (1976) has suggested that the Basin and Range province terminates along the Brothers Fault Zone, a zone of right lateral shear in south-central Oregon.

Extensional faults and feeder dikes for several units in the Yakima Basalt Subgroup in northeastern Oregon and western Idaho trend northwest. Whether they represent the products of another stress field, resulted from tension in a locally restricted secondary stress field, or are shear extension phenomena is not known with any certainty at this time. Pure extension may be compatible with a regional tectonic stress regime of right lateral shear (Wise, 1963; Atwater, 1970), but it could be a consequence of a rising and laterally spreading mantle plume or diapir (Karig, 1971; Scholz and Others, 1971).

Cascade Range

The Cascade Range is a composite of several geologically distinct terranes which experienced broad uplift in the Pliocene culminating in the development of large Quaternary volcanoes. Snoqualmie Pass essentially separates the older north Cascades from the younger south Cascades. The north Cascades consist of a complex core of lower Paleozoic or older metaplutonic and metasedimentary rocks that are bounded to the east by the Ross Lake fault zone and to the west by the east-dipping Shuksan thrust slices. As these rocks are west of the Precambrian cratonic border, Davis (1977) believes they were accreted to the continent in their present position by Paleozoic transcurrent faulting. The east-west-striking Shuksan unit consists of unique blue schist-grade metasedimentary units that are allochthonous (Davis, 1977). Granite intrusions in the north Cascades began in late Cretaceous time. The south Cascades, south of Snoqualmie Pass, are a geologically younger terrance that evolved as a lower Tertiary volcanic arc. The thick, interbedded, intermediate volcanics, volcaniclastics, pyroclastics, and tuffaceous sediments of the Ohanapecosh Formation attest to the onset of volcanism in the late Eocene. A younger sequence of similar lithology, but including some basalts and dacites of Oligocene to early Miocene age, rests unconformably on the older sequence. Folding and faulting along north-to-northwest trends, accompanied by emplacement of granitic batholiths, began in the middle Miocene. The south Cascades are partly covered with Quaternary andesitic volcanoes and especially by large fields of high-alumina basalt eruped from dikes and low-shield volcanoes.

The present Cascade Range began to develop with a broad arching uplift in the Pliocene. Accelerated uplift in the late Tertiary was culminated by eruption of andesitic volcanoes of the present Cascade Range. Eruption was not everywhere synchronous, as indicated by topography and radiometric dating. Eruption has continued intermittently to the present, with Mount Lassen being the last to erupt in 1915. Other Cascade volcanoes have erupted in historic time. Ashfalls from Cascade volcanoes are useful time stratigraphic horizons and are discussed elsewhere in this report.

Okanogan Highlands

North of the Columbia Plateau and east of the Cascade Range is a geologically complex area known as the Okanogan Highlands. The south-flowing Columbia River separates the area into two major sub-units. To the west is a complexly folded, faulted, and metamorphosed complex of upper Paleozoic and Mesozoic litharenite, chert, greenstone,

shale, and conglomerate, invaded by the large Colville and Similkameen Batholiths. East of the Columbia River, the area is underlain by mildly deformed Precambrian and lower Paleozoic shelf clastic and carbonate rocks. Rocks of granitic (quartz monzonite to quartz diorite) composition have intruded into Beltian rocks in the late Mesozoic and it is these contact zones that provide many of the minerals of the Coeur d'Alene district. Acidic to intermediate volcanic rocks of early Tertiary age are common.

Folds in the eastern region trend generally northeast and are cut by pre-Tertiary faults. Tertiary faults in the western region are generally steep-dipping, extensional faults with major displacement. Some bound the Republic Graben, a structure discussed later in this report. The Kootenai arc is a north-trending fold belt that separates the Okanogan Highlands from the northern Rocky Mountains.

Northern Rocky Mountains

The northern Rocky Mountains are an area of largely Precambrian shelf sediments that have been gently deformed and were slightly metamorphosed during late Precambrian intrusion of granite in an area that lies east of the Idaho Batholith. An Infracambrian stable shelf was the scene of accumulation of a thick section of carbonates and fine clastics of the Belt Supergroup. These rocks were gently folded and faulted along steeply dipping planes of rupture that trend generally north-south to northwest. The Rocky Mountain Trench separates the area of folded and faulted Precambrian rocks from those of the Rocky Mountain thrust belt. The trench is topographically a broad, sediment-filled valley that may reflect a buried structure, possibly a graben (Eardley, 1962; King, 1969). East of the trench, gently folded Paleozoic and Mesozoic sediments have been displaced eastward and westward along the northwest-trending thrust faults which developed during the Laramide orogeny of late Mesozoic and early Tertiary age.

Seismicity and focal mechanism solutions led Smith and Sbar (1974) and Smith (1978) to divide the American Plate into subplates. The northern Rocky Mountain subplate is bordered by diffuse zones of seismic activity to the east and south (the Intermountain and Idaho seismic belts), but evidence of seismic boundaries to the north and west is lacking. This subplate appears to be moving westward and extending along a north-south axis (Smith and Sbar, 1974).

Idaho Batholith

The Idaho Batholith is one of several granitic plutons of the western United States that developed during late Mesozoic orogeny. Rock types range from pure granite to quartz diorite, but quartz monzonite is the most abundant rock present. Weakly developed alignment of minerals is apparent at several localities suggestive of gneissic foliation. Broad, marginal zones of migmatite are present along the contact with the host rocks of the Belt Supergroup, an area of intense mineralization that has been highly productive. Elsewhere, the contact with host rocks is

obscured by a cover of Miocene volcanics suggesting that the batholith is much larger than its exposure. Radiometric dates indicate that the main mass of the batholith was intruded about 100 million years ago in middle to late Cretaceous time, an age that generally agrees with those for the Sierra-Nevada to the southwest and the Kaniksu, Loon Lake, and Nelson Batholiths to the north. Some late-stage plutonic activity apparently occurred in the late Cretaceous or early Tertiary as evidenced by smaller satellite and cross-cutting igneous bodies.

North of the Idaho Batholith is a zone of closely spaced, steeply dipping, oblique, slip faults termed by Wallace and Others (1960) the Lewis and Clark "Line." Secondary faults related to the several faults in the Lewis and Clark Line reflect local environments of stress in the area between faults. Right lateral, transcurrent movement along these faults has been suggested, even though the sense of offset between batholiths is left lateral. Folding and thrust faulting of rocks along the margins of the Idaho Batholith presumably reflect compressional tectonics during phases of the Laramide orogeny. The apparent offset of the line of Mesozoic Cordilleran batholiths along with a greater width of the United States Cordillera, compared with that for Mexico and Canada, led Wise (1963), following Carey (1958), to postulate a northwest-trending, broad zone of right lateral shear. While this outcrop pattern has not been explained, it suggests several intriguing possibilities regarding the tectonic development of the Pacific Northwest.

Snake River Plain

The Snake River Plain is an arcuate belt of late Cenozoic volcanic and volcaniclastic sediments that fill a broad lowland south of the Idaho Batholith. Geographically, it is divisible into a relatively narrow valley in western Idaho trending northwest from southeastern Elmore County toward LaGrande, Oregon, and a broad downwarp that trends northeast from this divide to Yellowstone National Park. The western part of the Snake River Plain is largely bounded by northwest-trending normal faults indicating that it is a graben (Malde and Powers, 1962; King and Beikman, 1974). The eastern Snake River Plain occupies a broad synclinal downwarp which Suppe and Others (1975) interpret as an axial downwarp along a broad linear updome. The western Snake River Plain is filled with sediments and volcanics of Tertiary and Quaternary age; the eastern half is similarly filled, but has a more extensive cover of Quaternary volcanics.

Although often compared with the Columbia Plateau, the Snake River Plain contains volcanic rocks that are chemically different and geologically generally younger than Columbia River basalt (Malde, 1965). Snake River basalts are olivine tholeiites distinct from alkali-olivine basalts of the Basin and Range province (Tilley and Thompson, 1970; Leeman and Rogers, 1970). A tripartite sequence of silicic ash flows, basalts and intercalated sediments, and sediments with intercalated basalts has been described in the western Snake River Plain (Malde and Powers, 1962). These belong to the Idavada Group, the Plio-Pleistocene Idaho Group, and the late Pleistocene Snake River Group (Malde, 1965). The Glenns Ferry Formation of the Idaho Group, at least in part, may be

correlative with the Ringold Formation that overlies Columbia River basalt in the Pasco Basin (Gustafson, 1978). The age of volcanic rocks along the Snake River Plain decreases from the west toward Yellowstone National Park from less than 1 million to about 15 million years which suggests migration of a mantle hot spot or plume northeastward in the late Cenozoic (Morgan, 1972). Heat flow data indicate that the western Snake River Plain has higher heat flow, but heat flow data from the eastern Snake River Plain come from shallow wells whose temperatures may be strongly influenced by ground-water flow (Brott and Others, 1978). Thermal springs and silicic volcanism continue today in Yellowstone National Park, an area of high heat flow and thin crust of low velocity.

The Snake River Plain is a relative anomaly in an area of high relief. Quaternary volcanic activity, fresh geomorphic features, and Quaternary faulting attest to the recency of tectonic processes which may be continuing, at least along the northwest-trending Great Rift near Craters of the Moon National Monument. Seismic activity is quiet; activity is apparently higher north of the Snake River Plain along the margins of the Idaho Batholith (Smith and Sbar, 1974; Vincent and Applegate, 1978). Several hypotheses have been advanced to explain this youthful tectonic feature, but none to date have satisfactorily accommodated all the geological and geophysical observations. The origin of the Snake River Plain results from the interaction of lithospheric plates, but the manner and chronology of interaction are yet to be determined.

