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Administrative Record, H6-08 (TSD#: D-2-11)

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RHO. (1981). RHO-BWI-ST-14. Chapter ~~28~~ 1-3, *Wanapum and Saddle Mountains Basalts of the Cold Creek Syncline Area*. Reidel, S.P., and Fecht, K.R. In, *Subsurface Geology of the Cold Creek Syncline*. Myers, C.W. and S.M. Price, editors, Rockwell Hanford Operations, Richland, Washington.

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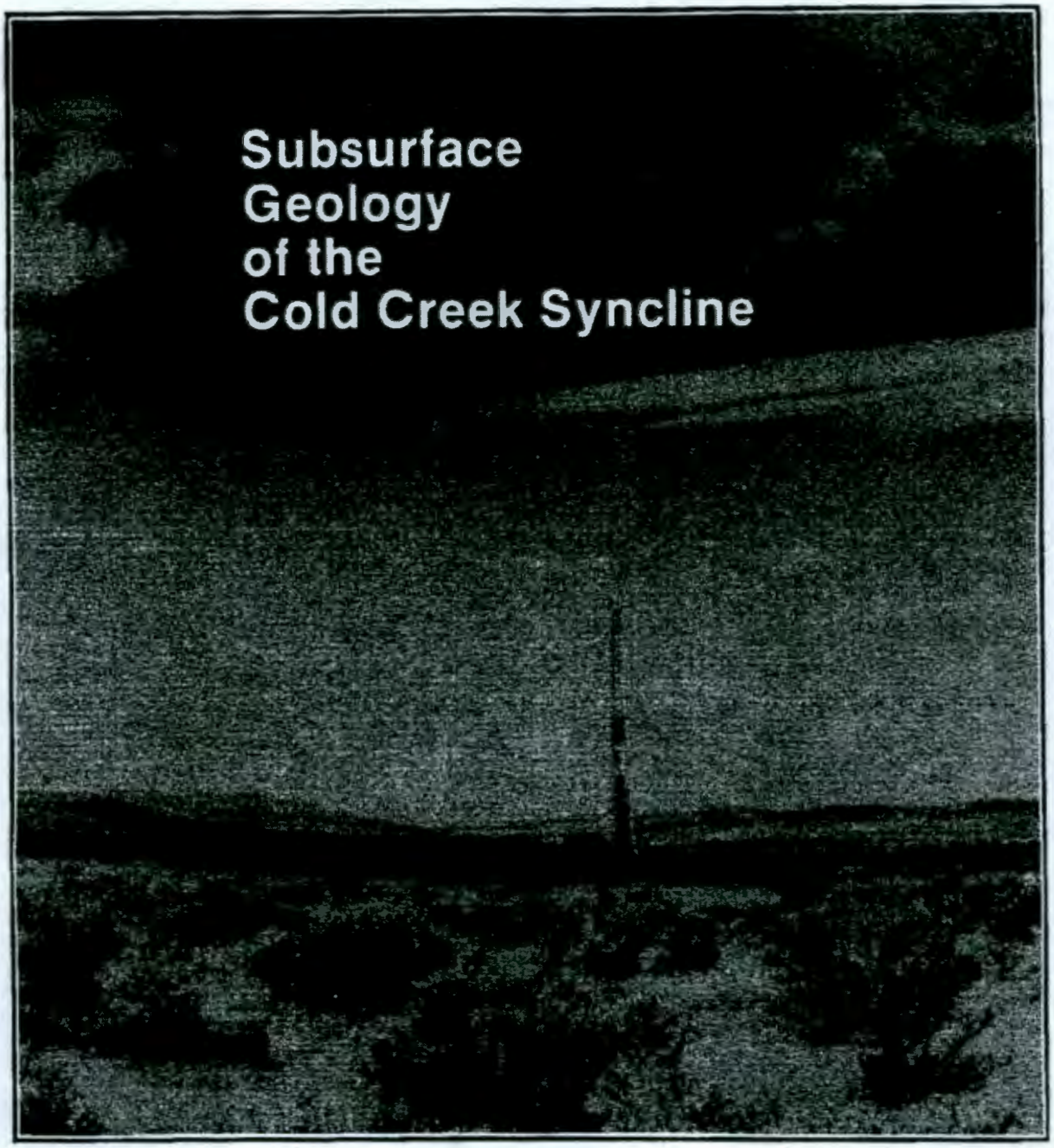

Subsurface Geology of the Cold Creek Syncline

Prepared for the United States
Department of Energy
Under Contract DE-AC06-77RL01030

Rockwell International

Rockwell Hanford Operations
Energy Systems Group
Richland, WA 99352

D-2-11

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RHO-BWI-ST-14
Distribution Categories
UC-11, -70, and -85

SUBSURFACE GEOLOGY OF THE COLD CREEK SYNCLINE

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July 1981

Prepared for the United States
Department of Energy Under
Contract DE-AC06-77RL01030

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EXECUTIVE SUMMARY

Staff

Bedrock beneath the Hanford Site is being evaluated by the Basalt Waste Isolation Project (BWIP) for possible use by the U.S. Department of Energy as a geologic repository for nuclear waste storage. Initial BWIP geologic and hydrologic studies served to determine that the central Hanford Site contains basalt flows with thick, dense interiors that have low porosities and permeabilities. Furthermore, within the Cold Creek syncline, these flows appear to be nearly flat lying across areas in excess of tens of square kilometers. Such flows have been identified as potential repository host rock candidates. The Umtanum flow, which lies from 900 to 1,150 m beneath the surface, is currently considered the leading host rock candidate. Within the west-central Cold Creek syncline, a 47-km^2 area designated as the reference repository location (RRL) is currently considered the leading candidate site.

The specific purpose of this report is to present current knowledge of stratigraphic, lithologic, and structural factors that directly relate to the suitability of the Umtanum flow within the Cold Creek syncline for use as a nuclear waste repository host rock. The BWIP geologic studies have concentrated on factors that might influence groundwater transport of radionuclides from this flow. These factors include: (1) intraflow structures within the interiors of individual lava flows, (2) interflow zones and flow fronts between adjacent lava flows, and (3) bedrock structures. Data have been obtained primarily through coring and geophysical logging of deep boreholes, petrographic, paleomagnetic, and chemical analysis, seismic-reflection, gravity, and magnetic (ground and multilevel airborne) surveys, and surface mapping. Results included in this document comprise baseline data which will be utilized to prepare a Site Characterization Report as specified by the U.S. Nuclear Regulatory Commission.

The Cold Creek syncline is part of the Pasco Basin, one of several structural and topographic basins within the western Columbia Plateau. The western and central parts of the Pasco Basin are located within the Yakima Fold Belt, a structural subprovince of the plateau characterized by east-west-trending, asymmetrical, anticlinal ridges and intervening synclinal valleys. Yakima folds bound the Pasco Basin on the north and south and plunge into the basin from the west. The Cold Creek syncline lies between the Umtanum Ridge-Gable Mountain anticlinal structure on the north and the Yakima Ridge and Rattlesnake Mountain anticlinal structures on the south. Two subtle depressions are present along the troughline of the Cold Creek syncline: (1) Cold Creek Valley depression, located within the area of the RRL; and (2) Wye Barricade depression, located ~25 km to the east. The Cold Creek Valley syncline plunges and dies out to the east in the vicinity of the Wye Barricade depression.

A key aspect of site-identification work has been the delineation of relatively intact volumes of basalt in the Cold Creek syncline area. These relatively intact volumes of bedrock are bounded by known or

inferred geologic structures, excluding intraflow structures. Such structures determine the size and geometry of basalt host rock within which a repository could be constructed, and represent zones of vertically oriented fractures which might affect shallow and deep groundwater flow systems. Based on the results of geophysical surveys and surface and subsurface mapping, the western Cold Creek syncline area is presently interpreted to consist of five, large, relatively intact volumes of bedrock whose boundaries are defined by structures such as first-order anticlines or other known or inferred structures. The interior of the RRL lies within one of these large relatively intact bedrock volumes.

The bedrock of the Cold Creek syncline is comprised of flows belonging to three formations of the Columbia River Basalt Group: (1) Grande Ronde Basalt, (2) Wanapum Basalt, and (3) Saddle Mountains Basalt. The over 2,500 m of Grande Ronde Basalt in the syncline consist of at least 50 flows, one of which is the Umtanum. These flows have an average thickness of 35 m and range in thickness from 4 to 150 m. The Wanapum and Saddle Mountains Basalts within the Cold Creek syncline are comprised of up to 20 flows, with a total maximum thickness of ~700 m. The basalt section is interbedded with sediments of the Ellensburg Formation and is overlain by up to 220 m of the fluvial-lacustrine Miocene-Pliocene Ringold Formation and catastrophic flood deposits of the Pleistocene Hanford formation.

The extent and thickness variations exhibited by basalt flows indicate that the Pasco Basin and Cold Creek syncline were active structural features by at least late Grande Ronde time; rates of uplift and subsidence during the period of late Grande Ronde through Saddle Mountains time are estimated to be <40 m/million years. The steeply inclined flows on anticlinal limbs contain the most extensive faulting and brecciation. Tectonic fractures are, in general, infrequent in the thousands of meters of core drilled in the synclinal areas of the Pasco Basin. The breccia zones that were identified are generally intact and <10 cm thick. Such small tectonic breccia zones and their associated fractures are viewed as typical strain features of folded basalt and should be expected within the limbs of any of the Yakima folds, including the Cold Creek syncline. None of the tectonic breccias identified in core were judged as being associated with large displacements.

The Umtanum flow is found throughout the Pasco Basin; a broad zone of relatively constant thickness (~64 m) occurs in the central Pasco Basin, including the RRL. In this area, the entablature appears to have a consistent, uniform, glass-rich texture, suggesting few differences in fracture abundance. The entablature also contains secondary minerals as fracture fillings. The high mesostasis abundance in the entablature means that it will alter and, hence, may react with and inhibit the migration of radionuclides more readily than will the colonnade which has a lower mesostasis abundance. The occurrence of fracture fillings of clay (smectite), zeolite (clinoptilolite), and silica acts to reduce the permeability of the basalts, as well as to provide highly sorbtive minerals along potential groundwater pathways.

The sequence of Grande Ronde Basalt flows which overlie the Umtanum flow consists of relatively thick laterally continuous flows intercalated with relatively thin flows, some of which are discontinuous. The thick laterally continuous flows are likely to be hydrologic barriers; whereas, the intervening thin flows with a relatively higher proportion of porous flow top are likely to provide the most transmissive zones. The discontinuous character of some of the thin flows may result in an increase in vertical permeability relative to those parts of the section with thick flows.

Drill core from some Grande Ronde Basalt flows in the Cold Creek syncline area, including the Umtanum, exhibits a type of fracturing known as disking. The degree of disking is variable, with individual disk thicknesses generally ≤1.5 cm. The mineralogy and intraflow structures of the Umtanum core have been studied in detail and no correlation with disking is apparent, except that disking does not occur in the flow top. It is concluded that the disking phenomenon probably results from higher horizontal than vertical in situ stresses in basalt.

Overall, the central and eastern parts of the Cold Creek Valley depression which lie within the RRL appear to contain a uniformly thick portion of the Umtanum flow and to be free of potentially adverse bedrock structures relative to other parts of the Cold Creek syncline area and Hanford Site. The structure of the top of basalt and the structure at deeper horizons within this area are interpreted as being nearly flat lying with very gentle dips toward the trough of the Cold Creek syncline and with a slight westward component of dip toward the deepest point of the Cold Creek Valley depression. Additional drilling and geophysical work will be designed to detect and characterize subtle structures which may be present within this depression and to test the predictive capabilities of interpretations outlined in this report.

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CHAPTER 1 - INTRODUCTION

C. W. Myers
S. M. Price

PURPOSE AND SCOPE

The Basalt Waste Isolation Project (BWIP), administered by Rockwell Hanford Operations (Rockwell), is one of the elements of the U.S. Department of Energy's (DOE) National Waste Terminal Storage (NWTS) Program. As such, BWIP is chartered with the responsibility of assessing the basalt beneath DOE's Hanford Site (Fig. 1-1) as a medium for the disposal of nuclear waste. Geologic and hydrologic studies performed by BWIP during the period from 1977 and 1979 are summarized in Myers, Price and others (1979) and Gephart and others (1979a), respectively. These studies served to determine that the central Hanford Site contains basalt flows with thick, dense interiors that have low porosities and permeabilities. Furthermore, within the Cold Creek syncline, these flows appear to be nearly flat lying across areas in excess of tens of square kilometers. Such flows within this area have been identified as potential repository host rock candidates. The Umtanum flow, which lies from 900 to 1,150 m beneath the surface, is currently considered the leading candidate.

For a discussion of the geology of the entire Pasco Basin and the approach used to study this area, the reader is referred to Myers, Price and others (1979); the interpretations to be discussed herein should be considered an update and expansion of those contained in that earlier report. The specific purpose of the present report is to review current knowledge of stratigraphic, lithologic, and structural factors that directly relate to the suitability of the Umtanum flow within the Cold Creek syncline for siting a repository. As such, Chapters 2 through 5 contain discussions of the stratigraphic setting of the Cold Creek syncline and lithologic properties of the Umtanum flow. The remaining three chapters (6, 7, and 8) contain discussions which relate to the bedrock structure of the study area. Borehole and geophysical data pertinent to these discussions are contained in the five appendices. The concluding sections of this chapter are devoted to brief summaries of the geologic setting of the Cold Creek syncline and status of the repository-siting effort. Results included in this document comprise baseline data which will be utilized to prepare the initial Site Characterization Report (NRC, 1981a and b).

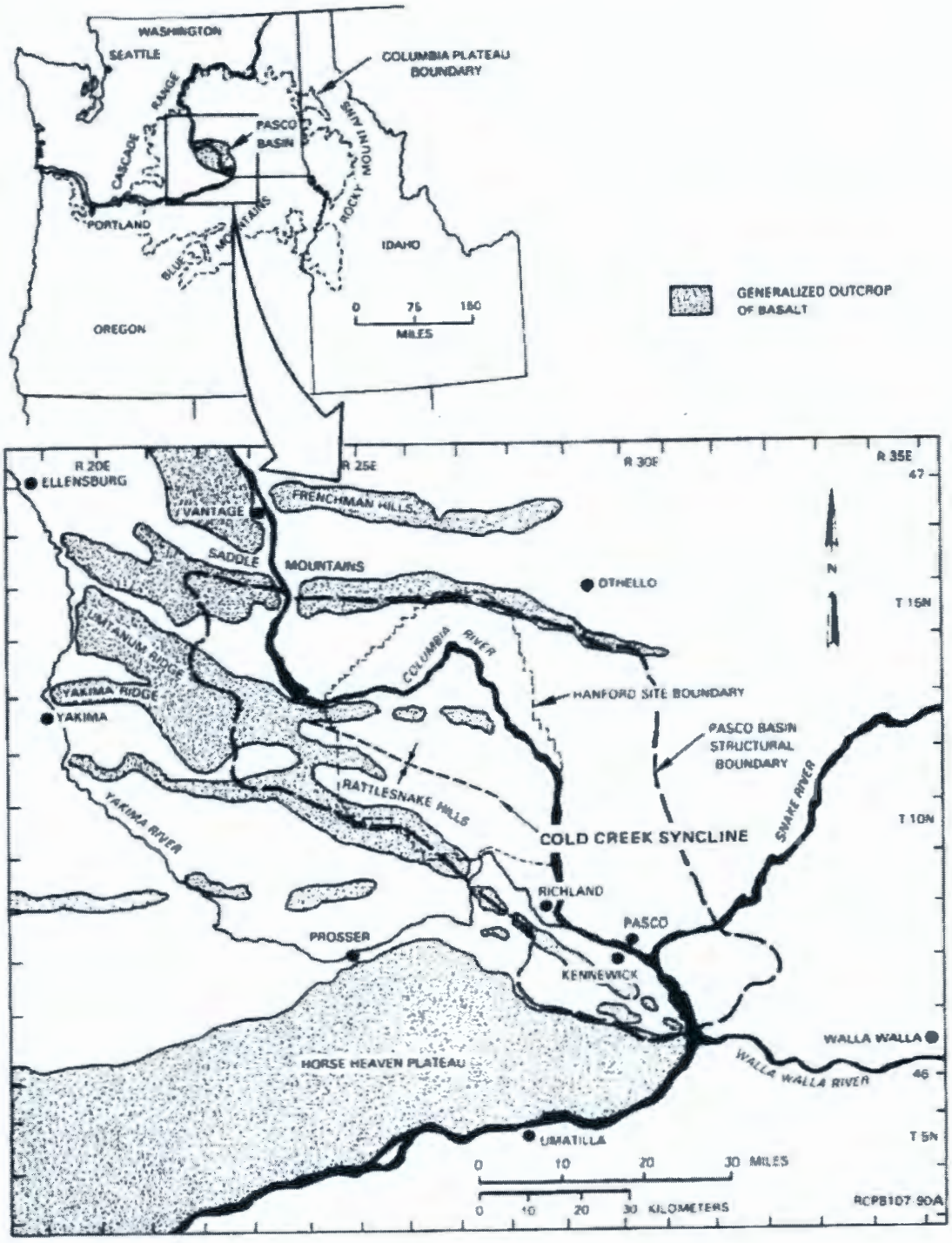

FIGURE 1-1. Location Map, Columbia Plateau, Pasco Basin, Hanford Site.

GENERAL GEOLOGIC SETTING

The Cold Creek syncline is a subdivision of the Pasco Basin, one of several structural and topographic basins within the western Columbia Plateau (Fig. 1-1). The plateau is primarily underlain by a Miocene volcanic sequence termed the Columbia River Basalt Group (Fig. 1-2). Lava flows of this group were erupted from linear vent systems, remnants of which are exposed as dikes primarily in the eastern and southeastern Columbia Plateau (Taubeneck, 1970; Price, 1977). Because of their high fluidity and large volume, the lavas spread considerable distances from their source fissures. In so doing, they covered vast areas, inundated older rocks and structures within the plateau interior, and onlapped highlands around the plateau margin. The thickest flows generally record ponding in pre-basalt valleys, in structurally controlled basins that developed during volcanism, or in narrow canyons previously eroded in older flows, termed intracanyon flows.