High Lava Plains

Separating the Columbia Plateau from the Great Basin is a broad, arcuate zone in southern Oregon that is named the High Lava Plains. The area is a generally barren plateau composed of Neogene volcanics that still exhibit geomorphic evidence of eruption from vents. The area is transitional, in that it is a plateau like the Columbia Plateau to the north, but is segmented into fault-bounded basins and uplifts like the Great Basin to the south (Christiansen and McKee, 1978). The typical north-south structural trends of the Great Basin and the northwest structural trends of the Columbia Plateau are both present. The area is underlain mainly by Quaternary basalts of different composition and age than those of the Columbia Plateau, but also contains rhyolitic domes and ash flow tuffs similar to the northern Great Basin. These rhyolitic rocks generally decrease in age toward the northwest where young cones and craters such as the Newberry Volcano occur. Christiansen and McKee (1978) consider the High Lava Plains to be the western part of a structural province (of the same name) that is continuous with the Snake River Plain.

Structurally, the area is characterized by major northwest- (N60°W) trending, right lateral, transcurrent faults that segment the area into blocks and that form the northern boundary of the Basin and Range province (Lawrence, 1976). Within each of these blocks, northwest- and northeast-trending normal faults (the former predominating) form a set of Riedel and conjugate Riedel shears (Tchalenko, 1970) indicative of right lateral displacement. East-west extension characteristic of the

Great Basin to the south apparently diminishes progressively northward across these fault zones and terminates north of the Brothers and Vale Fault Zones (Lawrence, 1976). The northwest trend of rhyolitic domes and their decreased age westward suggest growth of this fracture system westward. These faults offset Pliocene and younger rocks. Radiometric ages of some of the domes suggest activity within the last million years (Christiansen and McKee, 1978).

Basin and Range Province

The Basin and Range province is characterized by a series of parallel to sub-parallel, elongate, generally north-south ridges separated by lengthy basins. This topography has resulted from late Cenozoic extension along faults that bound ranges and basins, but the character, amount of extension, and origin of these faults are not clear. The area of the Great Basin was part of an extensive, sedimentary basin flanking the stable craton, in which extensive shelf and bottom sediments were deposited during the Paleozoic. After some deformation, sedimentation continued in the Mesozoic. These sediments were, in turn, folded and faulted and covered unconformably by early Tertiary volcanics.

Block faulting, extension, and volcanism leading to present structure and topography began in early to middle Tertiary time. According to some workers, this reflects a change from a compressive to an extensional regime that corresponds to the subduction of the East Pacific Rise and development of a right lateral transform fault system (Atwater, 1970). Thin crust, high heat flow, a regional gravity low, and anomalous upper mantle (Eaton and Others, 1978) have led others to postulate extension was a result of back arc lateral spreading resulting from a rising mantle diapir developed during subduction of the Farallon Plate (Scholz and Others, 1971; Stewart, 1978). Spreading above a rising mantle plume and subduction of the spreading East Pacific Rise have also been offered as hypotheses to explain the timing and onset of regional extension leading to the development of Basin and Range faulting (Menard, 1964; Matthews and Anderson, 1973; Smith and Sbar, 1974).

Details of the nature of faulting in the Great Basin remain to be determined; therefore, models to explain the origin of the Great Basin encounter difficulty. Most faults are of steep dip, but it has been suggested that some, if not all, become much less steeply dipping with depth (Moore, 1960). Faults that curve in plan and in cross section and dip less steeply below the surface resembling large slump planes are referred to as listric faults. Estimates of the total extension have ranged from 10 to 100 percent, depending on the interpretation of Basin and Range province faults. Whether the tilted, faulted ranges have resulted from listric faults or true horsts and grabens is not clear, but some combination of the two is probably true. Not all faults in the Basin and Range province are extensional. A system of northwest-trending, right lateral, transcurrent faults is present in southwestern Nevada and is known as Walker Lane. Focal mechanism solutions also indicate the existence of a strike-slip component of faulting, or at least a significant strike-slip component of faulting suggesting that at least some shear is occurring (Smith and Lindh, 1978). Proponents of

back arc spreading cite migration of volcanic and fault activity from a nearly north-south central axis in the Great Basin to the margins of the province (Scholz and Others, 1971). Christiansen and McKee (1978) agree that most activity is now concentrated along the margins of the Great Basin, but cite evidence to show that it began 10 to 14 million years ago in these locations and has not migrated radially from the central basin during the late Tertiary.

Blue Mountains

The Blue Mountains are a basalt-capped mass of older rocks that were uplifted in late Tertiary time. In the Blue Mountains, thin Columbia River basalt rests unconformably on folded, faulted, intruded, and metamorphosed rocks of upper Paleozoic and Mesozoic age. Deep canyons of the Snake River and its tributaries afford an opportunity to view the basement beneath Columbia River basalt. Fossiliferous, clastic, and carbonate rocks of Devonian to Jurassic age are interbedded with volcanic rocks of varied lithology. In places, these sediments attain aggregate thicknesses of a few thousand feet (meters). Emplacement of large plutons occurred during the Triassic and Cretaceous times, accompanied by folding and faulting of the surrounding country rocks. Triassic intrusions include gabbro and periodotite that are well altered; Cretaceous intrusions are similar in age and rock type to the Idaho Batholith and may be related.

Sedimentation and calc-alkaline volcanism in the Blue Mountains resumed during the Eocene with deposition of several hundred feet (meters) of volcanic mud flows and breccias, lavas of varying composition, and intercalated terrigenous clastic sediments of the Clarno Formation. Fossils within the Clarno indicate a warm, temperate climate, with lush vegetation and grazing herbivores. A few hundred feet (meters) of brightly colored volcanic ash and ignimbrite of the John Day Formation rest atop the Clarno in places. A rich fauna and flora indicates an Oligocene to lower Miocene age for the John Day Formation.

The nature of volcanism in the Blue Mountains changed markedly in the lower Miocene with the advent of fissure eruptions of tholeiitic basalt. The Picture Gorge Basalt of the Columbia River Basalt Group rests uncomformably above the John Day and resulted from rapid and widespread flooding of the area by highly fluid lava emanating from northwest-trending fissures in the Blue Mountains. A few hundred feet (meters) of basalt now cap the uplands, but the unit probably was formerly more widespread and has been reduced in areal extent by erosion.

The broad east-west-trending Blue Mountains uplift has been cut by northwest-trending, normal faults that are especially prominent near LaGrande where a graben occurs (Walker, 1977). The outcrop extent of Columbia River basalt indicates that the Blue Mountains uplift had begun by Wanapum time, and perhaps earlier (Swanson and Wright, 1978). Thus, deformation of Columbia River basalt and uplift of the Blue Mountains were under way by lower to middle Miocene time with coincident folding (Pigg, 1961; Ross, 1978) and faulting (Shubat, 1979). Northeast-trending structures, notably the Hite fault, are also considered late Cenozoic in age (Howard and Others, 1977).

Coast Range

The Coast Range that borders the Pacific Ocean in Oregon and Washington has been produced by uplift and erosion of a terrain that resulted from Cenozoic volcanism, sedimentation, and deformation. Unlike much of the Cordillera, the Cenozoic volcanism and sedimentation occurred mostly in a marine environment between the Juan de Fuca Ridge and the margin of the North American continent (Cady, 1975). Eocene volcanics as many as 9 miles (15 kilometers) thick are in fault contact with core rocks in the Olympic Mountains. The Crescent volcanics apparently thin westward and interfinger eastward with turbidites derived from the North American continent. The marine volcanics were apparently derived from two separate seamounts on the Juan de Fuca Plate and grade from an intensely pillowed, low-K_2O, TiO_2 basal zone upward to a jointed and partly scoriaceous shallow marine tholeiite that is higher in K_2O and TiO_2. Although given different names, the Crescent volcanics in Washington correlate with similar volcanics in the Oregon Coast Ranges (McKee, 1972).

Overlying the lower and middle Eocene volcanics are tuffaceous marine clastics that contain interbedded andesitic flows, tuffs, and breccia which mark the western edge of young Cascade volcanism. Unconformities occur in the section which dates from the middle Eocene to middle Miocene (Cady, 1975). These sediments and the Crescent volcanics are in fault contact with slightly metamorphosed Paleogene shales and turbidites that constitute the core of the Olympic Mountains and which were deposited in a basin floored with oceanic crust. Eocene mafic volcanics similar in composition to the Crescent volcanics are in fault contact with these core rocks.

Curving, U-shaped (in plan), major thrust faults separate the core rocks from the Crescent volcanics on the Olympic Peninsula (Cady, 1975). Within the core rocks, the attitude of units as well as faults along which they are displaced trend northwest. Broad, slaty shear zones up to 0.6 mile (1 kilometer) wide mark the trace of several faults in the area. Thrust faulting in Eocene to Miocene time was followed by late Miocene doming. Underthrusting of the core and younger rocks eastward occurred during the lower to middle Miocene as sediments resting on the Juan de Fuca Plate collided with the American Plate during subduction (Cady, 1975). Thrust sheet stacking similar to that in younger sediments (Silver, 1971) probably occurred during subduction. Short, dip-slip, and possibly one strike-slip fault of a few feet (meters) displacement has been mapped recently in the southeastern portion of the Olympic Peninsula (Wilson and Others, 1979). These faults are compatible with the extant stress field of the Puget Sound region (Crosson, 1972) and offset till of Fraser or pre-Fraser glaciation. Wilson and Others (1979) interpret these faults as the product of broad regional deformation involving a large volume of crust rather than concentrated along particular structures.

Puget Sound-Willamette Lowland

The physiographic and structural division of the Coast Range and the Puget Sound-Willamette Lowland is a product of late Cenozoic deformation

and glaciation. Unlike the present terrain, the area was part of a broad sedimentary basin west of the developing Cascade Range during early and middle Tertiary time. West of a chain of calc-alkaline volcanoes was a broad coastal plain that graded westward into a shallow marine shelf. Beyond the shelf was a deep sedimentary basin, the Juan de Fuca Basin, where sediments and volcanics accumulated on oceanic crust of the Juan de Fuca Plate (Snavely and Wagner, 1963). Streams draining the highlands of the ancestral Cascades and Klamath Mountains carried detritus which was deposited as a wedge of fluvial sediment that graded into shallow marine sediments beyond the strandline. Coal-bearing sequences of arkosic and volcanic litharenites and shales with some interbedded volcanics are present in several formations of the Puget Group (Vine, 1962; Waldron, 1962; Mullineaux, 1970). Sediments and volcanics of the Puget Group are overlain unconformably by poorly indurated marine and continental arkosic and volcanic litharenite and shale of the Lincoln Creek and correlative units. Local reworking of these units has produced a quartzitic sand and clay and a volcanic sand and gravel (Mullineaux, 1970) known near Renton, Washington, as the Hammer Bluff Formation of possibly Pliocene age.

All the Tertiary sequences are folded and faulted along north to northwest structural trends. Deformation is generally dated as middle to late Miocene. The dates and trends of deformation are similar to those in the Olympic Mountains and are probably synchronous and syngenetic. Many of the structures affect all Tertiary sediments and all but the youngest Quaternary drift (Mullineaux, 1970).

The Puget Sound-Willamette Lowland is a deep trough that, in large part, owes its existence to extensive Pleistocene glaciation. Outcrops are rare and generally restricted to the flanks of the Cascades and Olympic Mountains. Limited well data and a gravity low suggest over 984 feet (300 meters) of sediment may be present in all or at least part of the lowland. The present topography is a dissected drift plain that is underlain by a complex of glacial and non-glacial sediments reflecting changes between glacial and non-glacial climates during the Pleistocene. At least four glacial intervals separated by non-glacial intervals are present in the Puget Sound-Willamette Lowland (Crandell and Others, 1958; Crandell, 1965). Drift of the Orting, Stuck, Salmon Springs, and Vashon glaciations is separated by non-glacial sediments of the Alderton and Puyallup Formations, respectively. Erosion of several valleys in pre-Vashon time suggest that a non-glacial interval preceded advance of the ice which deposited the Vashon drift. Vashon and Salmon Springs drifts are Wisconsinan (Easterbrook, 1976); Orting and Stuck drifts are pre-Wisconsinan, but absolute ages remain to be determined.

REGIONAL STRUCTURES

Methow Graben

A northwest-trending zone of middle to late Mesozoic marine and non-marine sediments and volcanics extends from near Lake Chelan northwest for a few hundred miles (kilometers) into Canada. Bounded by major fault systems, the Methow graben contains a stratigraphic section

of Mesozoic and Tertiary rocks that is anomalous in the region both because the rocks occur nowhere else nearby and because the cumulative thickness exceeds 12 miles (20 kilometers). The Methow graben is bounded on the northeast by the Chewack-Pasayten fault that trends N30°W and by a series of subparallel faults on the southwest side known as the Skagit fault system (Shannon and Wilson, 1977b). Segments of the Skagit fault system that trend approximately northwest north of the international border are known as the Hozameen fault. A substantial amount of strike-slip movement on the border faults is suspected. Segments of the Skagit fault system are interrupted by a number of Mesozoic or Tertiary granitic plutons. The boundary faults of the graben merge near the southern end where the Mesozoic section pinches out. Whether the faults continue through the Okanogan Highlands to the Columbia Plateau is not known. Rocks within the graben have undergone a complex history of folding and faulting.

Barksdale (1975) has described the stratigraphic section in the Methow graben. The Hozameen group, which forms the base and is of questionable age, is a thick section of marine basalts interbedded with limestone and chert. The contact of the Hozameen group with surrounding units is a thrust fault, the Jack Mountain thrust (Misch, 1966); however, Vance (1977) interprets the Hozameen as an allochtonous mass of oceanic crust that forms the base of the stratigraphic sequence in the Methow graben. The remainder of the section is several thousand feet (meters) of interbedded calc-alkaline-volcanics, tuff, arkosic conglomerate, litharenite, and shale.

The history and nature of displacement of the Chewack-Pasayten fault and the Skagit fault system are long and complex. Facies relationships clearly indicate some dip-slip movement on these faults, but significant strike-slip motion cannot be eliminated (Vance, 1977). Relationship of segments of the Skagit fault system to plutonic rocks suggests cessation of movement during the mid-Cretaceous. Movement on the Chewark-Pasayten fault post-dates the early Tertiary Pipestone Canyon Formation, but pre-dates some presumably early Tertiary (no radiometric ages have been determined) andestic volcanics. Ground and aerial reconnaissance along both faults in 1977 revealed no evidence of movement younger than early Tertiary.

Chiwaukum Graben

The Chiwaukum graben is a northwest-trending wedge of Tertiary sediments that narrows from the border of Columbia River basalt to its termination near the crest of the Cascade Range. The graben is bounded by the Leavenworth fault on the west, a series of steeply dipping faults of varying (but generally north-northwest) trends which become one fault farther northwest (Vance, 1977). The Entiat fault is a single, steeply dipping, normal fault that strikes N30°W. Coarse conglomerates of the basal Swauk Formation thin and become finer grained toward the center of the graben. Along the border, cobble and boulder conglomerate terminates abruptly against complexly deformed and metamorphosed pre-Tertiary rock. Teanaway Basalt overlies this gently folded Swauk Formation beyond the graben borders. Feeder dikes for the

basalt cut through the older Swauk Formation but not the Chumstick Formation. The latter consists of more than 9,200 feet (2,804 meters) of fluvial and lacustrine litharenite and conglomerate which have been dated as late Eocene from fission track dating of interbedded tuff (Whetten and Laravie, 1976). This unit has been folded and is overlain near the graben by gently tilted sediments of the Wenatchee Formation. Tuffs interbedded with the fluvial shale, sandstone, and conglomerate of the Wenatchee Formation yield early Oligocene dates. The Wenatchee Formation was deposited across the southern end of the Entiat fault, thereby giving an Oligocene age of last movement for this segment (Vance, 1977).

Movement along the Leavenworth and Entiat faults that bound the Chiwaukum graben and other faults within the graben is Tertiary (Vance, 1977). Eocene extensional faulting led to development of the graben, with later faulting in latest Eocene or early Oligocene time deforming the Chumstick Formation and further offsetting the bounding faults of the graben. Uplift and deformation of the older Tertiary sediments was followed by uplift and erosion of the entire area. Lower Yakima Basalt spread across this old erosion surface in the mid-Miocene. Subsequent deformation resulted in folding of the lower Yakima Basalt and development of the Badger Mountain anticline and movement along the Chumstick and Entiat faults. Aerial and ground reconnaissance along the various faults that bound or are included in the Chiwaukum graben failed to reveal any evidence of late Quaternary displacement (Vance, 1977). Deformation apparently ceased before or in earliest Quaternary time, a timetable for tectonic activity also found for the nearby Kittitas Valley (Waitt, 1979a).

Republic Graben

The northeast-trending Scatter Creek and Sherman fault zones bound the Republic graben, a narrow band of Tertiary rhyodacite flows that extends from the Columbia River into Canada (Staatz, 1964). Metamorphosed Permo-Triassic sedimentary and igneous rocks of the Okanogan Highlands border the graben and crop out in limited areas within. Folded and faulted greenstone, phylitte, quartzite, and graywacke with some interbedded, impure limestone in the adjacent Okanogan Highlands attain a thickness of nearly 12,000 feet (3,657 meters). Deformation of these rocks accompanying regional metamorphism was followed by intrusion of Cretaceous granite to diorite. Unconformably overlying these rocks is a thick sequence of acidic pyroclastics, and volcanics with some related plutonic rocks. Ash, tuff, and volcanic breccia of the O'Brien Creek Formation attain thicknesses of up to 1,500 feet (457 meters) and in places grade conformably upward into the overlying Sanpoil volcanics. More than 950 feet (289 meters) of rhyodacite and quartz latite of the Sanpoil volcanic series were erupted as numerous flows that consist of abundant, moderately calcic, plagioclase in a potash-rich glass groundmass. Till and glaciofluvial deposits of Quaternary age unconformably overlie the volcanics through much of the area.

Several periods of deformation are recorded by the rocks in the Republic graben. Two periods of deformation occurred before the development of the graben, one perhaps an early phase of deformation resulting in intrusion of late Mesozoic batholiths. Deformation of the rocks within the graben is largely along northeast-trending folds and faults. Some of the reverse faults exhibit a significant strike-slip component. The northeast-trending normal faults that bound the graben apparently developed penecontemporaneously with those in the graben, but they suggest extension--possibly as an axial rift along a broad area of uplift. Vance (1977) has suggested late Eocene extension as the cause of the Republic and Chiwaukum grabens, perhaps a renewal of movement on pre-existing reverse faults. Staatz (1964) attributes graben formation to withdrawal of magma from beneath the area.

Olympic-Wallowa Lineament

After preparation of his "Landform Map of the Northwestern States" at a scale of about 1:1,000,000, Raisz (1945) noted a striking topographic lineation trending northwest to southeast that was apparent from Cape Flattery, Washington to the Wallowa Mountains of northeastern Oregon. He named this feature the Olympic-Wallowa Lineament (OWL) and summarized its manifestation on each of several small-scale maps along the entire lineament. Generally, there are ridges on the south side of the feature and topographic lows along the north side. However, the feature is not obvious on all maps and, where visible, its degree of expression varies from strong to very subtle. Along much of its length, topographic features are oblique to the lineament and the lineament is more a zone than a single distinct line.