The bulk of the Columbia River Basalt Group is comprised of flows which belong to the Yakima Basalt Subgroup (Fig. 1-2). The oldest formation of this subgroup, the Grande Ronde Basalt, was erupted between 16.5 and 14.5 million years before present (mybp). The Grande Ronde Basalt is the most voluminous unit of the group (~85 vol%) and underlies most of the Columbia Plateau. Grande Ronde Basalt is overlain by Wanapum Basalt. This unit is the secondmost voluminous formation of the group (~5 vol%) and was erupted between 14.5 and 13.5 mybp. The Saddle Mountains Basalt is the youngest formation of this subgroup, comprises <1 vol% of the group, and was erupted during a period of waning volcanism, 13.5 to 6 mybp (Swanson and others, 1979b).

Flows of the Columbia River Basalt Group are interbedded with and overlain 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. The youngest suprabasalt sedimentary units on the plateau are fluvial, lacustrine, glaciofluvial, and eolian deposits of Pliocene to Holocene age. Much of the plateau surface is dominated by erosional features and sedimentary deposits attributable to Pleistocene catastrophic floods. These floods resulted from the periodic breakup of ice dams impounding glacial lakes along the northern and northeastern margins of the plateau.

In general, the Columbia Plateau can be subdivided into three informal structural subprovinces: (1) Yakima Fold Belt subprovince, (2) Palouse subprovince, and (3) Blue Mountains subprovince (Fig. 1-3). The Yakima Fold Belt subprovince is characterized by east-west-trending, asymmetrical, anticlinal ridges and intervening synclinal valleys. The formation of these folds began as early as late Grande Ronde time. The Palouse subprovince is underlain by basalt flows with a regional dip of <5° to the southwest. The dip is a reflection of regional westward tilting which occurred throughout most of the period of basalt extrusion. The Blue Mountains subprovince is essentially a broad, northeast-trending, anticlinal arch.

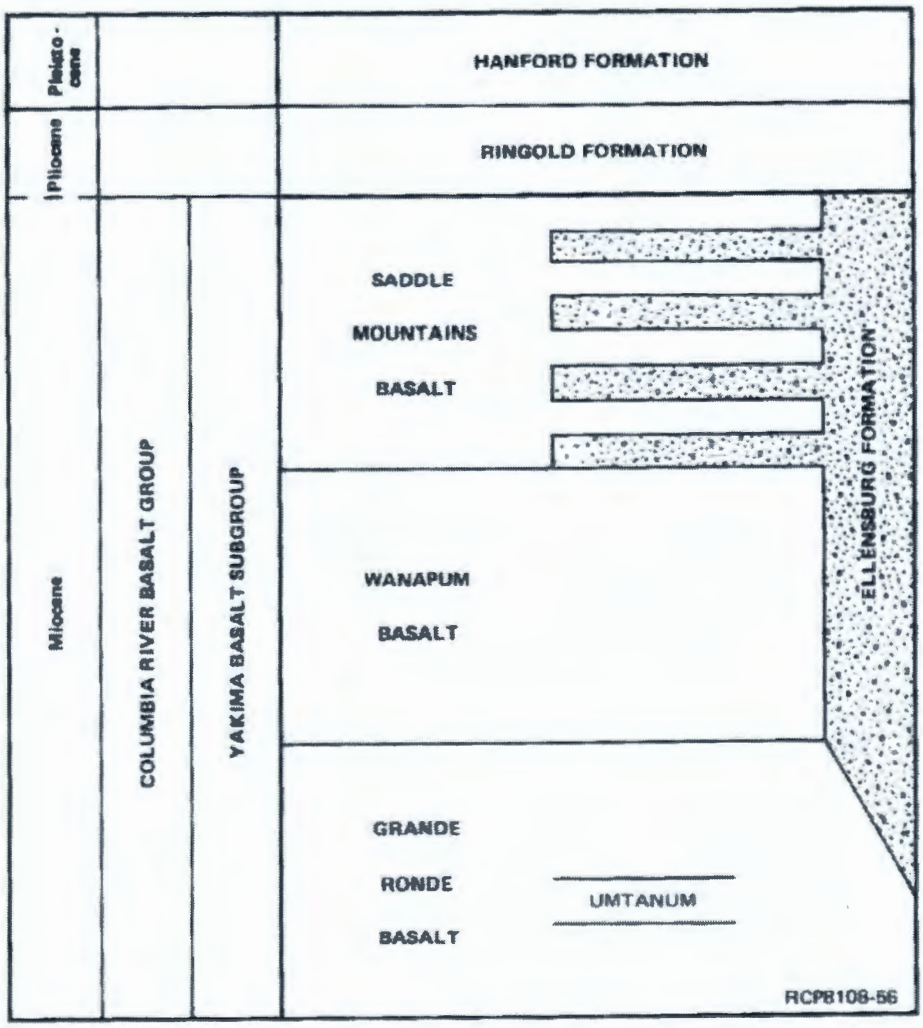

FIGURE 1-2. Stratigraphy of the Columbia River Basalt Group, Yakima Basalt Subgroup, and Intercalated and Suprabasalt Sediments within the Pasco Basin.

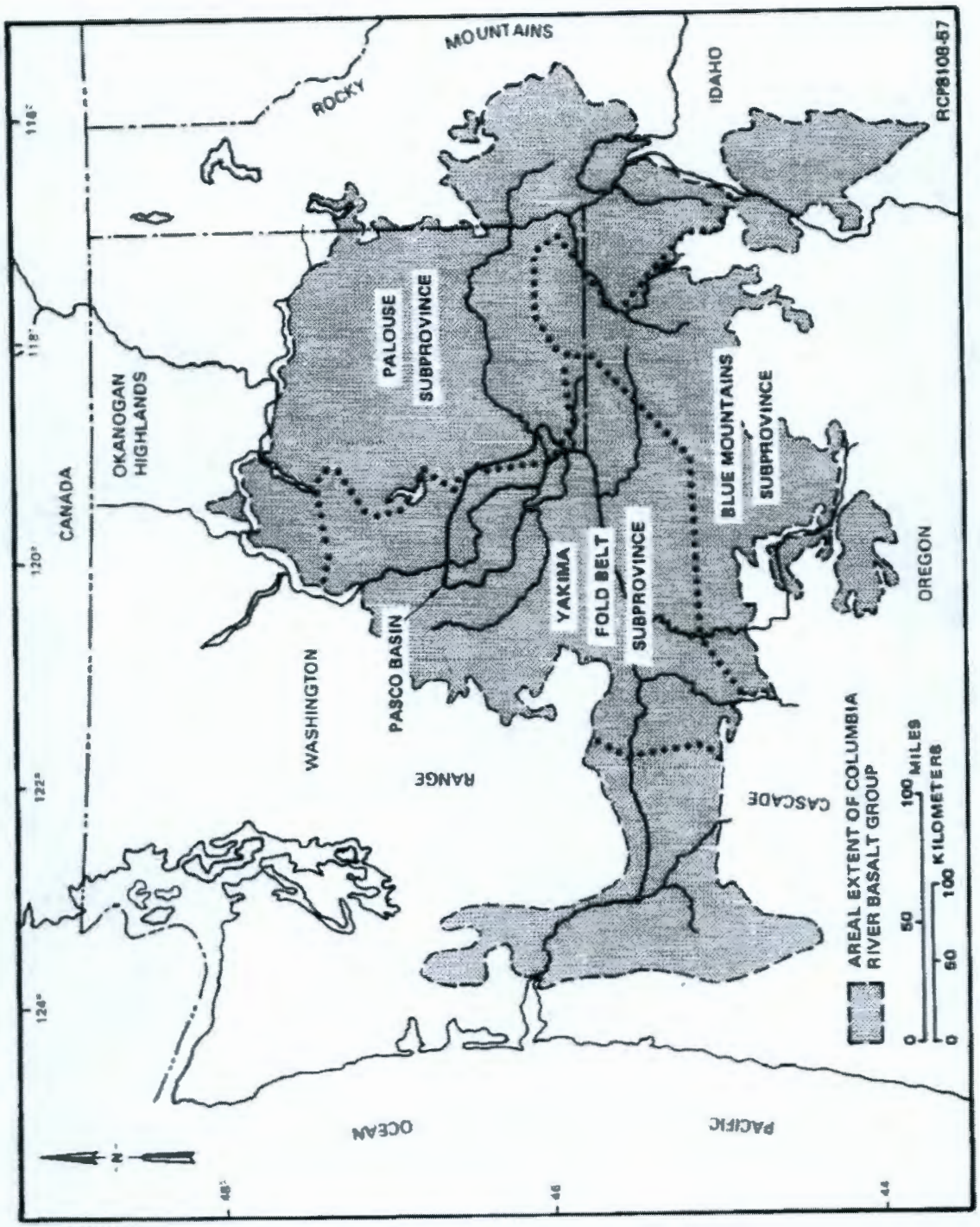

FIGURE 1-3. Informal Structural Subprovinces of the Columbia Plateau.

The Pasco Basin spans the area of transition between the Yakima Fold Belt subprovince and the Palouse subprovince. Yakima folds bound the basin on the north and south and plunge eastward into the basin from the west (Fig. 1-4). Most of the 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. 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; however, a few subsurface structures might be related to northwest-trending structures that appear to crosscut the east-west-trending Yakima folds.

Synclines between the anticlines are generally broad, open folds that are sediment filled. Major synclines within the Pasco Basin include the Wahluke and Cold Creek synclines. The Wahluke syncline lies between the Saddle Mountains and Umtanum Ridge-Gable Mountain anticlinal structures (Fig. 1-4). The Cold Creek syncline is the relatively low-relief, sediment-filled trough which is bounded by the Umtanum Ridge-Gable Mountain anticlinal structure and the Yakima Ridge and Rattlesnake Mountain anticlinal structures (Fig. 1-4).

The Cold Creek syncline is asymmetrical, with a steeper southern limb and a troughline much nearer the Yakima Ridge structure than the Umtanum Ridge-Gable Mountain structure. The eastern portion of the northern limb has been deformed into a series of northwest-trending folds. The "interior" of the syncline is a broad, open, undulatory structure with two minor depressions.

The bedrock of the Cold Creek syncline is comprised of flows belonging to all three formations of the Yakima Basalt Subgroup. Grande Ronde Basalt in the syncline consists of >2,500 m of basalt, including at least 50 flows. These flows have an average thickness of 34 m and range in thickness from 4 to 150 m. The basalt flows of this formation, which include the Umtanum (Fig. 1-2), are currently considered the most likely candidates for a repository host rock.

The Wanapum and Saddle Mountains Basalts within the Cold Creek syncline are comprised of up to 20 flows with a maximum thickness of ∿700 m. The basalt section is interbedded with sediments of the Ellensburg Formation (Fig. 1-2) and is overlain by up to 220 m of the fluvial-lacustrine, Miocene-Pliocene Ringold Formation and catastrophic flood deposits of the Pleistocene Hanford formation. Holocene eolian deposits of loess and dune sand mantle much of the syncline.

A preliminary assessment of the timing and rate of deformation of the Pasco Basin has been made using available geologic, geodetic, and seismologic data (Reidel and others, 1980; Caggiano and others, 1980). The thickness and distribution of flows indicate that basalt deformation began over 14 million years ago and progressed at a slow rate (<1 mm/yr). Decreasing dip with decreasing age of Pliocene sediments overlying basalt supports the proposed rate. Deformation, once localized, has apparently

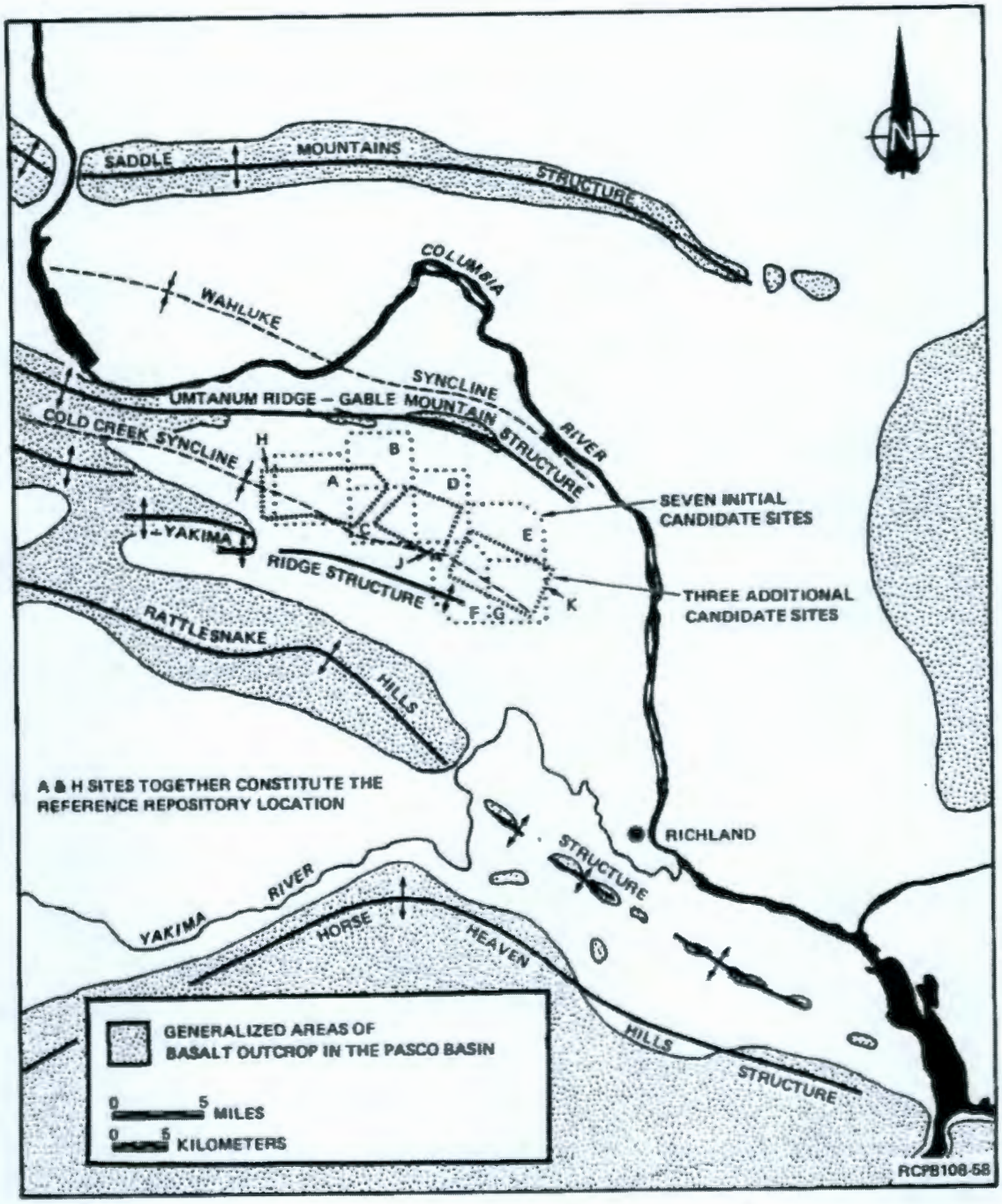

FIGURE 1-4. Location of Candidate Sites in the Cold Creek Syncline.

continued along the same trends and zones of weakness developed in the Miocene, as suggested by horizonal to sub-horizontal attitudes of Pliocene sediments in basins between anticlinal ridges. Historical seismicity indicates that moderate-sized earthquakes (<magnitude 6) are infrequent and separated by periods of relatively low-level, diffuse, stress release. Instrumental records of earthquakes reveal no concentrated stress release along mapped geologic structures or along planar zones. Focal mechanism solutions indicate rupture occurs on steeply dipping planes of varying orientation in volumetrically restricted zones in basalt (i.e., earthquake swarms) and in broad zones below basalt under nearly horizonal, north-south compression. Measurements of strain with trilateration arrays in the Pasco Basin indicate strain of <1 mm/yr. Available data currently support a model of slow, ongoing deformation.

SELECTION OF A REFERENCE REPOSITORY LOCATION WITHIN THE COLD CREEK SYNCLINE

The nationwide NWTS siting process is a stepwise procedure involving several phases, beginning with site screening and ending with site selection (DOE, 1980). All NWTS work is currently in the site-screening phase. Generic site-qualification criteria developed by the Office of Nuclear Waste Isolation (ONWI, 1981) are being used by various components of the NWTS, including BWIP, to help in the screening and site-identification process. To date, the BWIP geologic studies have concentrated on factors that might influence groundwater transport of radionuclides from a candidate host rock, such as the Umtanum flow. These factors include: (1) intraflow structures (discontinuities) within the interiors of individual lava flows, (2) interflow zones and flow fronts between adjacent lava flows, and (3) existing bedrock structures.

In 1979, available geologic and hydrologic information (Myers, Price and others, 1979; Gephart and others, 1979a) was combined with existing information on socioeconomics, land use, and the environment to identify seven initial candidate sites in the Cold Creek syncline area for further investigation (Fig. 1-4) (BWIP Staff, 1980; Woodward-Clyde Consultants, in press). Geologic information obtained subsequent to that presented in Myers, Price and others (1979) was used to identify three additional candidate repository sites (H, J, and K; Fig. 1-4). All candidate sites were evaluated by a committee comprised of personnel from Rockwell and Woodward-Clyde Consultants. One candidate site, the combination of candidate sites A and H (Fig. 1-4), emerged as the highest ranked. This candidate site is currently referred to as the reference repository location (RRL).

Current BWIP plans are to formally recommend to DOE a site for detailed characterization in 1981. The RRL site remains the leading candidate at this time. Information contained in the remainder of this report provides the basis for further review of the geologic qualifications of the A-H site. Consequently, special emphasis has been given in this report to the western part of the Cold Creek syncline where the RRL is located.

CHAPTER 2 - SUPRABASALT SEDIMENTS OF THE COLD CREEK SYNCLINE AREA

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J. T. Lillie
K. R. Fecht

INTRODUCTION

This chapter describes the general stratigraphy of the sediments overlying the basalt bedrock in the Cold Creek syncline. Included is a brief discussion of their distribution, lithology, stratigraphy, and age relationships in the Pasco Basin and a more detailed discussion for the western Cold Creek syncline area across the RRL.