Raisz proposed two hypotheses for the origin of the lineament: (a) coincidental alignment of relief features; and, (b) strike-slip faulting. While citing evidence in support of each, he came to no conclusion as to its origin.

Wise (1963) proposed a 300-mile (480-kilometer) wide zone of right lateral shear to account for the northeast kink in the broad belt of Mesozoic intrusives and the unusually wide United States Cordillera (compared to Canada and Central America). The limits of his mega-shear couple are two northwest-trending lineaments, the Walker Lane and Olympic-Wallowa Lineaments and possible offshore continuations. Right lateral shear across the zone began at least in the Paleozoic and has continued well into the Cenozoic. While admitting many problems existed with this "outrageous hypothesis," Wise proposed it be given due consideration as one of many working hypotheses.

Part of the northwest-trending Olympic-Wallowa Lineament approximately corresponds with a boundary between zones of different resistivity in southeastern Washington (Cantwell and Others, 1965; Cantwell and Orange, 1965). The discontinuity was found to be deep and not expressed in the upper 6 miles (10 kilometers) of crust. Skehan (1965), following Wise (1963), interpreted the lineament as a major discontinuity separating continental and oceanic crust.

Taubeneck (1966) found no offset of the Hite fault or the Blue Mountains front in northeastern Oregon, nor any change in orientation of dikes of the Grande Ronde-Cornucopia dike swarm where these features cross the Olympic-Wallowa Lineament. Absence of change of paleomagnetic properties of dike rocks on opposite sides of the lineament was cited as further evidence that the feature is strictly topographic.

Jones and Deacon (1966) suggested association of the July 15, 1936 Milton-Freewater earthquake with the Olympic-Wallowa Lineament based on a reconnaissance study of aerial photographs. The orientation of the zone of the aftershocks and isoseismals which trend northeast do not support such an association (WPPSS, 1974).

Atwater (1970) suggested a broad zone of right lateral shear inland from the Pacific-American Plate boundary based largely on diffuse seismicity across a broad zone of several hundred miles (kilometers). Detailed analysis of earthquake data suggests that earthquake activity is concentrated in broad linear zones that separate intraplate blocks (Sbar and Others, 1972; Smith and Sbar, 1974). These broad zones of shear or shear extension separate relatively rigid crustal blocks and are the zones where stress is relieved and deformation occurs (Smith, 1977, 1978). One of these zones trends northwest through the High Lava Plains of Oregon and separates the Columbia Plateau from the Sierra-Nevada. Such a zone of right lateral strike-slip faults has been described by Lawrence (1976) in the High Lava Plains of Oregon and consists of the Brothers, Vale, and Eugene-Denio fault zones which are the northern boundary of the Basin and Range province. These faults trend northwest and are parallel to the Olympic-Wallowa Lineament.

Recent geological mapping and geophysical anomalies suggest that the lineament is not continuous through the Cascade Range (WPPSS, 1977). The trend of topographic features between Cle Elum and Wallula, Washington (Kienle and Others, 1977a) indicates that these are the ends of a lineament in eastern Washington that is not traceable through the Cascades. Structures both parallel and oblique to the northwest-trending Cle Elum-Wallula Lineament (CLEW) are discussed in detail in the section on Pasco Basin tectonics.

MAJOR REGIONAL FAULTS

The western margin of the North American craton during Precambrian time was considerably east of the present western margin of the continent. Rocks west of a generally north-south line extending through western Idaho, but which jogs westward to join the Kootenay arc, have been accreted to the craton during Phanerozoic time. Isotopic ratios of $^{87}Sr/^{86}Sr$ suggest the location of the western border of the Precambrian craton (Armstrong and Others, 1977); however, Precambrian basement complexes are known or inferred considerably farther west, indicating lateral transform displacement of considerable magnitude during the Phanerozoic. Monger and Others (1972) speculate that all pre-Mesozoic rocks of the Canadian Cordillera west of the Omineca crystalline belt are allochthonous, a framework that can readily be extended into Washington (Davis, 1977). Several major regional faults

that may have functioned as transform faults during the Cretaceous separate crustal segments of northern Washington. These major faults along which lateral displacement of several tens of to several hundreds of miles (kilometers) has occurred are briefly described in the following paragraphs.

Skagit Fault

The Skagit fault is a complex of at least four fault segments that together comprise a fault system (Vance, 1977) which has had a complex geologic history. Three of these segments, the Ross Lake (Misch, 1966), Twisp, and Foggy Dew faults (Barksdale, 1975) form the southwestern boundary of the Methow graben and trend generally N45°W. The Yale fault of the Canadian Fraser River fault system is continuous with the Ross Lake fault north of the international border, but has a more northerly trend. The Skagit fault is a high-angle fault separating the highly complex metamorphic core of the north Cascades from moderately folded and faulted Tertiary sediments within the Methow graben. Elsewhere, it separates geologic units of distinct character within the north Cascades (Vance, 1977; Misch, 1966). While the youngest movement on the system is dip-slip, it is proposed as a major suture between partly Precambrian terrain to the west and younger rocks to the east. Some strike-slip motion on the Skagit fault occurred during the late Cenozoic immediately following closing of an interplate ocean (Vance, 1977). Davis (1977) proposed major strike-slip displacement on the Skagit fault, which he terms the Ross Lake fault, while Vance (1977) interprets the fault to have had a brief history of transform motion that was terminated by intrusion of the late Cretaceous Black Peak granite batholith. Misch (1966) proposes dextral strike-slip motion for at least a part of the fault; Barksdale (1975) suggests sinistral transcurrent motion for the Twisp and Foggy Dew faults.

While recognizing that the depositional basin of the Tertiary Chuckanut Formation was rapidly subsiding, Misch (1966) does not specifically mention the Methow graben; he refers to the depositional basin containing the Chuckanut Formation as a "rapidly subsiding tectonic trough" similar to an Alpine Molasse Basin. Before dip-slip motion took place on the Skagit and Chewack-Pasayten faults, each fault had an earlier independent history (Vance, 1977). While the nature and chronology of slip on the Skagit fault remain somewhat obscure, a middle to late Cretaceous time of last movement is generally agreed upon because the radiometrically dated Black Peak batholith interrupts segments of the faults and is not offset or sheared along the projected trace of the Skagit fault. Aerial reconnaissance and analysis of imagery revealed a subdued topography along the Skagit fault supporting a pre-Wisconsinan and probably pre-Quaternary age of this structure (Glass and Slemmons, 1977).

Chewack-Pasayten Fault

The Chewack-Pasayten fault is a major, northwest-trending, steeply dipping fault along which several thousand feet (meters) of dip-slip movement have occurred (Barksdale, 1975). Folded and faulted Jurassic, Cretaceous, and Tertiary sediments to the southwest in the Methow graben

are separated from gneisses of the Okanogan Highlands by a shear zone of up to several hundred feet (meters) thick. Foliation in the gneisses bordering the graben is cataclastic as revealed in thin section analysis. Recrystallization in the mylonite zone has produced an elongated fabric that is parallel to the fault and limited to a zone about 0.9 to 1.2 miles (1.5 to 2.0 kilometers) from the fault. Elsewhere, the gneisses are poorly foliated. Similar to the other faults in the area, it was reactivated as a normal fault after initial strike-slip and reverse movement that occurred in middle to late Cretaceous time. Subdued topography and modification by glaciation indicated a pre-Quaternary age for this fault (Glass and Slemmons, 1977).

Straight Creek-Fraser River Fault

The Straight Creek-Fraser River fault system is a major, steeply dipping, generally north-south-trending fault that extends for about 250 miles (400 kilometers) from the Cascades of Washington into British Columbia (Vance, 1977). North of the international border, the fault is known as the Hope fault, but it is not continuous with the Straight Creek fault in Washington. The Hope fault continues along the same trace north of the early Teritary Chilliwack Batholith. Between Hope and Boston Bar, British Columbia, the Hope and Hozameen faults converge and continue northward as the north-northwest-trending Fraser River fault zone. Because the segments in Washington and British Columbia are separated geologically by a batholith and politically by an international boundary, they have been generally studied separately and are treated as such here.

Straight Creek Fault

Unmetamorphosed and low-grade metamorphic volcanic and sedimentary rocks of middle to upper Paleozoic and Mesozoic age west of the fault are in contact along the Straight Creek fault with schists, gneisses, and migmatite that have been intruded by Mesozoic plutonic rocks. Several batholiths segment the fault. The Straight Creek, Evergreen, and Kachess segments are interrupted, respectively, by the Chilliwack, Grotto, and Snoqualmie Batholiths. The fault is expressed topographically by saddles and straight-stream segments and geologically by shear and mylonite zones.

The Straight Creek fault has a long and complex history of movement that was completed by Oligocene time, except for some later minor movements. Major dextral displacement of Cretaceous rocks by as much as 120 miles (192 kilometers) has been suggested by Misch (1966, 1977). Movement on the Straight Creek fault was apparently episodic, with major displacement in Late Cretaceous-Paleocene time and subsequent movement in late Eocene-early Oligocene time (Vance, 1977). Movement on the southernmost Kachess segment may have continued into late Oligocene time. Dates of last movement are largely provided by the three batholiths which have been dated as between 16 and 35 million years. Search for evidence of shear or major joint concentrations in the plutons that might be related to the fault and later movements thereon provided no evidence of post-intrusion movement along the Straight Creek fault.

Hope-Fraser River Fault System

The Hope fault continues on strike with the Straight Creek fault north of the Chilliwack Batholith and is also segmented by plutonic rock masses that are undisturbed along the fault trace projected through each pluton (Ryan, 1977). Topographic and geologic expression varies, but rocks juxtaposed along the fault suggest it to be a major suture. The fault trends just west of due north and is mapped as dipping nearly vertically from the linearity of the trace. The Silver Creek stock dated at 35 million years (Richards, 1971) is not offset along the trace of the fault. A 300-foot (92-meter) long, 3-foot (1-meter) deep trench across the suspected trace of the Hope fault in southern British Columbia revealed no offset of surficial sediments.

Movement on the Hope fault is variously estimated, but major, right lateral displacement of ≤120 miles (<192 kilometers) during the Cretaceous has been suggested (Misch, 1977). Early Teritary dip-slip motion has occurred, but no evidence of movement during the Quaternary was found (Ryan, 1977).

A series of north-northwest-trending faults extends northward along the Fraser and Yalakom River valleys. Faults in these two zones generally offset Cretaceous rocks, but not overlying Miocene or older volcanics. Some offsets of possible glacial origin wre observed at some localities (Ryan, 1977).

Yale Fault

The Yale fault is one of several north-trending, steeply dipping faults that merges with the Fraser River fault zone south of Boston Bar, British Columbia. It can be traced for about 42 miles (67 kilometers) from the Chilliwack Batholith into Fraser Canyon near China Bar, but is truncated by the Silver Creek stock south of Hope (Ryan, 1977). The degree of expression of the fault varies from subtle south of the Silver Creek stock to a well-defined lineament in the Fraser Canyon. Aerial reconnaissance revealed no shearing or other evidence that the Yale fault offsets or is younger than the plutons along its trace. North of Hope, lineaments suggest that the fault splays into several sub-parallel, closely spaced faults. Sheared contacts of the Custer Gneiss and the Yale intrusives account for some of the lineaments and suggest the possibility of a broad, major fault zone. The Custer Gneiss-Hozameen group contact has been mapped as a major fault that appears to be continuous with the Ross Lake fault (Misch, 1966).

Two trenches (≤75 feet long by 3 feet deep [<23 meters long by 1 meter deep]) across the main trace of the Yale fault north of the town of Yale revealed no evidence of offset of post-glacial sediments (Ryan, 1977). Modification by glaciation suggests that the fault is older than the Fraser glaciation. Numerous landslides are present in the Fraser Canyon, but these have apparently resulted from incision laterally into alluvial fans and vertically into late Quaternary talus and alluvium (Piteau, 1977). Much of the incision arises from post-glacial isostatic rebound and from river diversion by slides.

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Oregon Transcurrent Fault Zone

The Basin and Range province is terminated at its northern and southern margins by major transcurrent fault zones. To the south, Basin Range province extension is terminated by the sinistral Garlock fault (Davis and Burchfiel, 1973); to the north, basin-range extension is terminated by a series of northwest-trending dextral transcurrent fault zones in Oregon (Lawrence, 1976). The Brothers, Vale, Eugene-Denio, and Mount McLaughlin zones are here collectively termed the Oregon transcurrent fault zone. The trend of each of these zones is N50-60°W, but each zone is composed of a number of en echelon faults that trend generally N40°W. These latter faults are dip-slip faults, mostly normal faults, of 6 to 12 miles (10 to 20 kilometers) in length. Shorter, approximately 3-mile (5-kilometer) long fractures oriented about N30°E are also present on the north side of each of these N60°W zones.

Based on similarity of pattern to shear zones described by Tchalenko (1970), Lawrence (1976) interprets these fractures observed on satellite imagery as a right lateral shear zone. The N40°W trends are thus considered Riedel shears, and the N30°E fractures are conjugate Riedel shears. While the pattern of fractures is similar, the mechanism that produced the fractures in Oregon may be quite different than the purely translational slip of the Riedel experiment, shear box, and the transcurrent Dasht-e Bayaz earthquake fault (Ambraseys and Tchalenko, 1969) cited by Tchalenko (1970) as the causative mechanism. Davis (1977) interprets the same fault zone in Oregon as sinistral. Lawrence (1976) cites focal mechanism solutions of the Warner Valley and North Powder earthquakes (Couch and Johnson, 1968; Couch and Whitsett, 1969), right lateral offset of the Cascade Range volcanoes, and right lateral offset of the Sierra-Nevada and Idaho Batholiths (Taubeneck, 1971) as support for dextral shear along with the pattern of fractures.

These four fault zones represent a transition between east-west basin-range extension that produced north-south structures and a different stress field that produced east-west and northwest structures in the Columbia Plateau (Lawrence, 1976). According to this model, east-west extension diminishes progressively northward across these northwest-trending shear fracture zones from the full complement of basin-range extension to minimal east-west extension to the north in the Columbia Plateau. The model fails to account for the northwest-trending feeder dikes for Columbia River basalt and normal faults of similar trend in the LaGrande graben (Walker, 1977) north of the Vale fault zone. While the causative mechanism may be different, the timing hypothesized by Lawrence (1976) would seem to have these events as contemporaneous.

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APPENDIX H

PLATE TECTONIC SETTING OF THE REGION - A PRELIMINARY STUDY

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APPENDIX H

PLATE TECTONIC SETTING OF THE REGION - A PRELIMINARY STUDY

INTRODUCTION

The discovery that the earth's crust is a composite of several large, rigid plates which move about on a zone of plastically behaving material in the upper mantle has greatly enhanced the understanding of the mechanisms and locations of earthquakes and orogenic zones. The apparent fit of the Atlantic coast of South America with Africa led to hypotheses more than 200 years ago about drifting continents. These ideas culminated in Edward Suess' (Holmes, 1965) concept of a giant super continent in the southern hemisphere which he named Gondwanaland. Alfred Wegener (1929), a German meteorologist, published the most complete theory of continental drift, based on matching coastlines, and with paleontologic and paleoclimatic correlations. Meanwhile, Taylor and du Toit (in Holmes, 1965) had also proposed theories of drifting continents. Their hypotheses, however, were given little credence by the scientific community until exploration of ocean basins and islands began in the 1930's. The discovery of ocean ridges of high heat flow, normal faulting, and shallow extensional type earthquakes along with broad zones of oceanic crust of similar magnetic polarity disposed symmetrically about the ridges slowly convinced geologists that oceanic crust was created at ocean ridges and migrated laterally toward great trenches marginal to continents or island arcs. Heat flow, gravity, andesitic volcanic island arcs, and zones of earthquakes of increasing focal depth down to about 372 miles (600 kilometers) provided additional evidence that oceanic crust was consumed in great trenches bordering island arcs and the margins of some continents.

The principles of sea floor spreading and continental drift, known collectively as plate tectonics, are now accepted by nearly all geologists and geophysicists. The major plates of the crust (Figure H-1) were broadly defined by Wilson (1965) and more clearly delineated by Le Pichon (1968). The margins of plates are marked by: (a) ridges (zones of creation of crust); (b) trenches (zones of consumption of crust); or, (c) transform faults of the San Andreas type (zones where lithospheric plates move essentially horizontally past one another). Orogenic deformation, volcanism, and earthquakes can be explained by the interaction of lithospheric plates. A historical discussion of the development of early plate tectonic theory may be found in Wilson (1963); geologic effects, principles, and phenomena of plate tectonics have evolved through a number of papers which are summarized in Le Pichon and Others (1976).

TECTONIC SETTING OF THE PACIFIC NORTHWEST

The Columbia Plateau is underlain by the Columbia River Basalt Group, tholeiitic flood basalts that erupted during the Miocene Epoch, mostly in the interval 13 to 16 million years ago, from north-northwest-trending fissures that apparently existed only east of the Pasco Basin. These

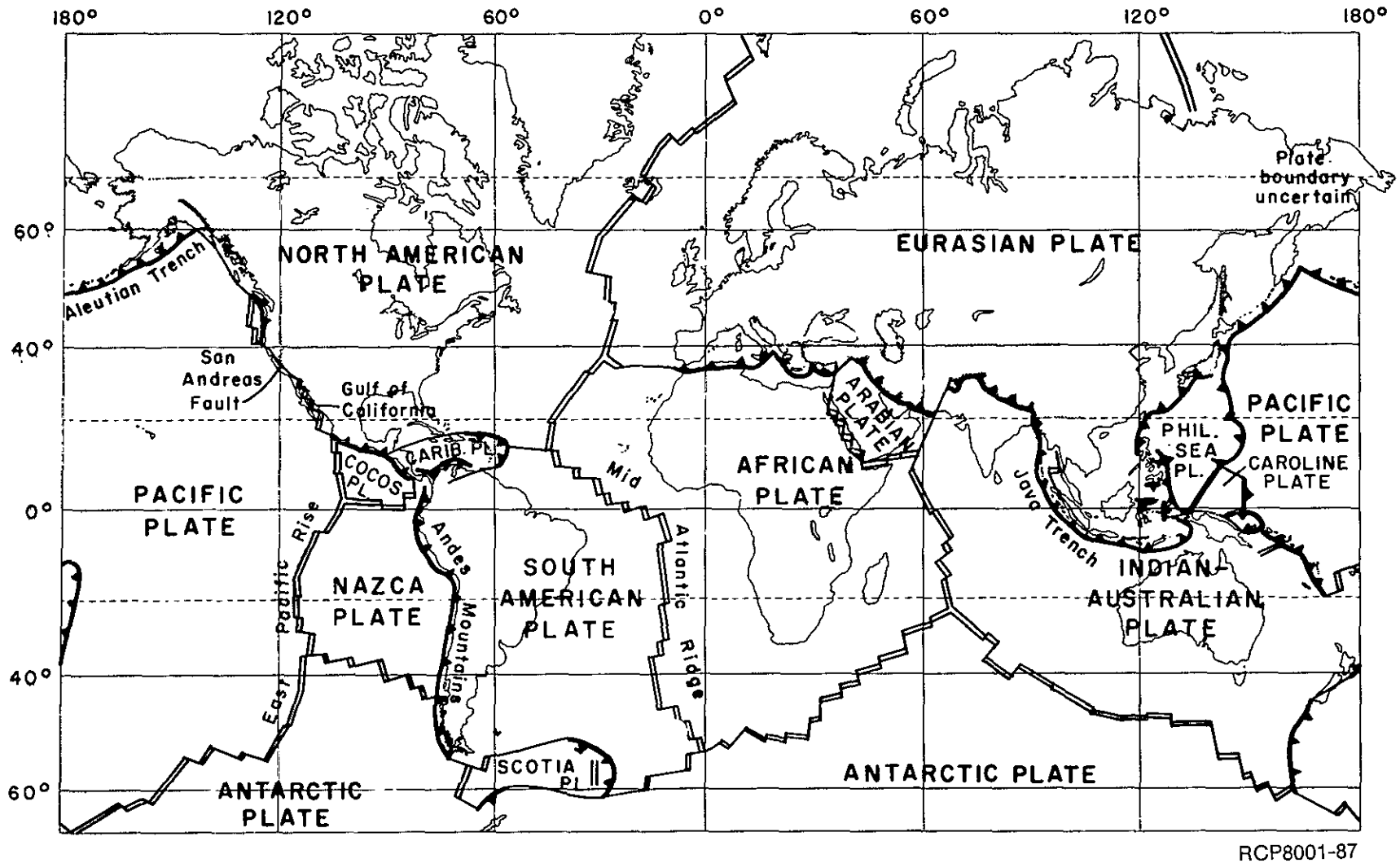


FIGURE H-1. Major Tectonic Plates of the World.