The study of these sediments is important to the identification and evaluation of candidate sites for a repository because: (1) Plio-Pleistocene geologic history of the Cold Creek syncline area is recorded in these sediments; (2) physical properties of these sediments, especially their lateral variations, affect the ability of seismic reflection surveys to resolve details of bedrock structure in the underlying basalt; (3) shafts constructed in the RRL will penetrate these sediments and require knowledge of their character; and (4) surface facilities constructed on or in these sediments will require information on their engineering properties.

The post-Columbia River Basalt Group sediments of the Cold Creek syncline are composed of two major units (Fig. 2-1): (1) Ringold Formation, a Miocene-Pliocene fluvial unit with some lacustrine facies; and (2) Pleistocene glaciofluvial sediments, informally termed the Hanford formation. Deposition of the Ringold Formation by ancestral streams flowing through the Pasco Basin started shortly after cessation of basalt flows. Talus and alluvium deposited on the flanks of basaltic ridges during Ringold time are also included in the Ringold Formation. The Hanford formation was deposited by catastrophic floodwaters which inundated the Pasco Basin when ice dams impounding glacial lakes failed in Montana, Idaho, northern Washington, and southern British Columbia. Minor units include the Pleistocene and Holocene talus, colluvium, alluvium, landslide debris and loess, and Holocene dune sand.

PREVIOUS WORK

Investigations of the sediments in the Cold Creek syncline area began during the 1940s during construction of the Hanford Site facilities in the 200 East and 200 West Areas and have continued since then with ongoing construction and groundwater-monitoring investigations (Newcomb and Strand, 1953; Brown, 1959; Newcomb and others, 1972; Liverman, 1975; Routson and Fecht, 1979; Tallman and others, 1979). Additional work was completed by

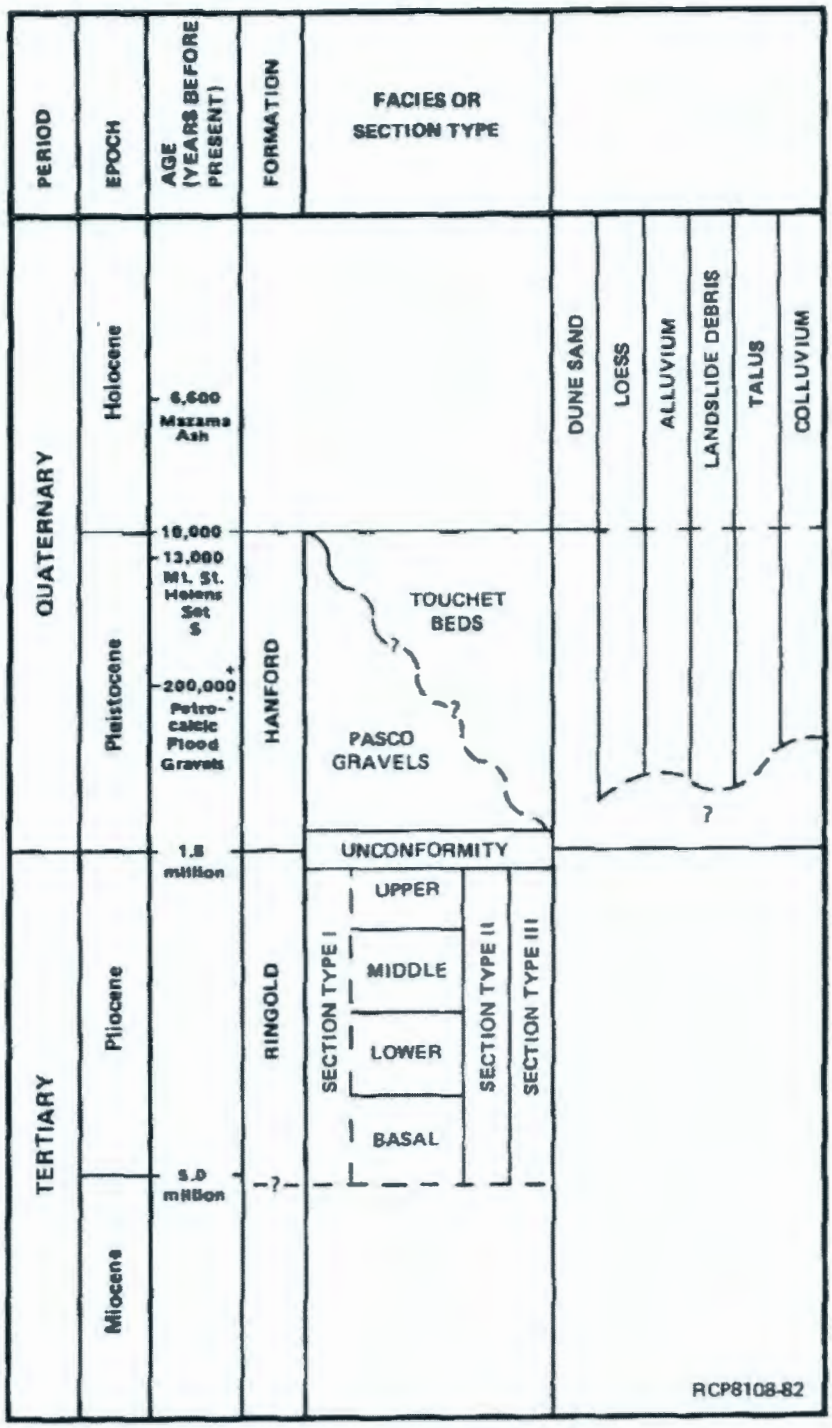

FIGURE 2-1. Sediment Stratigraphic Chart, Pasco Basin, Cold Creek Syncline.

Washington Public Power Supply System, Inc. (WPPSS, 1977, 1981) and recently by Northwest Energy Services Company. A summary of regional and Pasco Basin post-Columbia River basalt geology is presented in Myers, Price and others (1979).

METHODOLOGY

Reconnaissance field mapping (1:62,500) of sediments in the Cold Creek syncline was completed in 1978 (Lillie and others, 1978; Myers, Price and others, 1979) and more detailed field mapping (1:24,000) is currently being done by Rockwell.

Investigations of subsurface sediments in the Cold Creek syncline utilize primarily driller's logs and samples from boreholes. These boreholes were drilled using cable-tool, mud and air rotary, and diamond-coring drilling methods (Fecht and Lillie, in press; also see Appendix A). The quality of driller's logs and sediment samples is variable and is considered in the interpretations presented in this report. Granulometric analyses and calcium carbonate ($CaCO_3$) determinations were completed on sediments from selected boreholes to aid in delineation and correlation of major facies changes within the Hanford and Ringold Formations. Geophysical logs are available for some boreholes, and some areas are covered by geophysical surveys (see Appendix B).

Paleomagnetic analyses of sediments from the Ringold Formation were completed for exposures along the Columbia River and for three core holes on the Hanford Site (Woodward-Clyde Consultants, 1978; Packer and Johnston, 1979). These data are being used to delineate time-stratigraphic units and, in conjunction with fossils, can be used for dating and correlating the Ringold Formation.

GENERAL STRATIGRAPHIC SETTING

RINGOLD FORMATION

The Ringold Formation overlies the Columbia River Basalt Group within most of the Pasco Basin, except where: (1) basalt crops out, (2) glaciofluvial Hanford formation onlaps ridges above the margin of the Ringold Formation, and (3) it has been eroded and Hanford sediments were deposited directly on basalt.

The Ringold Formation within the Pasco Basin has been divided vertically into three textural facies, generally following the divisions of Newcomb (1958): (1) lower Ringold, the "blue clay" facies consisting of silt, clay, sand, and gravel extending upward from the basalt; (2) middle Ringold, conglomerate or gravel facies; and (3) upper Ringold, clay, silt, and sand, with some minor gravel lenses (Brown, 1959). Recent work (Routson and Fecht, 1979; Tallman and others, 1979; Myers, Price and

others, 1979; Brown, 1981) has distinguished a basal unit, the predominantly gravel facies in the bottom portion of lower Ringold, as described by Newcomb (1958) and Brown (1959).

The division of the Ringold Formation into a (1) basal, (2) lower, (3) middle, and (4) upper facies, based primarily on texture, is appropriate for much of the central Pasco Basin. On the edges of the basin, the character of the Ringold Formation differs because of derivation from local sources.

In general, three representative stratigraphic section types can be used to describe the lateral variations of the Ringold Formation in the Pasco Basin (Fig. 2-2). The central portion of the Cold Creek syncline and much of the central Pasco Basin are representative of section type I (the four facies listed above) and illustrated in DH-12 (Fig. 2-3). However, all four textural facies are not present throughout all the section type I area. Much of the upper Ringold is eroded and the lower Ringold pinches out on anticlinal ridges, and in some areas, the basal gravel unit is not present or cannot be distinguished from middle Ringold where the two are in contact. The lateral distribution is shown in Figure 2-2. A more detailed discussion of this section type is presented later in the discussion of the RRL stratigraphy.

Section type II of the Ringold Formation is found north and east of Gable Mountain (Fig. 2-2) and is composed predominantly of silt, sand, and clay as represented in DH-19 (Fig. 2-3). Minor gravel lenses are present, mostly north of Gable Mountain. Sediments of this section are interpreted as floodplain overbank deposits throughout Ringold time. Erosional unconformities and paleosols are present, but there is no evidence of high-energy, main-channel, sedimentation characteristics of the middle and basal Ringold facies in the central basin.

Section type III, the fanglomerate facies (Grolier, 1965), occurs on the flanks of anticlinal ridges and includes the talus, slope wash, and side stream facies which interfinger with the central basin deposits of section types I and II (Fig. 2-2 and 2-3). This facies of the Ringold Formation is composed chiefly of basalt clasts in a matrix of quartz and feldspar or basalt sand. Locally, some openwork, angular, basalt debris is present. It is generally compacted to cemented with silica and/or $CaCO_3$. The unit is the result of mass wastage and runoff on the emerging ridges during the deposition of the other Ringold section types in the lower elevations of the Pasco Basin.

Section types I and II were deposited by a major river system which flowed through the Pasco Basin. The middle Ringold gravel of section type I is present from Sentinel Gap to the west side of Gable Mountain and throughout the central Pasco Basin to Wallula Gap, except where it is locally eroded south of the city of Pasco (Fig. 2-2). The main channel meandered across the Pasco Basin, depositing the time-transgressive middle Ringold gravels and the associated finer grained sediments. Several fluvial cycles are recognized within section type I, but have not been correlated across the basin. The fine-grained sediments of section types I

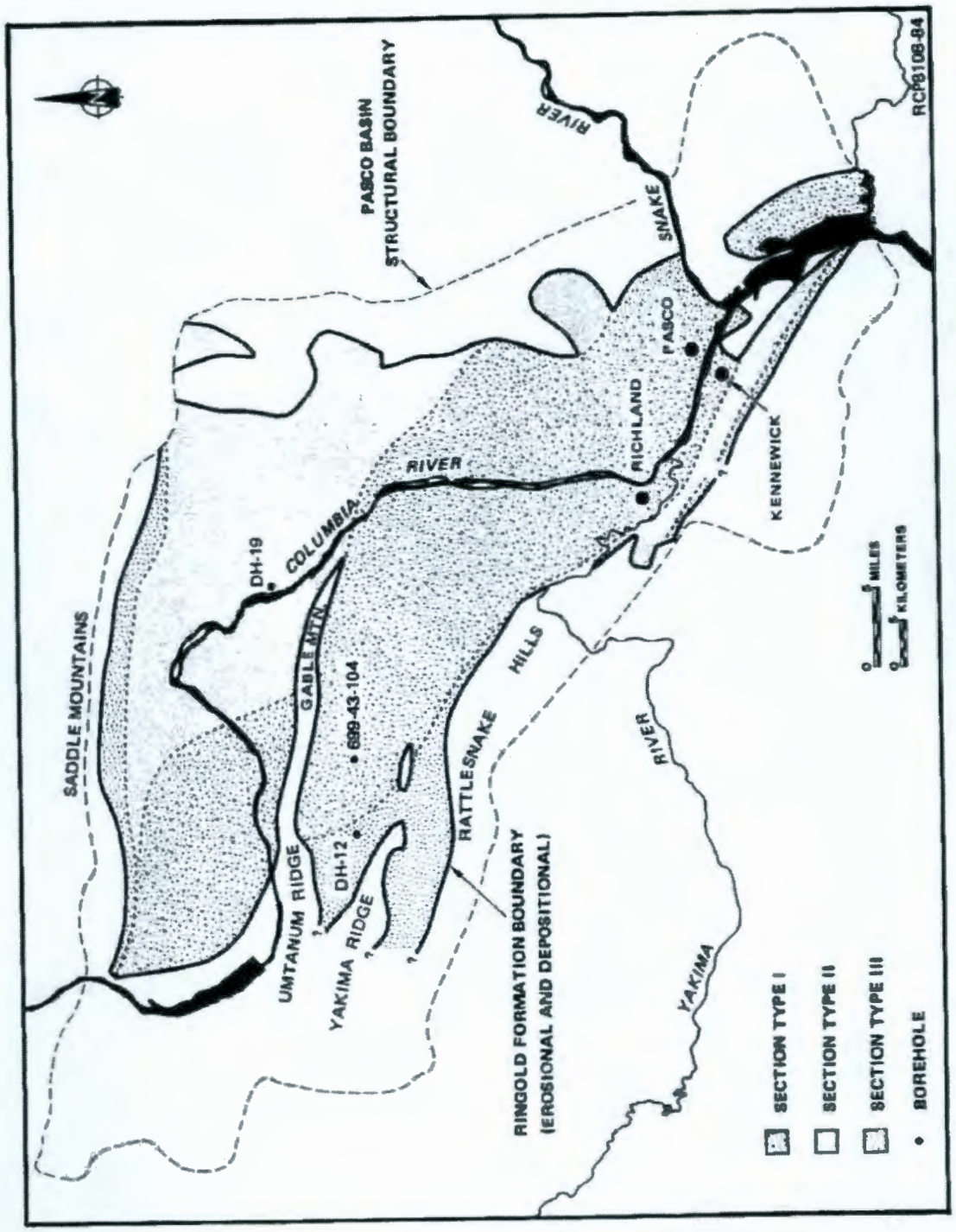

FIGURE 2-2. Distribution of Ringold Section Types.

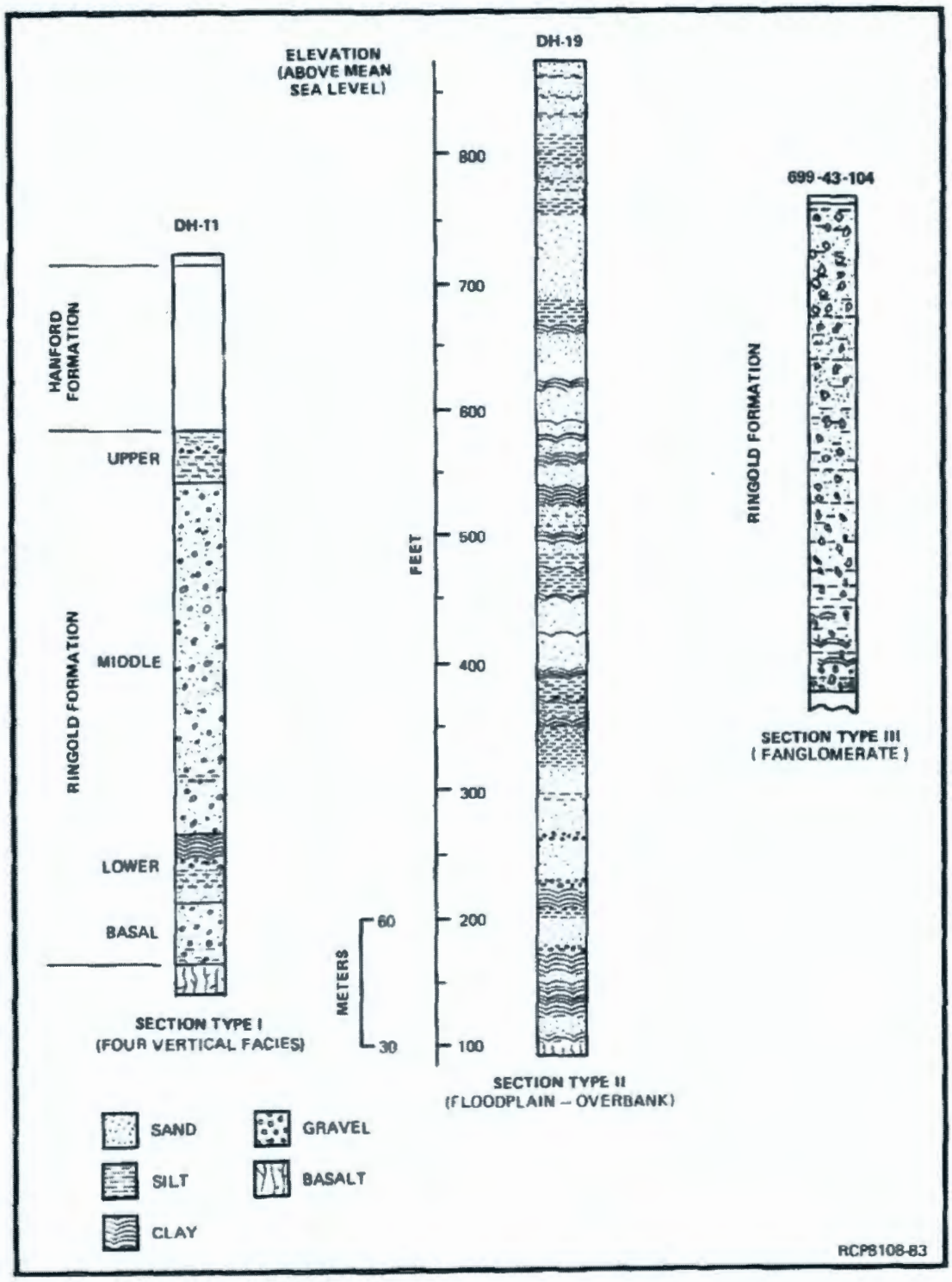

FIGURE 2-3. Ringold Section Types.

and II were deposited as lateral equivalents of the main-stream facies. After the deposition of the upper Ringold of section type I and before the deposition of the Hanford formation, there was a major period of fluvial incision and as much as 150 m of Ringold sediments were eroded across the central portion of the Pasco Basin. The nature of these missing sediments is not known, but the lateral equivalent, the upper Ringold of the White Bluffs, is a fine facies similar to the sand and silt of section type II. Erosional remnants of the upper Ringold are present in the west-central part of the basin. These fine-grained sediments are either the floodplain overbank equivalents of a now eroded channel deposit, or they represent a low-energy, fluvial-lacustrine environment throughout the basin for all of upper Ringold time.

HANFORD FORMATION

The Pasco Basin was inundated by multiple Pleistocene floods when ice dams failed along the glacier margin in northern Montana, Idaho, Washington, and southern British Columbia (Bretz, 1923, 1925; Baker, 1973). An estimated 2,000 km^3 of water from Glacial Lake Missoula surged across eastern Washington (Pardee, 1942), deeply scouring basalt and aggrading thick sequences of subfluvially deposited sediments. The floodwaters were diverted into numerous anastomosing channels which debouched into the Pasco Basin (Baker, 1973; Baker and Nummedal, 1978). Water was temporarily impounded behind the underfit water gap at Wallula, with the resultant temporary lake reaching an elevation of ∿365 m in the Pasco Basin.

The sediments deposited in the Pasco Basin during these flood events are informally referred to as the Hanford formation. The Hanford formation is divided into two textural facies: (1) Pasco Gravels (Brown, 1975) and (2) Touchet Beds (Flint, 1938). The Pasco Gravels (Fig. 2-4) range in texture from boulders to fine sand and represent varied energy environments during flooding. The Touchet Beds (Fig. 2-5) are made up of rhythmically bedded, fine-grained sediments deposited in low-energy, slackwater environments.

Floodwaters entered the Pasco Basin by three routes: (1) through Sentinel Gap, (2) across the northeastern flanks of the Pasco Basin in several well-developed coulees, and (3) down the Snake River (Fig. 2-6). The texture of the Hanford formation varies throughout the Pasco Basin. In general, the Pasco Gravels are coarsest immediately south of Sentinel Gap and south of the Gable Mountain-Gable Butte constriction, where coarse debris was deposited when the floodwaters spread out into the Pasco Basin and deposited a swath of gravels to Wallula Gap. Coarse gravels are also present in the southern Pasco Basin, where floodwaters entered the basin via the Snake River (Brown, 1981; Lindberg and Brown, 1981). The Touchet Beds are generally restricted to higher elevations on the flanks of ridges and up tributary valleys of the Pasco Basin away from the higher energy, main-channel flow.

The number of Pleistocene floods in eastern Washington and the Pasco Basin is not known. Stratigraphic evidence for as many as 12 floods is reported in the Spokane area by Stradling and others (1980). In work done

FIGURE 2-4. Pasco Gravels, Reference Repository Location.

FIGURE 2-5. Touchet Beds, Pasco Basin.

FIGURE 2-6. Floodwater Routes into the Pasco Basin.

for Rockwell, L. G. Hansen reported stratigraphic evidence for at least seven floods in the Columbia River Valley in the northwestern Columbia Plateau. The Touchet Beds in the Walla Walla Valley are interpreted to represent "about 40" individual floods (Waitt, 1980) based on the assumption that each major sedimentary cycle represents one flood. Bjornstad (1980) concluded that these cycles represented energy pulses in one major flood, but he did find evidence for at least two separate floods. Within the Pasco Basin, multiple, graded sequences of Pasco Gravels and Touchet Beds have been observed in boreholes and outcrop. Whether each sequence represents an individual flood or merely changes in the environment during deposition is not known.

Locally, three sedimentary sequences identified in boreholes in the Pasco Basin (Brown, 1981) are interpreted to be three separate flood events. In an excavation in the south-central basin, three main sequences of Hanford sediment are interpreted to represent multiple flood events in the late Pleistocene (Wisconsinan, ~80,000 to 10,000 yr before present). Older gravels in Badger Coulee contain a petrocalcic horizon and are interpreted as pre-Wisconsinan flood sediments. More detailed analysis of borehole samples and exposures is needed to refine the flood history of the Pasco Basin.

Clastic dikes (Fig. 2-7) commonly occur in the Touchet Beds and Pasco Gravels. They are also found in the Ringold and Ellensburg Formations and in basalt. The dikes are generally vertical- to irregular-dipping fissure fillings in the host sediments that are filled with clay-to-gravel sediments. The mechanism for the formation of the clastic dikes is not known, but they have been interpreted not to be related to permafrost, desiccation, or seismic activity (Black, 1979). Most dikes observed appear to be filled from above and display intricate fluvial bedding with evidence for multiple, filling events. The mechanism for opening of the fissure may be related to loading and dewatering during Pleistocene catastrophic flooding (Black, 1979; Baker 1973).

SURFICIAL DEPOSITS

Relatively minor amounts of alluvium, dune sand, loess, talus, colluvium, and landslide debris occur in the Pasco Basin. Most of these deposits are Holocene, but some may be as old as the Pleistocene (Lillie and others, 1978; Myers, Price and others, 1979).

Alluvium occurs in the floodplains of the Yakima and Columbia Rivers and in the Cold Creek and Dry Creek Valleys. Alluvium below the elevation of major Pleistocene catastrophic flooding is Holocene, but ranges from Pleistocene to present above flood level. Some Pleistocene alluvium may be overlain by the Hanford formation.

Dune sand is present throughout much of the Pasco Basin and consists of medium- to fine-grained sand with minor amounts of silt. Active dunes are present in the central Pasco Basin and to the north and east along the

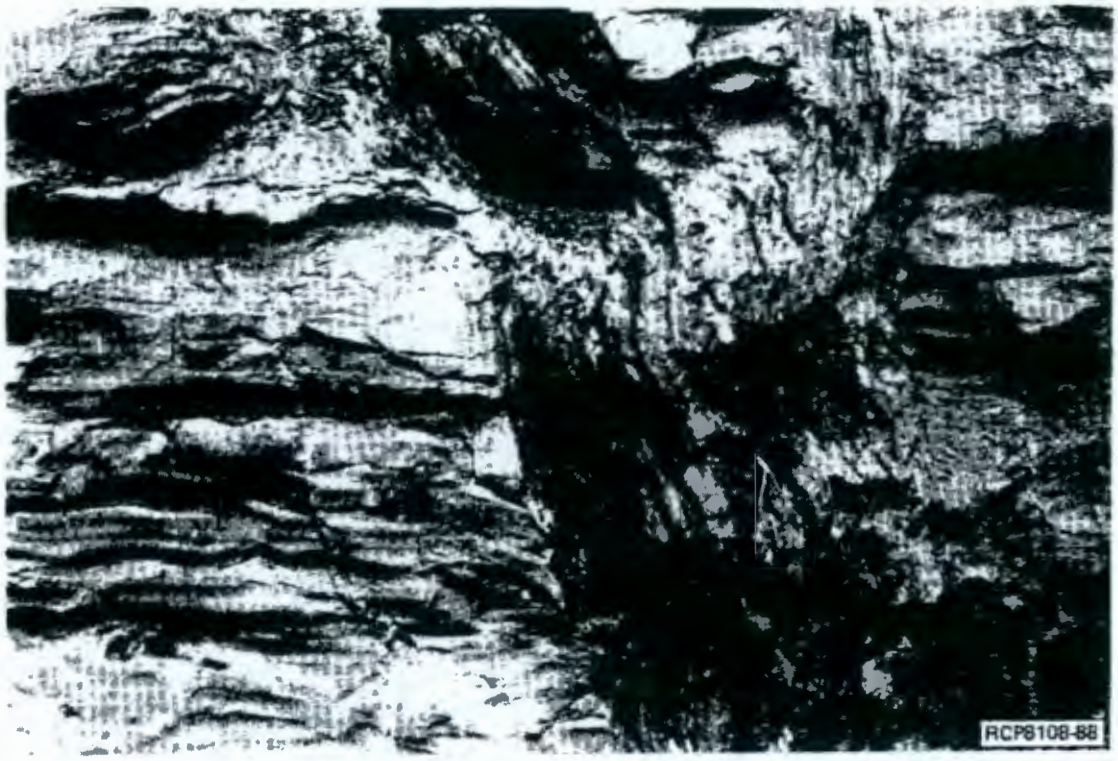

FIGURE 2-7. Clastic Dike in Touchet Beds, Pasco Basin.

Columbia River. Stabilized, longitudinal dunes occur in the south-central portion of the Pasco Basin. Dune sand is chiefly reworked Hanford sediments.

Talus and colluvium are present on ridge flanks. These deposits are primarily Holocene, but are in part Pleistocene at elevations above flood level. Basalt landslide debris is present along anticlinal ridges. Large, partly eroded landslides and landslide complexes are probably Pleistocene or older. Landslides in the Ringold Formation along the White Bluffs are predominantly Holocene; however, some large landslide complexes are overlain by the Pleistocene Hanford formation. Active landsliding on the White Bluffs chiefly is related to increased irrigation on top of the White Bluffs as well as undercutting by the Columbia River.

STRATIGRAPHY OF THE REFERENCE REPOSITORY LOCATION

The Ringold and Hanford formations overlie the Columbia River Basalt Group in the RRL area (Fig. 2-8 and 2-9). Dune sand veneers the Hanford formation in parts of the area.

RINGOLD FORMATION

The Ringold Formation within the RRL is composed of the basal, lower, middle, and upper units (section type I), with some interfingering of the fanglomerate and side-stream facies (section type III) in the western part of the area (Fig. 2-2 and 2-3).

Basal Ringold

The basal Ringold unit overlies the Elephant Mountain Member of the Saddle Mountains Basalt in the RRL and is chiefly a silty, sandy gravel to a gravelly sand that varies in thickness from 0 to >45 m (Fig. 2-8 and 2-9). The bedding structure is not known from available borehole data. Clasts are predominantly basalt, but include quartzite, granitic rocks, metamorphic rocks, and other lithologies from outside the Pasco Basin. The sand fraction is primarily quartz and feldspar. The exotic lithologies indicate a through drainage in the Pasco Basin during deposition of the basal Ringold. The dominance of basalt reflects the influence of the side-stream and fanglomerate debris of section type III and proximity to basalt highs. The unit is commonly well cemented with silica and/or calcite. It is generally thicker in the deepest part of the Cold Creek syncline in the RRL area and is folded with the basalt, suggesting that this unit was deposited during deformation of the Cold Creek syncline (Fig. 2-10). Previous work on the northern flank of the Cold Creek syncline suggested that the unit was generally the same thickness throughout (Routson and Fecht, 1979; Tallman and others, 1979) and that most deformation occurred after deposition.

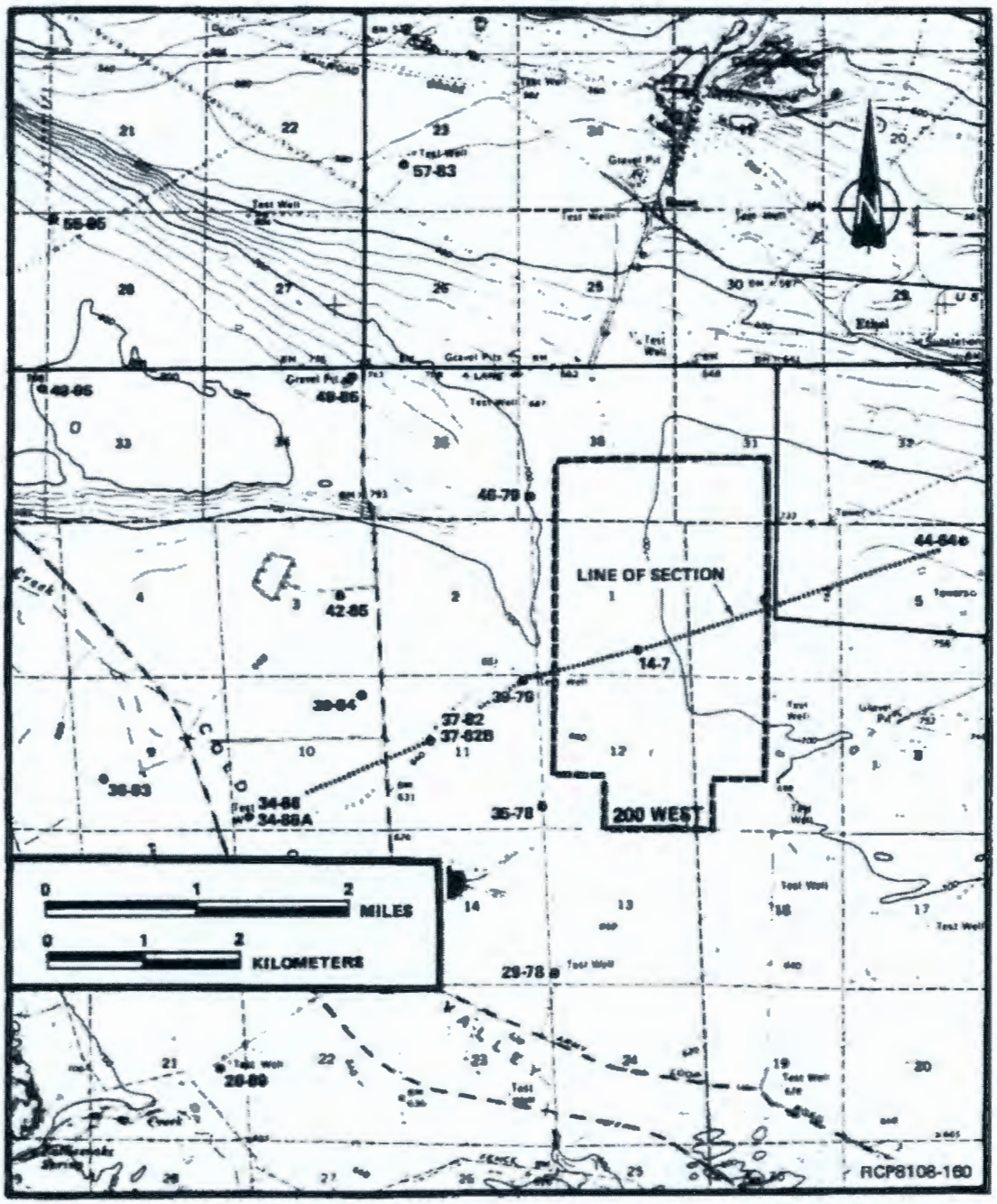

FIGURE 2-8. Index to Location of Fence Diagram Wells and Cross Sections.

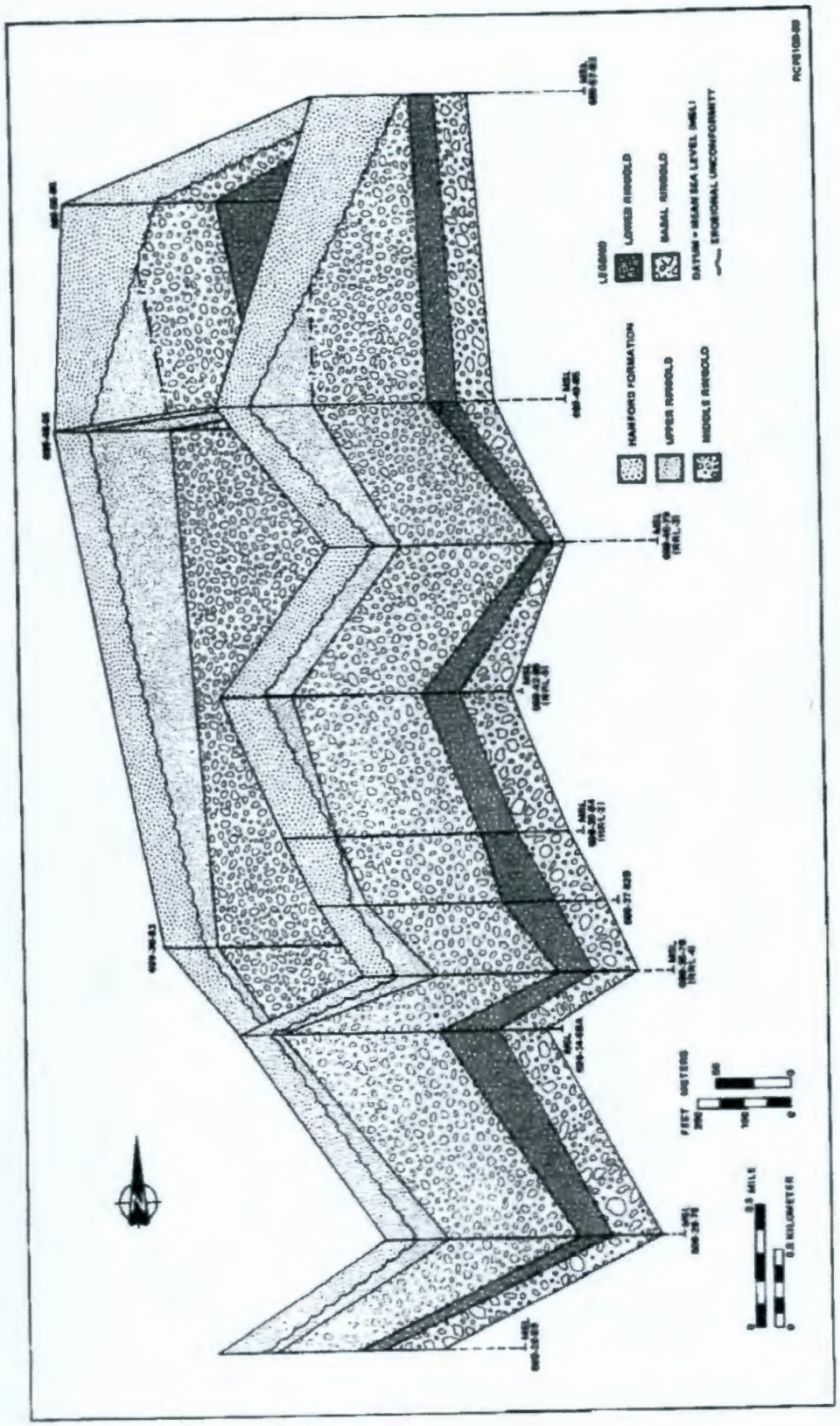

FIGURE 2-9. Fence Diagram, Reference Repository Location.