fissures imply regional extension. Whether this tensional stress was primary, or a secondary stress associated with a larger regional stress field, perhaps affecting the entire Cordillera of the western United States, is not certain. The origin of this stress field may be at least partially explained by the interaction of rigid lithospheric plates and segments thereof.

New oceanic crust generated along the East Pacific Rise accretionary plate boundary spread northwestward as part of the Pacific Plate and southeastward as part of the Farallon Plate beginning in the Mesozoic. The direction of spreading of new oceanic crust was parallel to several transform faults (fracture zones) along which the East Pacific Rise is offset. Figure H-2 shows progressive stages of spreading of these two plates relative to the American Plate during the Cenozoic. The Farallon Plate spread eastward and was subducted along a trench which existed along the western margin of the American Plate. About 29 million years ago, relative motion of the Farallon and American Plates resulted in the oblique impingement of the East Pacific Rise along the marginal trench (Atwater, 1970). When the Mendocino Triple Junction reached the American Plate, the compressive regime along the western American Plate changed from subduction along a marginal trench to that of right lateral shear along a transform fault. The San Andreas Fault grew in length as more of the East Pacific Rise and bordering fracture zones reached the American Plate boundary. With subduction of the ridge separating the Farallon and Pacific Plates, the American and Pacific Plates were in direct contact along a right lateral transform fault system. Triple junctions of the Farallon, Pacific, and American Plates then migrated along the zone of transform shear both northward and southward. Continued westward spreading (Figure H-2) then resulted in subduction of most of the Farallon Plate to the extent that only a few relict pieces remain. With fragmentation of the Farallon Plate, the relict pieces began to act in a manner reflecting progressive interaction with the American Plate to the extent that the small, remaining segments of the Farallon Plate acted as small, independent plates. The Cocos, Rivera, and Juan de Fuca Plates are small, relict pieces of the Farallon Plate that have behaved as independent plates with directions and rates of spreading different from those of the parent Farallon Plate. Ridges, fracture zones, and plate geometry of the Juan de Fuca Plate are shown on Figure H-3.

Geological and geophysical evidence clearly indicates subduction of the Farallon Plate and its relict successor the Juan de Fuca until the Quaternary (Atwater, 1970; Riddihough and Hyndman, 1976). Whether subduction has permanently or temporarily ceased or is proceeding at a very slow rate, or the Juan de Fuca and American Plates have decoupled, are presently open questions. The age and pattern of the sea floor magnetic and gravity anomalies east of the Juan de Fuca Ridge, the gravity anomalies and heat flow patterns marginal to the American Plate in southwestern British Columbia (Figure H-4), the shoreward slope of the sea floor, the wedge of sediment and deformation therein, and the Cascade volcanoes all strongly suggest eastward spreading of the Juan de Fuca Plate and subduction along the margin of the American Plate during the late Cenozoic (Riddihough and Hyndman, 1976; Davis, 1977).

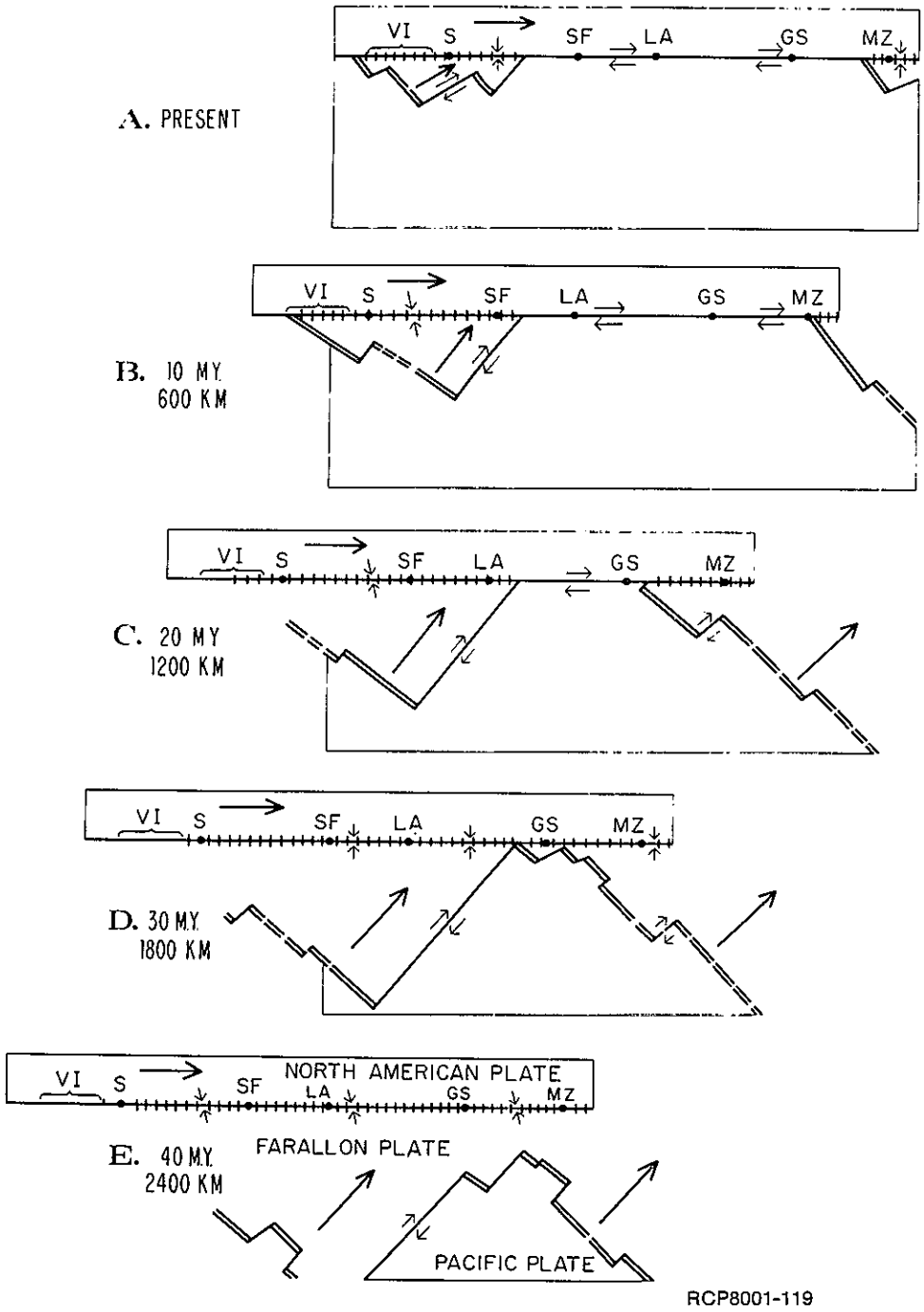
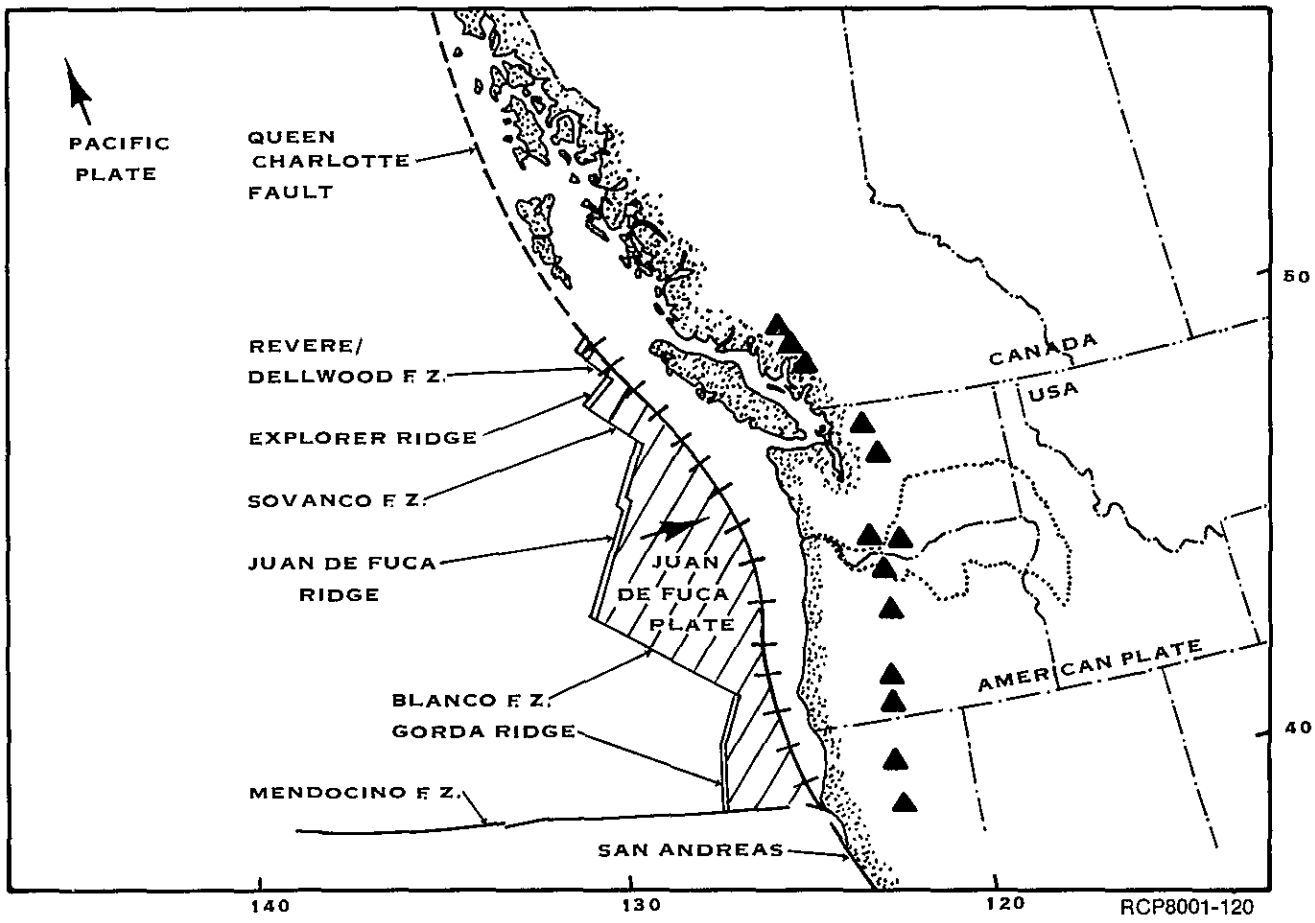