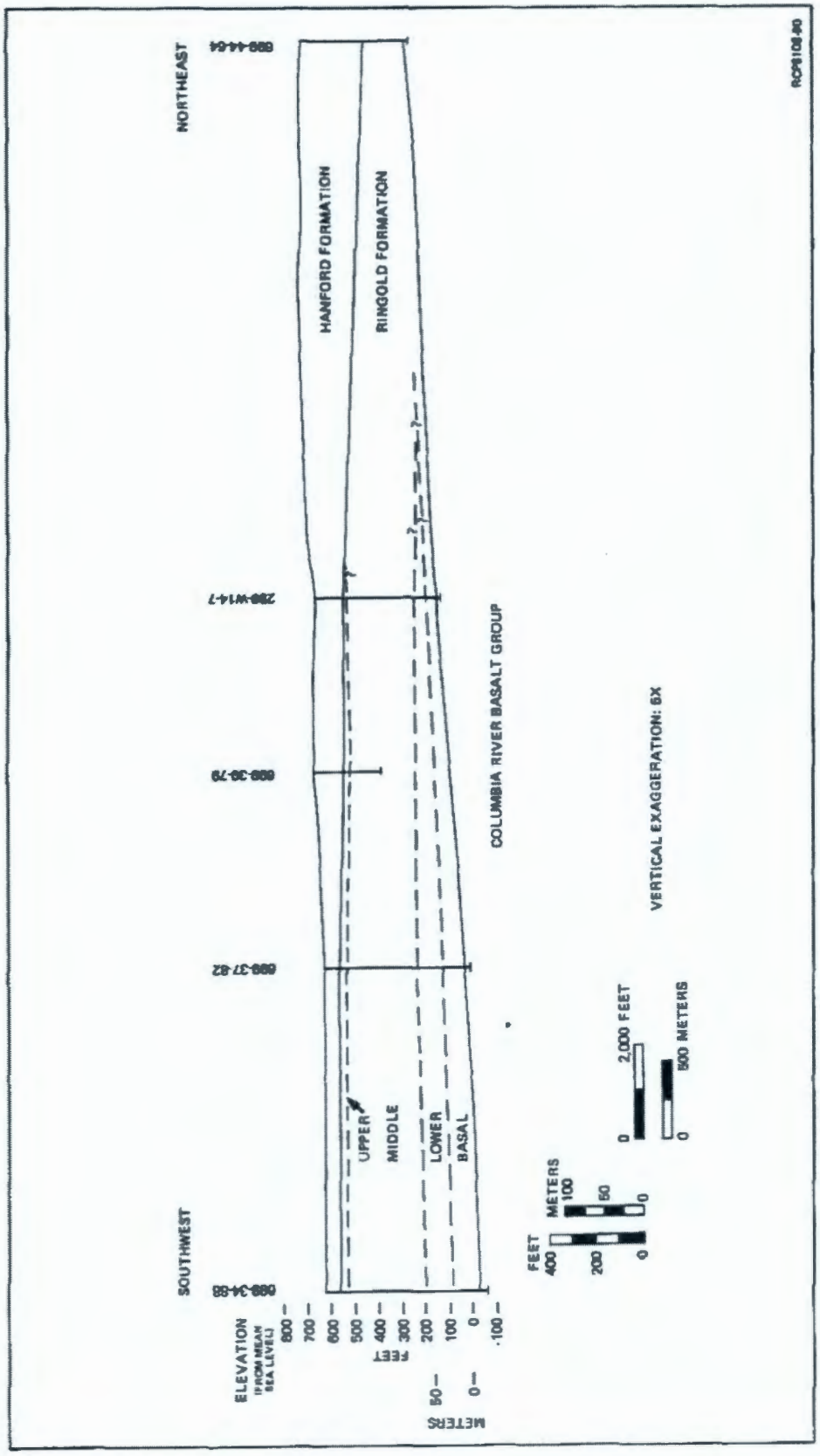

FIGURE 2-10. Structure Cross Section, Reference Repository Location.

The nature of the contact between the basal Ringold and the basalt is not fully understood, but it is assumed that regional drainage was the dominant influence on sediment deposition in the Pasco Basin very soon after the deposition of the last basalt flow (Ice Harbor Member) in the southern Pasco Basin. In the RRL, the Ringold overlies the Elephant Mountain Member, but the sediments differ from the tuffaceous Levey interbed between the Ice Harbor and Elephant Mountain Members in the southern part of the Pasco Basin (Chapter 3). It is, therefore, assumed that most deposition of the highly basaltic Ringold gravels occurred after deposition of the Ice Harbor Member. Upon continued deformation, the main channels were confined primarily to synclinal areas with local slope wash off the synclinal limbs. The unit includes gravel deposited in high-energy, main-channel environments and associated fine sediments from floodplain and local lacustrine environments.

Lower Ringold

A sand, silt, and clay facies with some gravel stringers overlies the basal Ringold gravels throughout the RRL area (Fig. 2-8 and 2-9). This represents a low-energy, fluvial unit with some lacustrine facies; the unit varies in thickness from 5 to 35 m. The unit is thickest in the deepest parts of the syncline, generally thins updip, and pinches out on anticlinal ridges (Fig. 2-10). Fining, upward, sedimentary cycles are observed in grab samples from wells, but the low well density precludes correlating these cycles between wells. In core, the silt-clay fraction is finely laminated to massive (Fig. 2-11).

The sand and silt are composed of quartz, feldspar, and mica with lithic fragments of Columbia River basalt and rocks from outside the Pasco Basin. The sediments are generally compacted with variable induration.

The thinning of the lower Ringold unit on the flanks of the Cold Creek syncline indicates that the unit was deposited during or after deformation of the Cold Creek syncline (Fig. 2-10). During lower Ringold time, the RRL area, as well as most of the Cold Creek syncline, was a region of low-energy deposition. Floodplain deposits are dominant, with some relatively thick sequences of lacustrine deposits. Minor gravel horizons indicate that there was periodic, minor, channel deposition throughout the region. The contact between the basal and lower units is generally gradational, indicating a general decrease in fluvial energy. It is not known whether this low-energy environment is representative of the entire Pasco Basin, with subsequent erosion of the lower Ringold sediments on the anticlinal highs, or is only present in the synclinal areas with coeval, major, channel deposition outside major synclinal areas.

Middle Ringold

The middle gravel facies overlies the lower Ringold and is present throughout the RRL (Fig. 2-9 and 2-10). It consists of pebble-to-cobble gravel with a matrix of sand, silt, and some clay. The unit is up to

FIGURE 2-11. Lower Ringold Sediments, Borehole DH-19.

100 m thick in the RRL and contains horizons of sand and silt. The gravel is composed of basalt and quartzite with metamorphic, granitic, and porphyritic-volcanic rocks. The sand fraction is predominantly quartz and feldspar, with mica and basalt commonly a significant constituent. The silt and clay fraction is quartz, feldspar, and smectite. The conglomerate observed in cores from the 200 West Area and exposed at the White Bluffs, 30 km east of the RRL, has a massive appearance with minor imbrication of clasts. Cross bedding is common in the sand lenses from cores and at the White Bluffs exposure (Fig. 2-12).

Induration varies from essentially no cementation to well cemented by $CaCO_3$ and/or silica (SiO_2). Much of the well-indurated conglomerate facies is matrix supported (Fig. 2-13).

Openwork, uncemented gravel is occasionally found in core. Limited data within the RRL do not reveal deformation of the middle Ringold (Fig. 2-10), but a general, arcuate, concave, upward contact with the upper Ringold throughout much of the Cold Creek syncline suggests there has been some deformation of the middle Ringold. The variations in thickness are generally related to channels of middle Ringold into the lower Ringold and erosion of the middle Ringold by post-Ringold fluvial activity, primarily Pleistocene flood channels.

The contact with the lower Ringold is generally sharp, indicating an abrupt change in fluvial energy environment. The conglomerate was deposited in a high-energy environment and the particle roundness and exotic lithologies suggest transport over considerable distance. The Ringold Formation has long been considered to be of Columbia River drainage origin (Merriam and Buwalda, 1917). The presence of modern Snake River lithologies indicates an influence of the present Snake River drainage (Tallman and others, 1979; Brown, 1981). Recent studies indicate that lithologies of the modern Clearwater and Salmon River drainages are present in the middle Ringold in the southeastern Pasco Basin (Richman, 1981; Webster and others, in press). This facies is interpreted as main-channel deposition, undoubtedly recording multiple erosional unconformities and sedimentary cycles.

Upper Ringold

The upper Ringold unit is present in parts of the RRL as an erosional remnant overlying the conglomerate facies (Fig. 2-9 and 2-10). The unit is composed of well-sorted sand and silt with minor amounts of clay. Thin horizons of pebble gravel are common. The sand and silt fraction is primarily quartz and feldspar, with locally large amounts of mica and basalt. Quartz, smectite, and mica make up the clay fraction. Caliche horizons are common and usually are present on the upper erosional surface where the unit is moderately to well cemented. The unit generally appears to grade from the silty-sandy-gravel of the middle Ringold facies. The upper surface is erosional throughout the RRL (Fig. 2-9).

FIGURE 2-12. Cross-Bedded Sand Lens of Middle Ringold, White Bluffs.

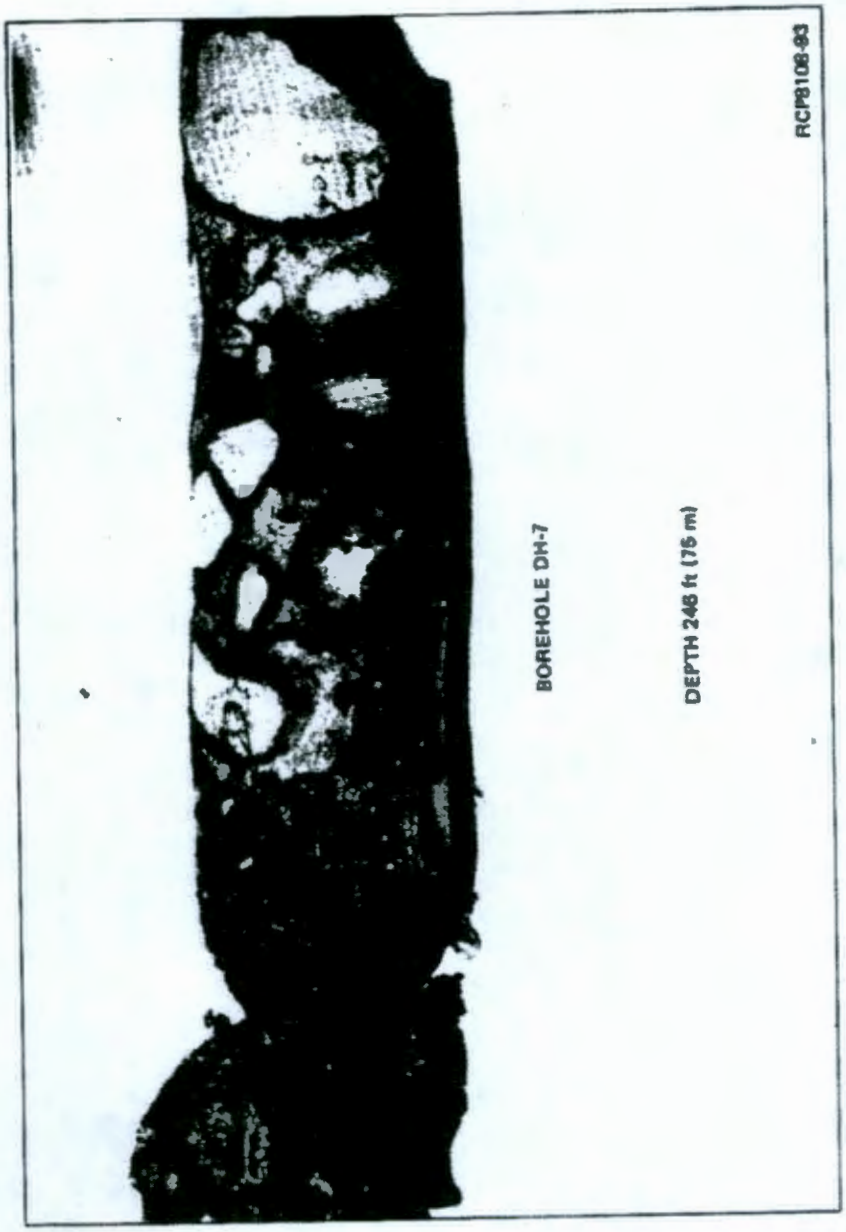

FIGURE 2-13. Matrix-Supported Clast of Middle Ringold, Borehole DH-7.

Core samples outside the RRL show alternating sand, silt, and clay horizons similar to those observed in the White Bluffs (Fig. 2-14). Only the lowermost part of the upper Ringold section found at the White Bluffs is present in the RRL. It represents a low-energy, fluvial environment with some lacustrine facies, probably a floodplain of a major fluvial system. Pebble gravels indicate small channels or perhaps extensive sheet-wash periodically inundated the area, and paleosols represent extended periods of subaerial exposure. Sediments interpreted to be loess overlie the fluvial sequence and are included in the upper Ringold unit.

Erosion removed an unknown amount of the upper Ringold in the RRL; that which remained was buried by the sediments of the Quaternary Hanford formation. The timing of loess deposition relative to the major erosion of the upper section of this unit is not known. If the major erosion of the upper Ringold occurred before the deposition of the loess, as suggested by the caliche horizon below the loess, the loess unit may be considerably younger than the underlying fluvial sediments. The extensive caliche horizon on most of the upper erosional surface of the upper Ringold unit, be it loess or fluvial sediments, suggests that the surface existed for some time prior to deposition of the glaciofluvial Hanford formation. It also suggests that very little erosion took place during Pleistocene flooding in this area of the Pasco Basin as it was generally protected in the lee of the Umtanum Ridge-Gable Mountain structure.

HANFORD FORMATION

The Hanford formation, chiefly the Pasco Gravels, overlies the Ringold Formation throughout the RRL (Fig. 2-9 and 2-10). The sediments are made up of gravel to sand and represent relatively high-energy, subfluvial deposition during Pleistocene flooding. A thin sequence of Touchet Beds is present at or near the surface mainly to the west of the RRL.

The surface of the subfluvial bars is commonly armored with a lag gravel, resulting from the winnowing of fine sediments during waning stages of flooding. This has been further accentuated by eolian deflation during the Holocene.

Clastic dikes occur within the RRL. The surface expression of these dikes is polygonal-patterned ground with polygons up to tens of meters across.

Bergmounds are very common up the Cold Creek Valley and on the flanks of Rattlesnake Mountain (Fecht and Tallman, 1978). These relatively unique landforms resulted from the grounding of large, glacial icebergs on the surface of the Hanford formation, thus protecting the underlying sediments from erosion during draining of the floodwaters.

Pasco Gravels

The Pasco Gravels range from boulders to fine-grained sand and display varied bedforms (Routson and others, 1979). The best exposures of the

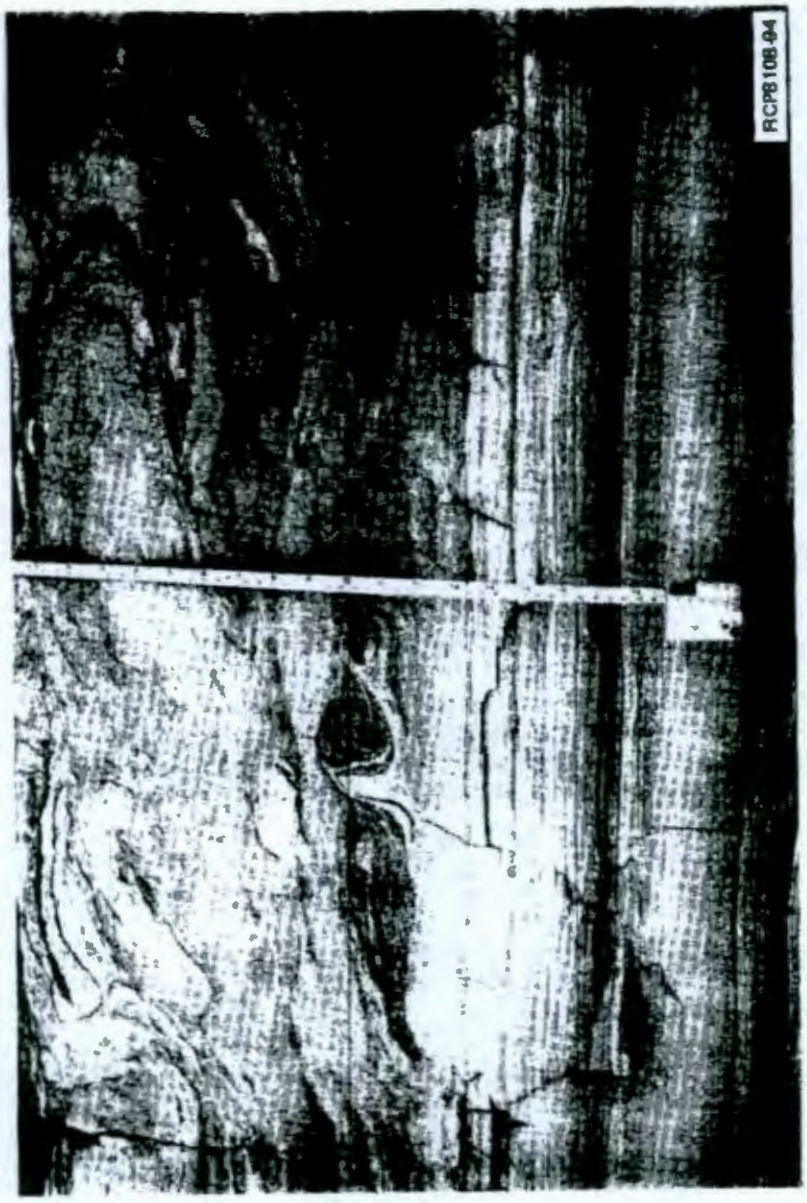

FIGURE 2-14. Laminated Upper Ringold Sediments, White Bluffs.

Pasco Gravels are in excavations for waste facilities east of the RRL. Massively bedded, horizontally bedded (often with fine laminations), cross-bedded, and graded-bed sequences have been observed in these excavations. Pasco Gravels are poorly exposed in the RRL, except for one, small, gravel pit in the northern part where the gravels are cross bedded (Fig. 2-4). Bedding present elsewhere in the Cold Creek syncline is assumed present in the RRL.

The gravel generally consists of <50% basalt, with some intrusive, igneous, metamorphic, and sedimentary rocks. Source areas for the non-basaltic rocks are the glaciated terrain to the north. Most of the sand is arkosic, with some horizons containing a relatively high basalt content. Mt. St. Helens Set S ash is locally present in the finer facies of the Pasco Gravels.

The Pasco Gravels are not generally indurated, but some horizons are moderately to well cemented with $CaCO_3$. These horizons are sometimes difficult to differentiate from the Ringold Formation in boreholes.

Two coarse- to fine-graded sequences are recognized in boreholes from the RRL. In areas where the Pasco Gravels form or fill channels in the Ringold Formation, as many as four, graded sequences are present. It is not known if these sequences represent separate floods or energy variations in the depositional environment during a single flood. Current interpretation honors two discrete floods and is based on borehole data, which include driller's logs (lithology, texture, and penetration rate), geophysical logs, and stratigraphic position relative to sediments known to represent multiple floods in the south-central Pasco Basin. Both graded sequences generally are composed of a relatively thin basal unit, consisting of poorly sorted silty-sandy-gravel with clasts ranging from pebbles to >30-cm boulders. This grades upward to a better sorted, silty-sandy, cobble-gravel unit overlain by sand and silt. The lower, graded sequence often has a calcic horizon on the upper surface, resulting in a slower drilling rate, and appears to be denser on geophysical logs.

Touchet Beds

The Touchet Beds are composed of rhythmically bedded silt to fine sand with stringers of coarse sand and gravel. A discrete horizon of Mt. St. Helens Set S ash is common.

Relatively minor, isolated exposures of Touchet Beds are present in the RRL. Touchet Beds in Cold and Dry Creek Valleys occur in generally protected areas distal to the main flood channel(s).

AGE RELATIONSHIPS

The age of the sediments overlying the Columbia River Basalt Group in the Pasco Basin is extremely important in the determination of deformation

rates. The Ringold and Hanford formations record deformation which may have taken place since the last basalt flow entered the Pasco Basin. To establish deformation rates, it is necessary to determine as precisely as possible the absolute age of the sediments. The methods used and results to date are discussed for both the Ringold and Hanford formations.

RINGOLD FORMATION

The Ringold Formation was assigned a Pliocene age by Gustafson (1973, 1978) based on vertebrate fossils. Caliche from the surface of the Ringold Formation at White Bluffs was dated using thorium/uranium methods at >500,000 yr before present, or beyond the limits of the method. Attempts to date Ringold ash horizons using fission-track methods have proved unsuccessful because of the lack of heavy minerals and large shards suitable for dating. The major emphasis in dating has been on the determination of the paleomagnetic stratigraphies and relating these to paleontologic data.

The upper Ringold at the White Bluffs contains microtine rodent fossils, 3.7 to 4.8 million years old (Repenning, in press). A Hemphillian (>4.8 million years old) rhinoceros was identified by Gustafson (1978) in the middle Ringold of the White Bluffs just above river level. This indicates that the predominantly reversed magnetic section of the White Bluffs (Packer and Johnston, 1979) represents the Gilbert Reversed Epoch, or 3.4 to 5.25 mybp.

The upper part of the Ringold Formation in the RRL is interpreted to be stratigraphically equivalent to the White Bluffs section. The erosional remnant of the upper Ringold in the RRL is, therefore, >3.7 million years and the middle Ringold is >4.8 million years. The underlying Elephant Mountain Member (10.5 million years) limits the maximum age of the Ringold Formation in the RRL. However, in the southern part of the Pasco Basin, the Ice Harbor Member (8.5 million years) and the Levey interbed are stratigraphically above the Elephant Mountain Member. Based on stratigraphic position, the basal Ringold in the Pasco Basin is interpreted to be post-Ice Harbor Member (8.5 million years) in age. Therefore, the Ringold Formation in the RRL is concluded to be >3.7 and <8.5 million years old.

HANFORD FORMATION

The number and age of Pleistocene floods that inundated the Pasco Basin is not known, but at least three events have been dated using ^{14}C and thorium/uranium methods and the Mt. St. Helens Set S ash horizon.

Pre-Wisconsinan Flood Deposits

Gravels cemented with $CaCO_3$ and assumed to be of Pleistocene flood origin are present in Badger Canyon. Three thorium/uranium age dates on the caliche from the petrocalcic horizons in these gravels yielded ages of

200,000 (+250,000 -70,000), 220,000 (+380,000 -70,000), and >210,000 yr (Tallman and others, 1978). These gravels may be correlative to flood gravels in the Cheney-Palouse channeled scabland tract north of the Pasco Basin (Patton and Baker, 1978; Baker and Nummedal, 1978). The Cheney-Palouse gravels are interpreted to be pre-Bull Lake in age (155,000 to 130,000 yr old) (Pierce and others, 1976). Gravels of this age range have not been identified in the RRL boreholes to date, but ∿8 km northwest of the RRL is an isolated outcrop of gravels which have similar field characteristics as the Badger Canyon gravels and may be correlative.

Wisconsinan Flood Deposits

The oldest ^{14}C date on the Hanford formation is in a normal-graded sequence containing clastic dikes located in the south-central part of the Pasco Basin. This sequence was eroded during a later flood that truncated the clastic dikes and deposited a later flood sequence. Wood fragments from the truncated clastic dike were dated at >32,000 radiocarbon years before present. The upper limit of the age is not known, but wood samples from flood gravels near Wanapum Dam were dated at 32,700 ± 900 radiocarbon years before present (Fryxell, 1965). These may represent the same flood.

The last major Pleistocene scabland flood occurred ∿13,000 yr ago, based on the occurrence of Mt. St. Helens Set S ash within the flood deposits and ^{14}C dates on organic sediments above and below Mt. St. Helens Set S ash near the source (Mullineaux and others, 1977). Mt. St. Helens Set S ash is present throughout the Pasco Basin, commonly occurring in the Touchet Beds, but also present in the Pasco Gravels. In Cold Creek and Dry Creek Valleys, Mt. St. Helens Set S ash is present in Touchet sediments under bergmounds (Fecht and Tallman, 1978).

Wood from a clastic dike in a flood bar southeast of Gable Mountain was dated at 18,705 (+1,515 -1,275) radiocarbon years. These sediments are stratigraphically related to the most recent, major, flood deposits and the current interpretation is that the wood was redeposited from older material. Another factor to support this conclusion is that evidence from radiocarbon dates in southern British Columbia indicate that the last major Wisconsinan advance in the northern United States began after 17,500 to 18,000 radiocarbon years before present (Clague and others, 1980). This makes an 18,705 (+1,515 -1,275) radiocarbon years flood in the Pasco Basin highly unlikely, if not impossible.

In summary, there are three, dated, flood sequences in the Pasco Basin: (1) a pre-Wisconsinan flood or floods with a well-developed calcic cement, (2) a Wisconsinan event >32,000 radiocarbon years before present, and (3) a late Wisconsinan flood(s) associated with Mt. St. Helens Set S ash ∿13,000 radiocarbon years before present (Fig. 2-1).

SUMMARY AND CONCLUSIONS

The post-Columbia River Basalt Group sediments of the Cold Creek syncline are composed of two major units: (1) Ringold Formation, a Miocene-Pliocene fluvial unit with some lacustrine facies; and (2) Pleistocene glaciofluvial sediments, informally termed the Hanford formation. Deposition of the Ringold Formation by ancestral streams flowing through the Pasco Basin started shortly after cessation of basalt flows. The Hanford formation was deposited by catastrophic floodwaters which inundated the Pasco Basin when glacial ice dams failed in Montana, Idaho, northern Washington, and southern British Columbia. Minor units include the Pleistocene and Holocene talus, colluvium, alluvium and loess, landslide debris, and Holocene dune sands.

The Ringold Formation overlies the Columbia River Basalt Group within most of the Pasco Basin. The division of the Ringold Formation into a basal, lower, middle, and upper facies, based primarily on texture, is appropriate for much of the central Pasco Basin. The predominant texture of each of these four facies is as follows: (1) basal--silty, sandy gravel to a gravelly sand; (2) lower--sand, silt, and clay; (3) middle--pebble-to-cobble gravel with a sand, silt, and clay matrix; and (4) upper--sand and silt.

In general, three representative stratigraphic sections can be used to describe the lateral variations of the Ringold Formation in the Pasco Basin. The central portion of the Cold Creek syncline and much of the central Pasco Basin are of representative section type I, the four vertical facies listed above. Section type II of the Ringold Formation north and east of Gable Mountain is composed predominantly of silt, sand, and clay. This section is interpreted to represent floodplain overbank sedimentation throughout Ringold time.

Section type III is the fanglomerate facies on the flanks of anticlinal ridges and includes the talus, slope wash, and side-stream facies which interfinger with the central basin deposits of section types I and II. This facies of the Ringold Formation is chiefly composed of basalt clasts with a matrix of quartz and feldspar or basalt sand. The unit is the result of mass wastage and runoff on the emerging ridges during the deposition of other Ringold section types in the lower elevations of the Pasco Basin. Section types I and II were deposited by a major river system which flowed through the Pasco Basin.

The sediments deposited in the Pasco Basin during catastrophic flood events are informally referred to as the Hanford formation. The Hanford formation is divided into two textural facies: (1) Pasco Gravels and (2) Touchet Beds. The Pasco Gravels range in texture from boulders to fine sand, representing varied energy environments during flooding. The Touchet Beds are made up of rhythmically bedded, fine-grained sediments deposited in low-energy, slackwater environments.

The number of Pleistocene floods in eastern Washington and the Pasco Basin is unknown. Within the Pasco Basin, multiple, graded sequences of Pasco Gravels and Touchet Beds have been observed in boreholes and outcrops. Whether each sequence represents an individual flood or merely changes in the energy environment during deposition is not known. Locally, three sedimentary sequences have been identified in the Pasco Basin boreholes and are interpreted to be three separate flood events.

The Ringold and Hanford formations record the deformation which has taken place since the last basalt flow entered the Pasco Basin. In order to establish deformation rates, it is necessary to determine, as precisely as possible, the absolute age of these sediments.

The major emphasis for age determination of the Ringold Formation has been on the determination of the paleomagnetic stratigraphy, and using paleontologic data, assigning age ranges to the formation. Fossils from the upper Ringold Formation indicate an age of 3.7 to 4.8 million years and that the predominantly reversed magnetic section represents the Gilbert Reversed Epoch. The basal Ringold is interpreted to be mainly post-Ice Harbor in age. Based on these assumptions, the Ringold Formation in the RRL is interpreted to be >3.4, but <8.5 million years old.

The number and age of Pleistocene floods to inundate the Pasco Basin are not known, but at least three events have been dated. These three flood sequences in the Pasco Basin are: (1) a pre-Wisconsinan flood or floods, (2) a Wisconsinan event >32,000 radiocarbon years before present, and (3) a late Wisconsinan flood(s) associated with Mt. St. Helens Set S ash ∿13,000 radiocarbon years before present.

CHAPTER 3 - WANAPUM AND SADDLE MOUNTAINS BASALTS OF THE COLD CREEK SYNCLINE AREA

S. P. Reidel
K. R. Fecht

INTRODUCTION

This chapter describes the stratigraphy of the Wanapum and Saddle Mountains Basalts (Fig. 3-1) in the Cold Creek syncline area of the Pasco Basin. More information is presently known about flows of these formations than the Grande Ronde Basalt because of the greater number of surface exposures and drill holes that penetrate them (Appendix A). Emphasis is placed upon primary physical and chemical characteristics that were used to map the area and to determine the distribution and emplacement history of the basalt flows. A discussion of the geologic history of the Cold Creek syncline area during Wanapum and Saddle Mountains time concludes this chapter.

Basic information on the stratigraphy of the Wanapum and Saddle Mountains Basalts is derived from the study of surface exposures (Fig. 3-2) and core and chip samples from drill holes. Surface exposures occur primarily along the edges of the Cold Creek syncline, where uplift along Yakima folds has exposed thick sections of the basalt. The spacing and depth of boreholes in the Cold Creek syncline area (Fig. 3-2) provide relatively good subsurface data coverage for the Saddle Mountains Basalt, but only fair coverage for the Wanapum and Grande Ronde Basalts (Appendix A); thus, less information is available. The stratigraphy of the basalt and correlations from borehole to borehole and from borehole to outcrop are determined by using chemical composition, paleomagnetism, and physical characteristics.

PREVIOUS WORK

The nomenclature and stratigraphic relationships of the Columbia River basalt in the Pasco Basin are based on that developed for the Columbia Plateau by Mackin (1961), Waters (1955, 1961), Schmincke (1967a and b), Wright and others (1973), Myers (1973), Bingham and Grolier (1966), Bingham and Walters (1965), Brown and Ledgerwood (1973), Myers and Brown (1973), Laval (1956), and ARHCO (1976). Swanson and others (1979b) summarized the important relationships discussed in these and other studies and related them to regional stratigraphic relationships. The nomenclature and stratigraphic framework for the Columbia River basalt that is currently used in the region and in the Pasco Basin and Cold Creek syncline area is shown in Figure 3-1. Myers, Price and others (1979) summarized the work

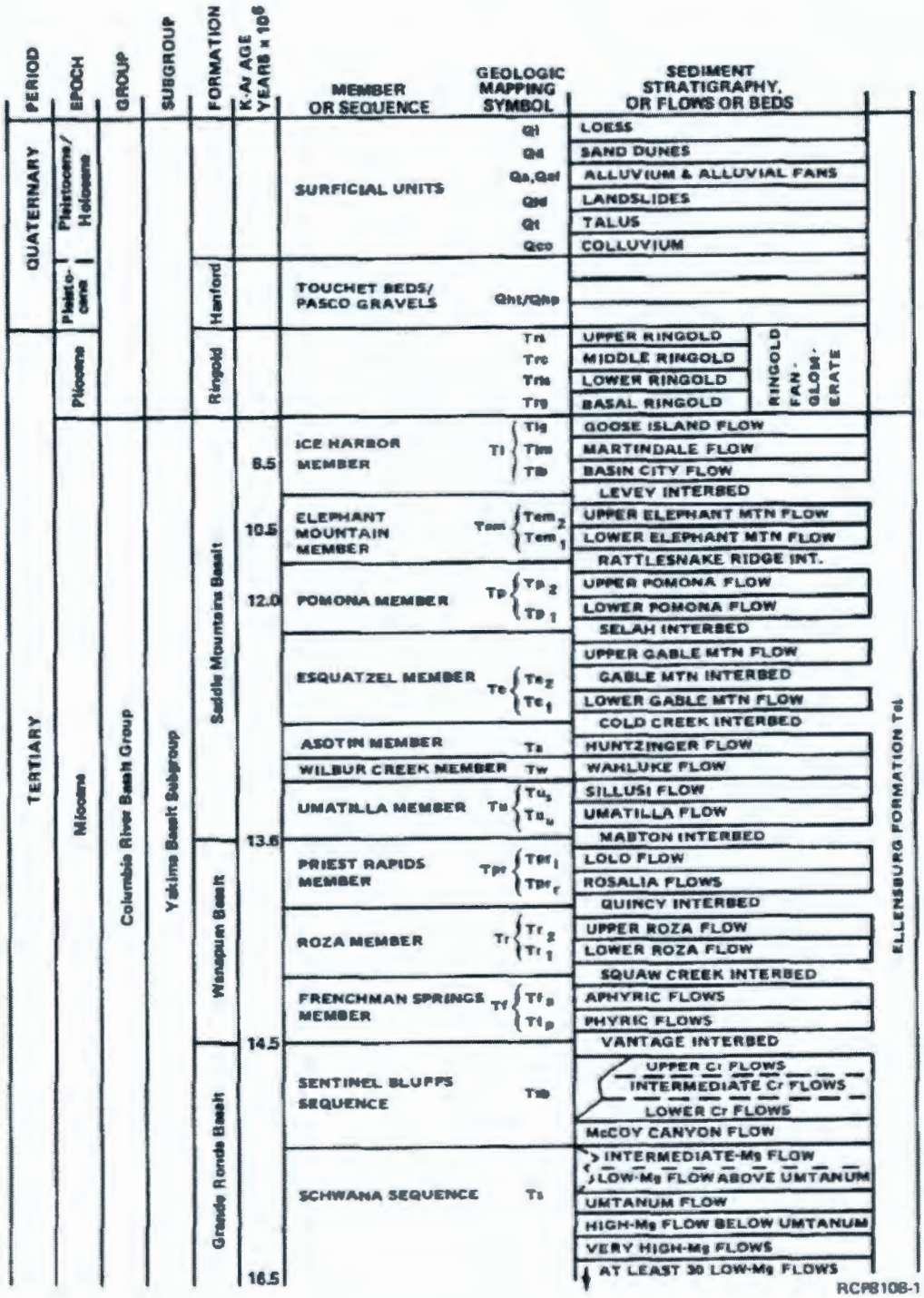

FIGURE 3-1. Stratigraphic Nomenclature, Columbia River Basalt Group, Pasco Basin.