FIGURE H-2. Schematic Illustration of Lithospheric Plate Interactions during the Cenozoic (after Atwater, 1970).



LEGEND

RIDGE

TRANSFORM FAULT

CONSUMPTIVE (?) PLATE BOUNDARY

CASCADE VOLCANO

BORDER OF COLUMBIA RIVER BASALT

FIGURE H-3. Ridges, Fracture Zones, and Plate Boundaries in the Northeast Pacific (after Riddihough, 1978).

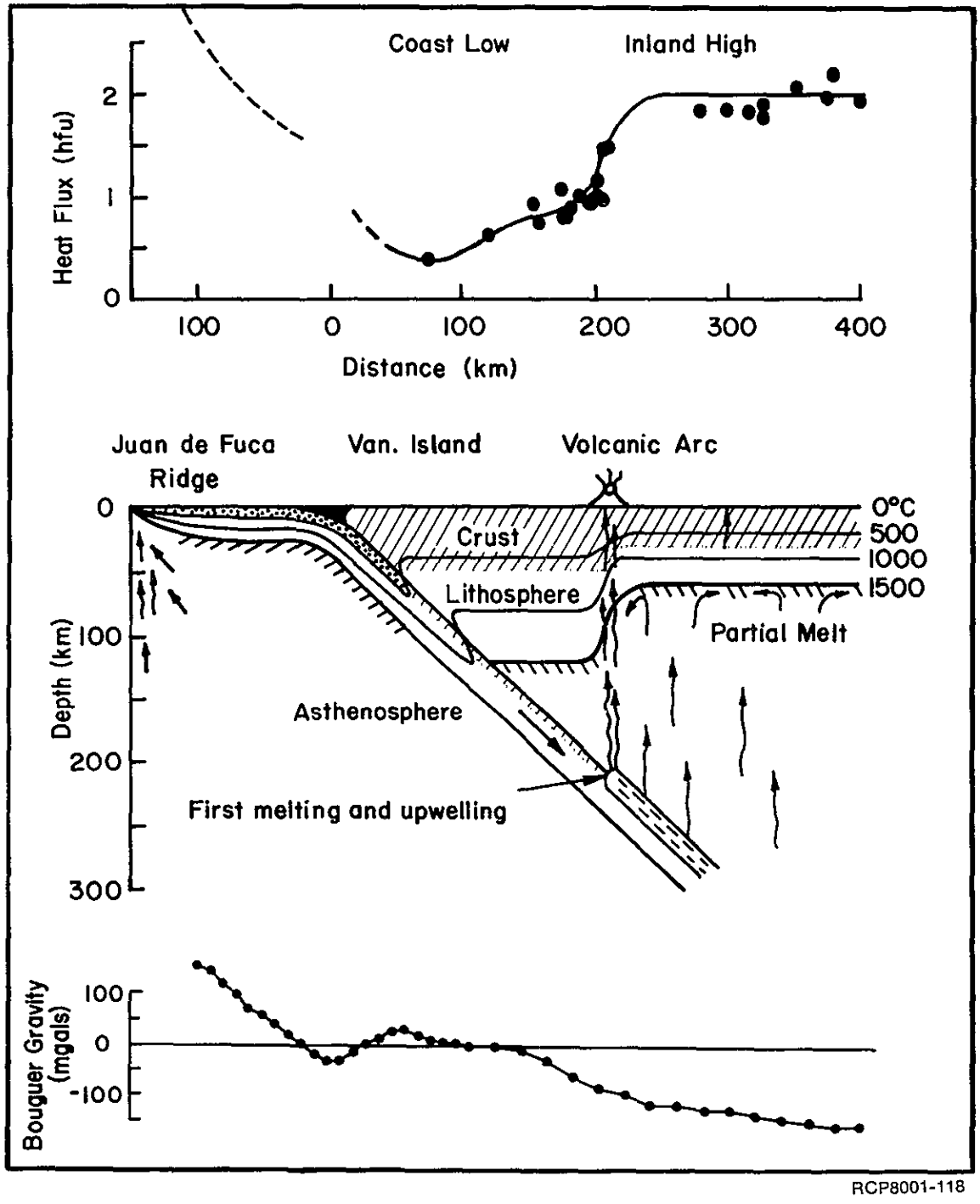


FIGURE H-4. Schematic Cross Section through Southern British Columbia (after Riddihough and Hyndman, 1976).

Earthquake hypocenters less than 42 miles (70 kilometers) deep in western Washington State indicate the existence of a brittle slab or at least a thickened crust beneath the Puget Sound Lowland (Crosson, 1972). Increasing focal depths of earthquakes eastward from the Washington coast and a concentration of earthquake activity less than magnitude 7 in the Puget Sound Lowland led Davis (1977) to hypothesize that the axis of the Puget Sound Lowland lay along a zone where the angle of subduction of the Juan de Fuca Plate changes from about 14 to 40 degrees. While calc-alkaline volcanic rocks of the Cascade volcanoes suggest oceanic crust descending to some considerable depth, modern earthquake records do not support the existence of a classic Benioff Zone (Crosson, 1972).

The few focal mechanism solutions that do exist for the Puget Sound area are inconclusive as to the exact stress field. Hodgson and Storey (1954) determined a northwest-striking (N76°W), south-dipping (12 degree) fault plane for the magnitude 7.1 April 13, 1949 Puget Sound earthquake, while Algermissen and Harding (1965) determined a northwest-striking (N53°W) southwest-dipping (35 degrees) plane for the magnitude 6.5 April 29, 1965, Puget Sound shock. Thrust faulting was determined for the 1949 event, while normal faulting was found for the 1965 event. Composite focal mechanisms for shallow events in the Puget Sound area (Crosson, 1972) suggest northwest-striking focal planes that ruptured under a compressive north-northwest to north-northeast stress regime to produce thrust or strike-slip faulting. Those advocating active subduction of the Juan de Fuca Plate cite the 1965 earthquake as evidence of extension in the upper part of the down-going oceanic crust as it plunges beneath the American Plate along a northeast trend. While focal mechanism data are too few to be conclusive, they suggest that the Juan de Fuca Plate is either decoupled from or not being actively subducted beneath the American Plate (Crosson, 1972; Davis, 1977). The north-south compressive stress regime matches that to the north where earthquakes are confined to the upper 9 miles (15 kilometers) of crust and right lateral strike-slip is occurring on the Queen Charlotte Transform Fault (Chandra, 1974; Riddihough and Hyndman, 1976). The north-south compression in the Puget Sound area may be related to isostatic or eustatic effects (Crosson, 1972), or perhaps associated with stress changes related to a glacial forebulge (McGinnis, 1968). If the Puget Sound area is presently experiencing north-south compression, then the stress field matches that east of the Cascades where the crust is thinner and earthquakes are smaller, less frequent, and commonly occur in swarms (Hill, 1972,; Malone and Others, 1975; Malone, 1977). The eastern Washington stress field, as determined from focal mechanism solutions, appears similar to one that produced late Miocene and Pliocene folding of the Yakima Basalt, indicating its existence for several million years of geologic time.