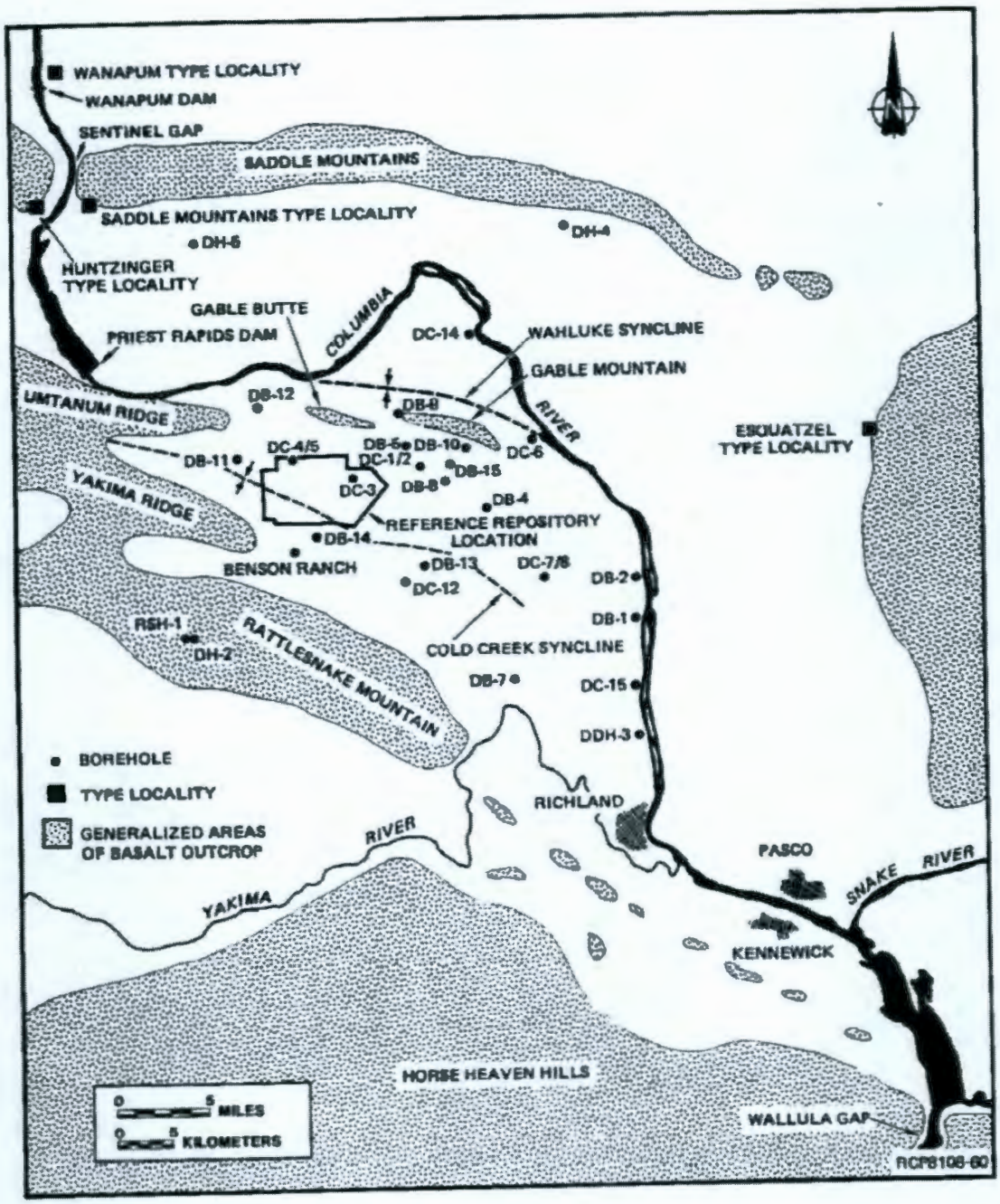

FIGURE 3-2. Location of Referenced Features, Pasco Basin and Nearby Area.

done by geologists for the BWIP. The results of a more detailed study on the Wanapum and Saddle Mountains Basalt flows were recently summarized by Reidel and others (1980). This study related the distribution of flows to the deformational history of the Pasco Basin.

WANAPUM BASALT

The Wanapum Basalt consists of three members in the Pasco Basin: (1) Frenchman Springs, (2) Roza, and (3) Priest Rapids. The Vantage interbed separates this formation from the underlying Grande Ronde Basalt; the Mabton interbed separates the Wanapum Basalt from the overlying Saddle Mountains Basalt (Fig. 3-1).

The Wanapum Basalt is typically fine to medium grained with some flows containing olivine and plagioclase phenocrysts. The petrographic characteristics combined with distinct chemical differences, termed the "TiO_2 discontinuity" (Siems and others, 1974), permit easy distinction of the Wanapum Basalt from the Grande Ronde Basalt.

The Wanapum Basalt is between 14.5 and 13.5 million years old (Watkins and Baksi, 1974) and was erupted from linear vents on the east side of the plateau (Swanson and others, 1979a). It is thickest in the central area of the Cold Creek syncline (Table 3-1; Fig. 3-3), but thins from west to east and over the Rattlesnake Mountain and Umtanum Ridge-Gable Mountain structures.

FRENCHMAN SPRINGS MEMBER

The Frenchman Springs Member is the oldest member of the Wanapum Basalt in the Pasco Basin and consists of seven to nine (possibly in borehole RSH-1) flows in the Cold Creek syncline (Fig. 3-4). It varies in thickness from ∿192 to ∿229 m (Fig. 3-4). The flows are all medium to fine grained and contain plagioclase pheocrysts. Within the Pasco Basin, the flows can be grouped into "phyric" and "aphyric" units based upon relative phenocryst abundance.

The average chemical composition of the Frenchman Springs Member is given in Table 3-2. It falls within the Frenchman Springs chemical type of Wright and others (1973), but there is no obvious difference in chemical composition between the phyric and aphyric flows from the Pasco Basin area.

The flows of the Frenchman Springs Member near Vantage were sampled for remanent magnetic polarity by Van Alstine and Gillett (in press) as part of BWIP stratigraphic studies. Their findings are comparable with those of Rietman (1966), Kienle and others (1978b), and Sheriff and Bentley (1980). Van Alstine and Gillett (in press) found that the magnetic polarity of the two lowest flows near Vantage, the Ginkgo and Sand Hollow flows (Table 3-3), are nearly identical with mean declinations of 146.1° and

TABLE 3-1. Map Explanation.

The following symbols are used throughout this report on maps and diagrams. In specific instances, additional special symbols are used and are defined for the specific diagram.

FOR ISOPACH MAPS

500	Isopach; line representing equal stratigraphic thickness; number is expressed in feet
DC-3 27	Borehole location, identifying borehole (if applicable); thickness measured in feet
67	Field section location indicating thickness measured in feet
	Contour interval in feet varies, but is indicated per each figure

FOR GEOLOGIC MAPS

	Solid lines with stippling inside delineate areas of basalt outcrop
	Contact; dashed where concealed
	Fault; dashed where inferred; ball and bar appear on downthrown side

Map Units

Saddle Mountains Basalt

Ti	Ice Harbor Member
Tem	Elephant Mountain Member
Tp	Pomona Member
Te	Esquatzel Member
Ta	Asotin Member
Tw	Wilbur Creek Member
Tu	Umatilla Member

Wanapum Basalt

Tpr	Priest Rapids Member
Tr	Roza Member
Tf	Frenchman Springs Member

Grande Ronde Basalt

Tsb	Sentinel Bluffs Sequence
Ts	Schwana Sequence

FOR STRUCTURE-CONTOUR MAPS

200	Structure contour; line representing equal elevation on a stratum; number is elevation in feet in relation to mean sea level; queried where trend or elevation is uncertain; shown with "e" where eroded, principal contours shown by bold line, intermediate contours by narrow line; contour interval varies, but is always in relation to the solid, continuous lines. Accuracy is ± one contour interval
	Anticline; showing trace of crest and plunge of crest; dashed where approximately located; queried where uncertain
	Syncline; showing trace of trough and plunge of trough; dashed where approximately located; queried where uncertain
	Monocline; showing trace of axis; dashed where approximately located
DC-3 42	Borehole location identifying borehole (if applicable); elevation measured in feet from mean sea level
	Fault; dashed where inferred; ball and bar appear on downthrown side

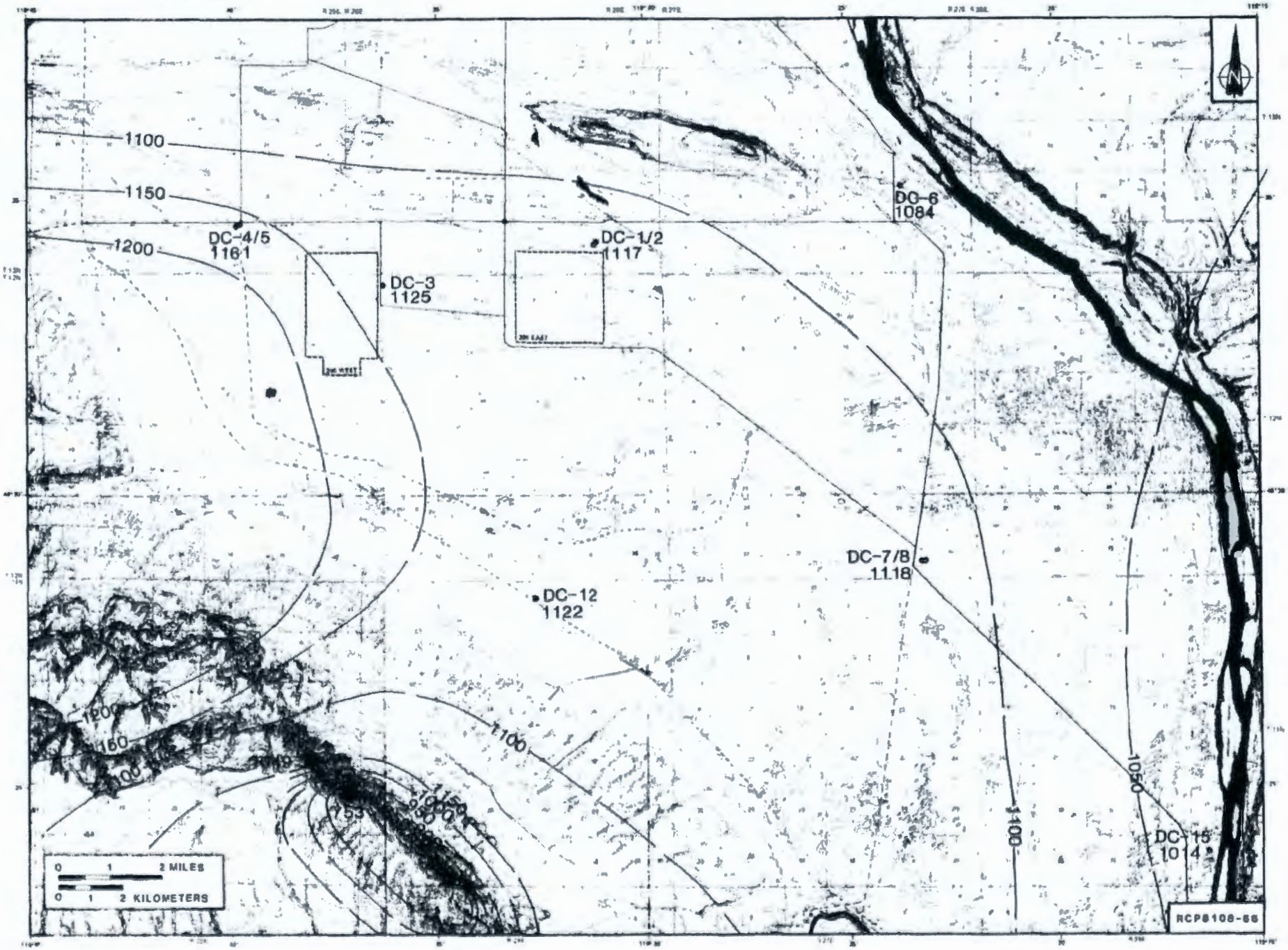

FIGURE 3-3. Isopach Map, Saddle Mountains Basalt, Cold Creek Syncline. Contour interval is 50 ft. See Figure 3-2 for location of structural features and Table 3-1 for explanation.

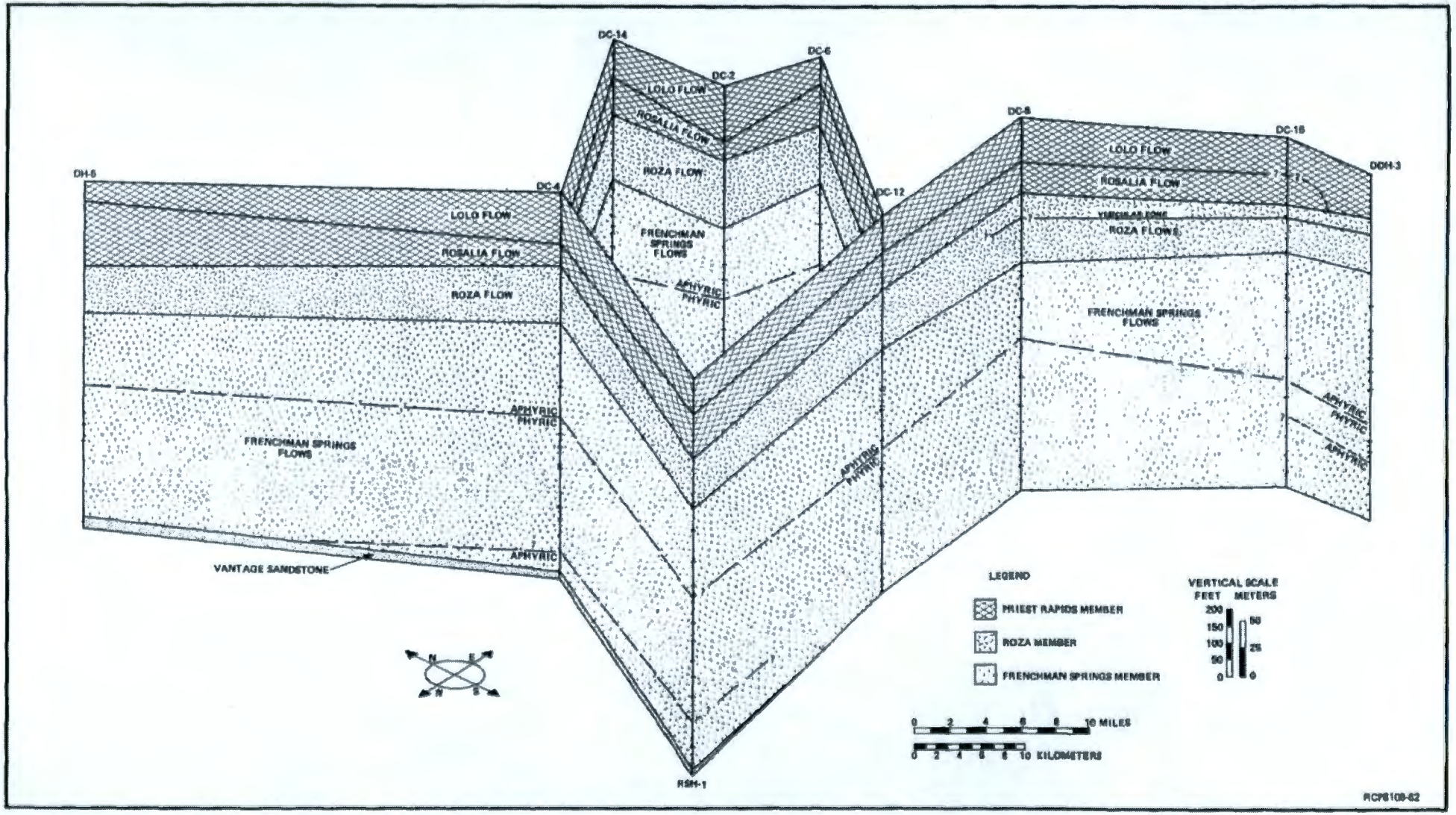

FIGURE 3-4. Fence Diagram, Wanapum Basalt, Cold Creek Syncline. See Figure 3-2 for location of boreholes. Individual flows or flow lobes are shown as horizontal lines on the boreholes and connections are shown only where there is confidence in the correlations.

TABLE 3-2. Average Chemical Composition of Flows from the Wanapum and Saddle Mountains Basalts, Pasco Basin. (Sheet 1 of 2)

Flow	Frenchman Springs Member plagioclase phyric flows		Frenchman Springs Member aphyric flows		Roza Member		Priest Rapids Member Rosalia flow	
	N = 43		N = 28		N = 13		N = 15	
Mean, One Std. Dev.	$\bar{X}$	1σ	$\bar{X}$	1σ	$\bar{X}$	1σ	$\bar{X}$	1σ
SiO_2	51.24	0.37	51.27	0.39	50.60	0.35	49.85	0.35
AL_2O_3	13.93	0.29	14.04	0.32	14.35	0.37	13.70	0.21
TiO_2	2.98	0.08	2.92	0.08	3.01	0.11	3.48	0.05
FeO*	12.83	0.44	12.69	0.37	12.44	0.54	13.47	0.31
MnO	0.24	0.01	0.23	0.01	0.23	0.01	0.24	0.01
CaO	8.34	0.17	8.34	0.15	8.65	0.20	8.55	0.19
MgO	4.22	0.25	4.21	0.23	4.59	0.31	4.49	0.22
K_2O	1.15	0.14	1.29	0.12	1.17	0.13	1.05	0.20
NA_2O	2.54	0.14	2.49	0.17	2.43	0.20	2.50	0.22
P_2O_5	0.53	0.05	0.52	0.04	0.54	0.03	0.66	0.02

Flow	Priest Rapids Member Lolo flow		Umatilla Member Sillusi flow		Umatilla Member Umatilla flow		Wilbur Creek Member Wahluke flow	
	N = 19		N = 26		N = 24		N = 4	
Mean, One Std. Dev.	$\bar{X}$	1σ	$\bar{X}$	1σ	$\bar{X}$	1σ	$\bar{X}$	1σ
SiO_2	49.87	0.53	54.31	0.73	53.65	0.59	53.43	0.35
AL_2O_3	14.28	0.30	14.70	0.60	14.51	0.27	15.01	0.28
TiO_2	3.15	0.09	2.83	0.30	2.99	0.11	1.87	0.02
FeO*	12.20	0.45	10.48	0.92	10.87	0.72	9.66	0.21
MnO	0.24	0.01	0.22	0.02	0.22	0.05	0.19	0.01
CaO	9.00	0.63	6.60	0.64	6.68	0.37	8.50	0.19
MgO	5.18	0.31	2.61	0.26	3.00	0.31	4.61	0.25
K_2O	0.98	0.11	2.62	0.36	2.52	0.14	1.90	0.16
NA_2O	2.45	0.17	2.82	0.25	2.84	0.24	2.37	0.15
P_2O_5	0.66	0.02	0.81	0.05	0.72	0.02	0.45	0.01