Geological and geophysical evidence from the ocean basins, as well as from the margin of the American Plate, leave little doubt that western North America has been in a broad regional compression since the Mesozoic. The timetable and the geometry of plate interaction are reasonably well known, but the nature and effect of the stresses that developed during plate interaction are still largely conjecture. Atwater (1970) suggested that compression between the two plates was accommodated

by transform shear along the San Andreas Fault, as well as across a broad zone of western North America east of the San Andreas, an area characterized by generally diffuse seismicity. Analysis of earthquake records has shown that seismicity is not uniformly distributed across the Cordillera, but is largely concentrated in broad zones such as Walker Lane and the Intermountain Seismic Belt (Sbar and Others, 1972; Smith and Sbar, 1974). These broad zones of earthquakes have recently been interpreted as broad zones of shear and/or shear extension that border large, relatively rigid blocks within the American Plate (Smith 1977, 1978). Right lateral shear resulting from interaction of the Pacific and American Plates may not be entirely relieved along transform faults, but may be transmitted effectively through intact blocks of continental crust and relieved along broad zones of deformation. Figure H-5 illustrates one view of the distribution of crustal blocks and marginal zones of deformation.

Thin crust, high heat flow, and extensive normal faulting (some reverse and strike-slip faults or strike-slip components, of dip-slip faults are present) have suggested that an alternative mechanism of Pacific-American Plate interaction may produce the earthquakes and late Cenozoic deformation in parts of the Cordillera (Scholz and Others, 1971). Back arc spreading resulting from a rising and laterally spreading mantle plume or diapir that forms in the Benioff Zone (Karig, 1971) may account for the thin crust, high heat flow, and extension in the Basin and Range province. While a similar model may explain the Columbia Plateau, details of crustal thickness and deep velocity remain unknown and heat flow is not uniformly high throughout the plateau (Davis, 1977; Blackwell, 1978; Sass and Others, 1971).

In summary, the poorly understood present stress field of the Columbia Plateau and region probably results from direct or indirect effects of the interaction of the Juan de Fuca, Pacific, and American Plates. It is not clear whether a broad regional compression is accommodated through active subduction, transfer of stress over a broad zone of right lateral shear, or through an active or fossil mantle diapir arising from subduction, a migrating mantle plume, or some other mechanism. More information on crustal thickness and velocity, heat flow, in situ stress, and focal mechanisms of earthquakes will be necessary before major tectonic questions can be answered.

THE COLUMBIA PLATEAU TECTONIC SETTING

Although the Columbia River basalts constitute the youngest flood basalt province, fundamental questions remain unanswered regarding its origin and its distribution over a limited area of the American Plate. The origin of the stress field that produced extension leading to the development of source fissures and vents is still speculative. The origin and nature of the basin in which the lavas accumulated remain a problem that is addressed briefly in the ensuing paragraphs.

A basin of the size in which Columbia River basalts accumulated may develop as a topographic feature, a structural feature, or some combination of topography and structure. The thickness and areal

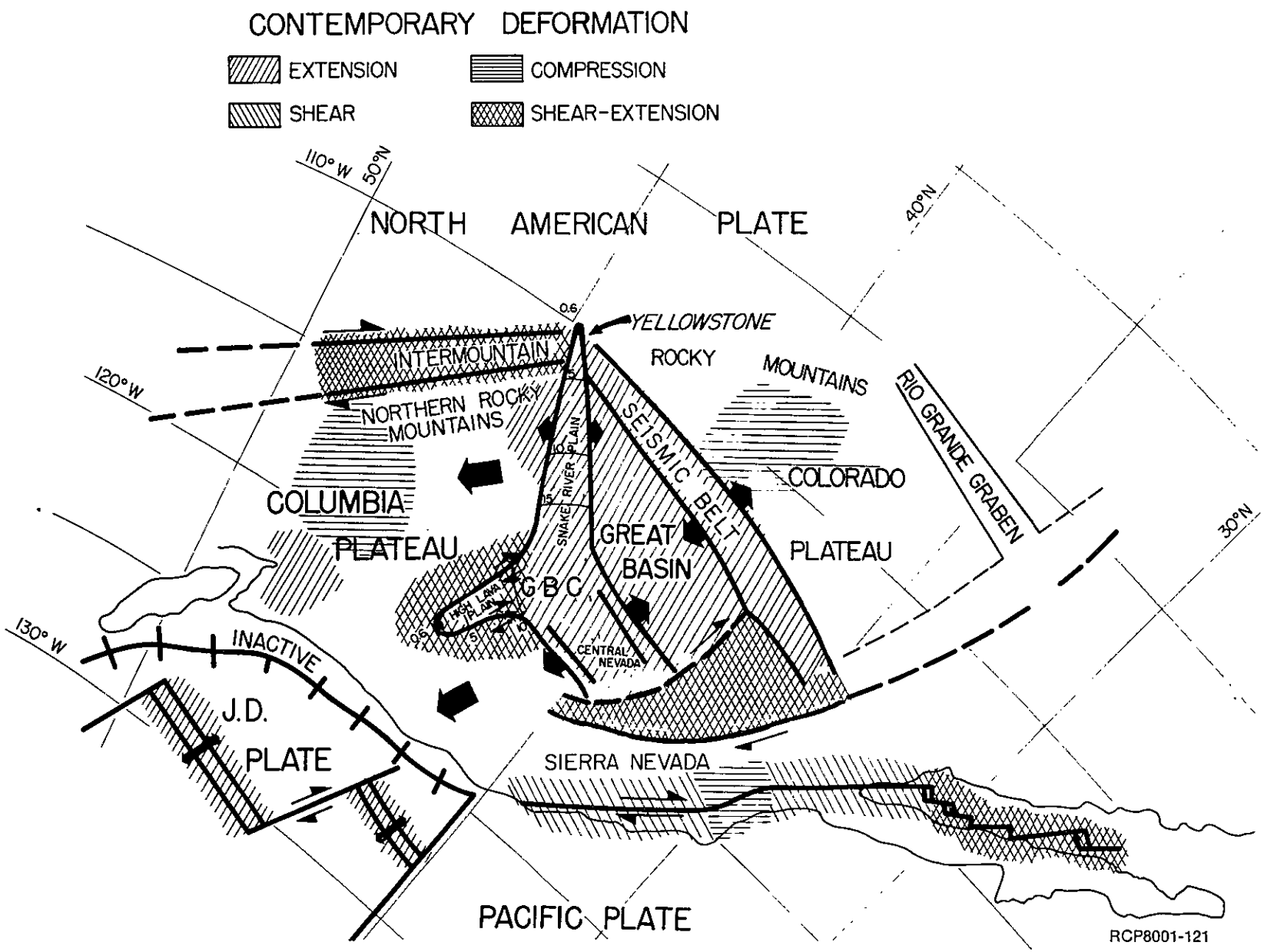


FIGURE H-5. Schematic Illustration of Plage Boundaries and Crustal Blocks in Western North America (after Smith, 1978).

distribution of exposed flows indicate that units generally thicken toward the center of the basin, except that units appear to have terminated against a topographic high (probably the ancestral Cascades) toward the west. Lava flowed with remarkable fluidity over great distances along slopes of about 1:1,000. Mapping to date does not suggest that the Columbia River basalt was confined to or emanated from a rift or fault-bounded basin. Relief near and along the margin of the Columbia River basalt suggests that the erupted lava flowed over a terrain of moderate to high relief (Swanson and Wright, 1978; Robbins and Others, 1975).

Few deep wells have been drilled in the Columbia Plateau, but a 10,655-foot (3,248-meter) deep test well, Rattlesnake Hills Well Number 1, was drilled by Standard Oil Company of California in 1957 and 1958 in search of sedimentary rocks below the basalt. Logging and analysis of core chips have revealed some information on the age and nature of the rocks in the deep basin. The well encountered basalt and andesite near the bottom, but passed through some interbedded bituminous shale, coal, and weathered horizons or sediments at depths of a few to several thousand feet (meters) (Raymond and Tillson, 1968). Analysis of pollen from coal beds in the 2,000 to 5,000-foot interval suggests the existence of a diversified pre-middle Miocene flora that is perhaps as old as Oligocene Age (Newman, 1970). The flora suggests a sub-tropical to warm climate, indicating that the area was not in a rainshadow of a large mountain range as is true today.

Therefore, the barrier on the west side of the plateau was apparently the low hills of the ancestral Cascades, a probable source for arkosic, tuffaceous sediments of the Puget Group. The thick, possibly weathered horizon suggests a terrain of relatively low relief at the point where the well was drilled. Exploratory wells near Union Gap and Odessa, Washington and Condon, Oregon near the margins of the plateau penetrated a much thinner basalt section.

The thickness and nature of the crust beneath the Columbia River Basalt can be inferred from the propagation velocity of elastic waves generated by earthquakes and/or explosions. Hill (1972) detected arrivals from detonations in British Columbia along a north-south profile through the Columbia Plateau. The line extended for 480 miles (800 kilometers) into the High Lava Plains of Oregon and passed through the southeastern part of the Pasco Basin. The interpretation of the line suggested either a thin crust (less than 14 miles [23 kilometers]) resting atop a high in the mantle, or the presence of a high-density, high-velocity zone beneath the basalt. Hill (1972) suggested that a dense array of feeder dikes in the basement rocks beneath the basalt might account for the high-velocity zone. However, recent interpretation by Hill and Eaton in Smith (1978) and results of magnetotelluric surveys by Rockwell Hanford Operations (Appendix E) indicate that crustal thinning is the preferred interpretation.

The crustal model used to locate earthquakes in the Columbia Plateau was refined by Malone (1977) when the regional earthquake detection array was expanded to the north. In both models, the crust was assumed to be

17 miles (28 kilometers) thick, but the original 5-layer model used by the U.S. Geological Survey was modified to one that differed north and south of 47 degrees north. A 4-layer model to the north corresponds to an area of thin basalt (less than 3 miles [5 kilometers]). South of approximately the Frenchman Hills, the basalt thickens to slightly greater than 6 miles (10 kilometers) (Malone, 1977). Whether the thickness of basalt reflects an original deep basin south of 47 degrees north, in which more lava accumulated, or whether greater isostatic subsidence has occurred to the south because of the greater mass of basalt are indeterminate at this time.

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