TABLE 3-2. Average Chemical Composition of Flows from the Wanapum and Saddle Mountains Basalt, Pasco Basin. (Sheet 2 of 2)

Flow	Esquatzel Member		Asotin Member Huntzinger flow		Pomona Member		Elephant Mountain Member Lower flow	
	N = 44		N = 45		N = 67		N = 23	
Mean, One Std. Dev.	$\bar{X}$	1σ	$\bar{X}$	1σ	$\bar{X}$	1σ	$\bar{X}$	1σ
SiO_2	52.78	0.47	51.43	0.82	51.81	0.38	50.76	0.33
AL_2O_3	14.24	0.27	16.06	0.56	15.41	0.28	13.76	0.30
TiO_2	3.02	0.10	1.58	0.12	1.63	0.06	3.49	0.06
FeO*	11.68	0.50	8.32	0.54	8.68	0.39	13.08	0.51
MnO	0.21	0.02	0.18	0.02	0.19	0.01	0.23	0.01
CaO	7.65	0.22	10.51	0.69	10.62	0.30	8.38	0.19
MgO	3.75	0.22	6.82	0.97	6.73	0.27	4.22	0.14
K_2O	1.78	0.13	0.67	0.42	0.53	0.10	1.30	0.10
NA_2O	2.50	0.14	2.16	0.20	2.16	0.12	2.29	0.21
P_2O_5	0.37	0.02	0.26	0.06	0.24	0.02	0.49	0.01
Flow	Elephant Mountain Member upper flow (Ward Gap)		Ice Harbor Member Basin City flow		Ice Harbor Member Martindale flow		Ice Harbor Member Goose Island flow	
	N = 10		N = 8		N = 14		N = 4	
Mean, One Std. Dev.	$\bar{X}$	1σ	$\bar{X}$	1σ	$\bar{X}$	1σ	$\bar{X}$	1σ
SiO_2	50.57	0.28	47.62	0.29	48.44	0.49	47.46	0.67
AL_2O_3	13.78	0.22	14.04	0.21	14.18	0.36	13.17	0.39
TiO_2	3.43	0.08	3.59	0.04	3.25	0.13	3.64	0.05
FeO*	13.26	0.39	13.54	0.28	12.38	0.87	15.32	0.44
MnO	0.22	0.01	0.23	0.01	0.23	0.01	0.28	0.01
CaO	8.54	0.13	9.71	0.28	10.20	0.59	8.85	0.11
MgO	4.26	0.24	5.57	0.20	5.65	0.36	4.31	0.15
K_2O	1.20	0.12	0.68	0.11	0.68	0.17	1.22	0.06
NA_2O	2.27	0.14	2.23	0.11	2.30	0.13	2.25	0.16
P_2O_5	0.47	0.02	0.78	0.04	0.68	0.04	1.49	0.04

NOTE: Analyses are in wt%. Samples are core that was collected from drill holes and specimens from type localities.
*Total Fe expressed as FeO.

TABLE 3-3. Paleomagnetic Polarity of Wanapum and Saddle Mountains Basalts.

Member	Flow or location	Mean declination	Mean inclination	α95	Source of information
Ice Harbor	Goose Island	51.3 33.5	+19.2 +31.9	11.7 13.3	1
	Martindale	185.1 168.2	-55.1 -65.0	3.0 3.3	1
	Basin City	317.0 319.3	+34.7 +49.5	4.2 6.3	1
Elephant Mountain	Site 1 Site 2	6.9 14.2	+59.6 +62.5	4.2 8.3	1
	Site 3 Site 4	111.5 127.9	-25.6 -39.5	9.3 9.8	1
		133.2	-39.2	8.6	2
Pomona	Site 1 Site 2	187.8 186.3	-519.1 -53.4	1.7 2.2	1
	Site 3 Site 4	203.4 195.4	-54.6 -50.6	2.0 2.9	1
		193.5	-52.7	9.5	2
Esquatzel	Site 1 Site 2	340.8 308.0	+63.0 +81.0	3.6 11.4	1
		348.4	+64.8	8.6	2
Asotin	Huntzinger	23.7	+80.6	4.5	2
Wilbur Creek	Wahluke	345.7	+72.1	3.4	2
Umatilla	Sillusi Umatilla	321.7 324.3	+32.2 +31.7	2.6 3.4	2 2
Priest Rapids	Lolo	190.5	-64.9	2.8	2
Roza	Site 1 Site 2	214.2 184.7	-14.7 -38.7	7.3 7.0	1
Frenchman Springs	Sentinel Gap Sand Hollow Ginkgo	5.0 144.7 146.1	+62.8 +39.8 +42.1	2.2 3.6 2.6	2 2 2

[1]Choinier and Swanson (1979)

[2]Van Alstine and Gillett (in press).

144.7° and mean inclinations of 42.1° and 39.8°, respectively. The youngest flow, the Sentinel Gap flow (Table 3-3), has a mean declination of 5.0° and a mean inclination of 62.8°. Packer and Petty (1979) found that the inclination of the lowest Frenchman Springs flow in core from borehole DC-2 (Fig. 3-2) had a mean inclination of 21° and all younger Frenchman Springs flows had higher inclinations. Van Alstine and Gillett (in press) suggested that the lowest flow in DC-2 could be either the Ginkgo or Sand Hollow flow and that the inclination of the younger flows in DC-2 were much closer to the Sentinel Gap flow. These results suggest that either the Ginkgo or Sand Hollow flow is not present in the Cold Creek syncline.

The total thickness of the Frenchman Springs Member thins from south to north and from east to west across the Pasco Basin (Reidel and others, 1980). The greatest number of flows is present near Wallula Gap (Fig. 3-2) in the southeastern part of the Pasco Basin and the least number in the northwestern part near Sentinel Gap (Fig. 3-2). In the central part of the Cold Creek syncline area, there are between seven and nine flows or flow lobes (Fig. 3-4). An abrupt thinning occurs onto the Rattlesnake Mountain structure at the southern edge of the Cold Creek syncline. The greatest thickness occurs on the east side of the Cold Creek syncline (Fig. 3-5). Due to the similarities between flows, the correlation of individual flows across the area is currently not possible.

ROZA MEMBER

Between one and two flows or flow lobes of similar physical and chemical composition comprise the Roza Member in the Pasco Basin. The Roza flows were erupted from a narrow, linear, vent system in eastern Washington and northeastern Oregon (Swanson and others, 1975). The member varies in thickness from 41 to 69 m. It is distinguished in hand specimen, typically by the presence of single plagioclase phenocrysts up to 1.5 cm in size set in a fine-grained groundmass.

The average chemical composition of the Roza Member from the Pasco Basin is given in Table 3-2. It generally falls within the Frenchman Springs chemical type of Wright and others (1973) and cannot be distinguished from the Frenchman Springs flows on chemical composition alone.

The magnetic polarity of the Roza Member was determined by Rietman (1966) to be transitional, but Choinier and Swanson (1979) found that in the southeastern part of the Columbia Plateau, the oldest Roza flow has reversed polarity. Van Alstine and Gillett (in press) found that the two Roza flows in core from DH-5 (Fig. 3-2) have low-mean inclinations (+3.3° and 7.5°), lower than that reported by Choinier and Swanson (1979) (Table 3-3). Packer and Petty (1979) sampled the Roza flow from core in DC-2 (Fig. 3-2) and found results similar to those of Van Alstine and Gillett (in press).

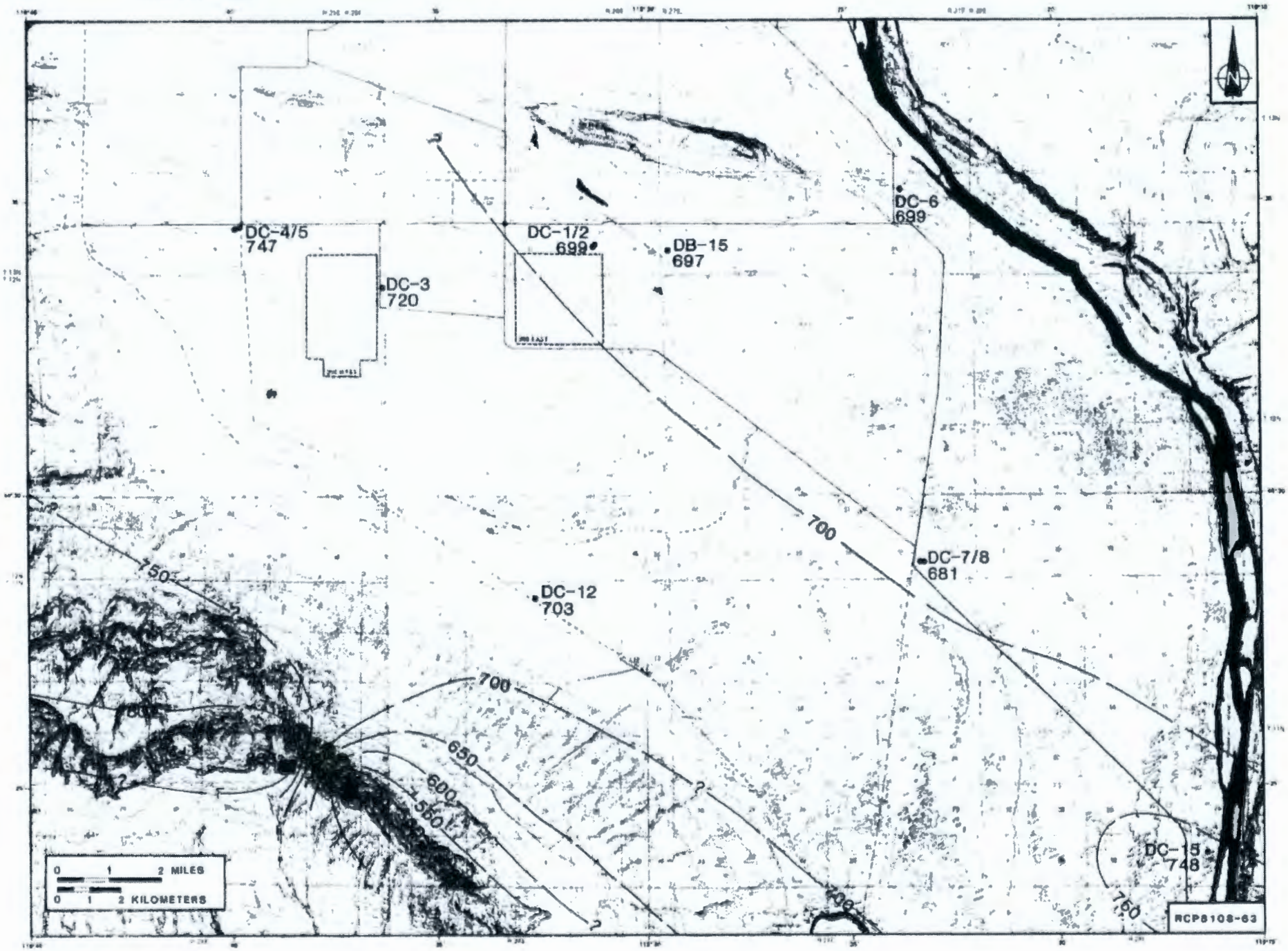

FIGURE 3-5. Isopach Map, Frenchman Springs Member, Cold Creek Syncline. Contour interval is 50 ft. See Figure 3-2 for location of structural features and Table 3-1 for explanation.

The Roza Member reaches its greatest thickness (Fig. 3-6) in the central part of the Cold Creek syncline and just north of Gable Mountain. It consists of one flow in the western part of the syncline, but is two flows or two flow lobes in the eastern part (Fig. 3-4). It thins across Rattlesnake Mountain and the Umtanum Ridge-Gable Mountain structure, but thickens along the northern flank of the Umtanum Ridge-Gable Mountain structure in the Wahluke syncline.

PRIEST RAPIDS MEMBER

The Priest Rapids Member is the youngest member of the Wanapum Basalt (Swanson and others, 1979b) and consists of two distinct flows in the Cold Creek syncline as elsewhere in the Pasco Basin. In core from the Priest Rapids Dam site (Fig. 3-2), four flows are present, but the three lowest are now considered to be flow lobes of the same flow (Reidel and others, 1980). The Priest Rapids flows were erupted from vents near the eastern margin of the plateau in Idaho (Camp, in Swanson and others, 1979a). The member varies in thickness from 40 to 75 m (Fig. 3-7) in the Cold Creek syncline. The older flow is typically coarser grained with rare olivine and plagioclase phenocrysts. The younger flow has small olivine phenocrysts (<5 mm) and rare glomerocrysts or phenocrysts of plagioclase. This texture varies from glassy to fine grained with distinct zones having a diabasic texture.

Both flows have distinct chemical compositions (Table 3-2). The older flow is chemically similar to the Rosalia chemical type of Swanson and others (1979b), while the younger flow is chemically similar to the Lolo chemical type of Wright and others (1973). The Lolo flow has lower TiO_2 and higher iron oxide (FeO) than the Rosalia flow.

Van Alstine and Gillett (in press) sampled a surface exposure of the Lolo flow in the Saddle Mountains for magnetic polarity. The flow was found to have a mean declination of 190.5° and a mean inclination of -64.9° (Table 3-3). These data are comparable to the inclination of the Lolo flow in core from DC-2 (Fig. 3-2) sampled by Packer and Petty (1979). Packer and Petty (1979) also found the Rosalia flow in DC-2 to have reversed magnetic polarity.

The Priest Rapids Member reaches its greatest thickness (Fig. 3-7) along the northern flank of Rattlesnake Mountain in the Cold Creek syncline, but thins abruptly across the structure. It also thins along the Umtanum Ridge-Gable Mountain structure and along a small, northwest-trending zone on the east side of the Cold Creek syncline.

Both the Rosalia and Lolo flows of the Priest Rapids Member are present throughout most of the Cold Creek syncline area (Fig. 3-4). The lower flow, the Rosalia, is thickest in the trough of the Wahluke syncline (Fig. 3-2) and Cold Creek syncline, and thins across the Umtanum Ridge-Gable Mountain structure and Rattlesnake Mountain (Reidel and others, 1980). It is thicker on the south side of the Cold Creek syncline and thins northward, abruptly pinching out on the southeast edge of the Cold Creek syncline between DC-15 and DDH-3 (Fig. 3-4).

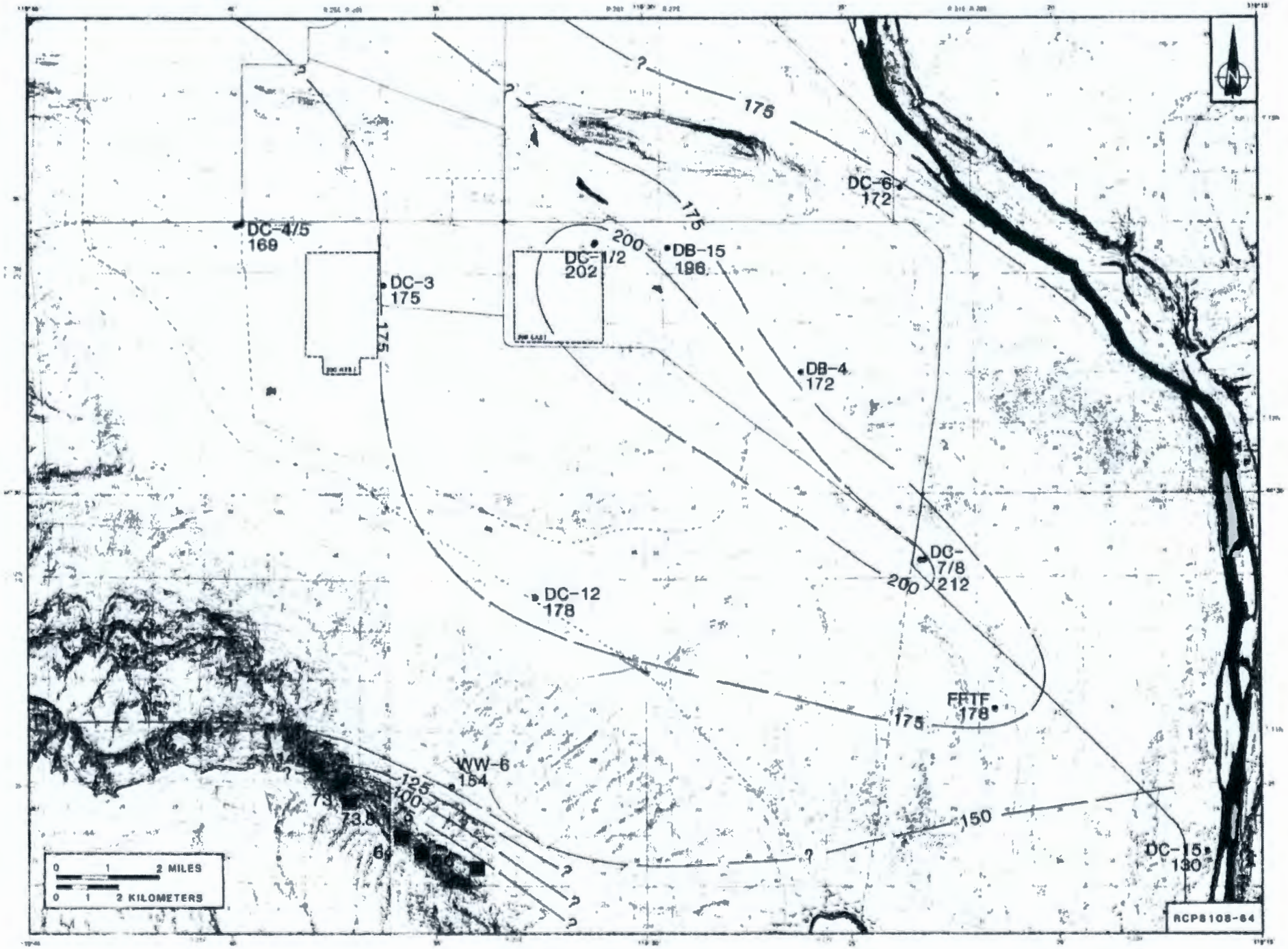

FIGURE 3-6. Isopach Map, Roza Member, Cold Creek Syncline. Contour interval is 25 ft. See Figure 3-2 for location of structural features and Table 3-1 for explanation.

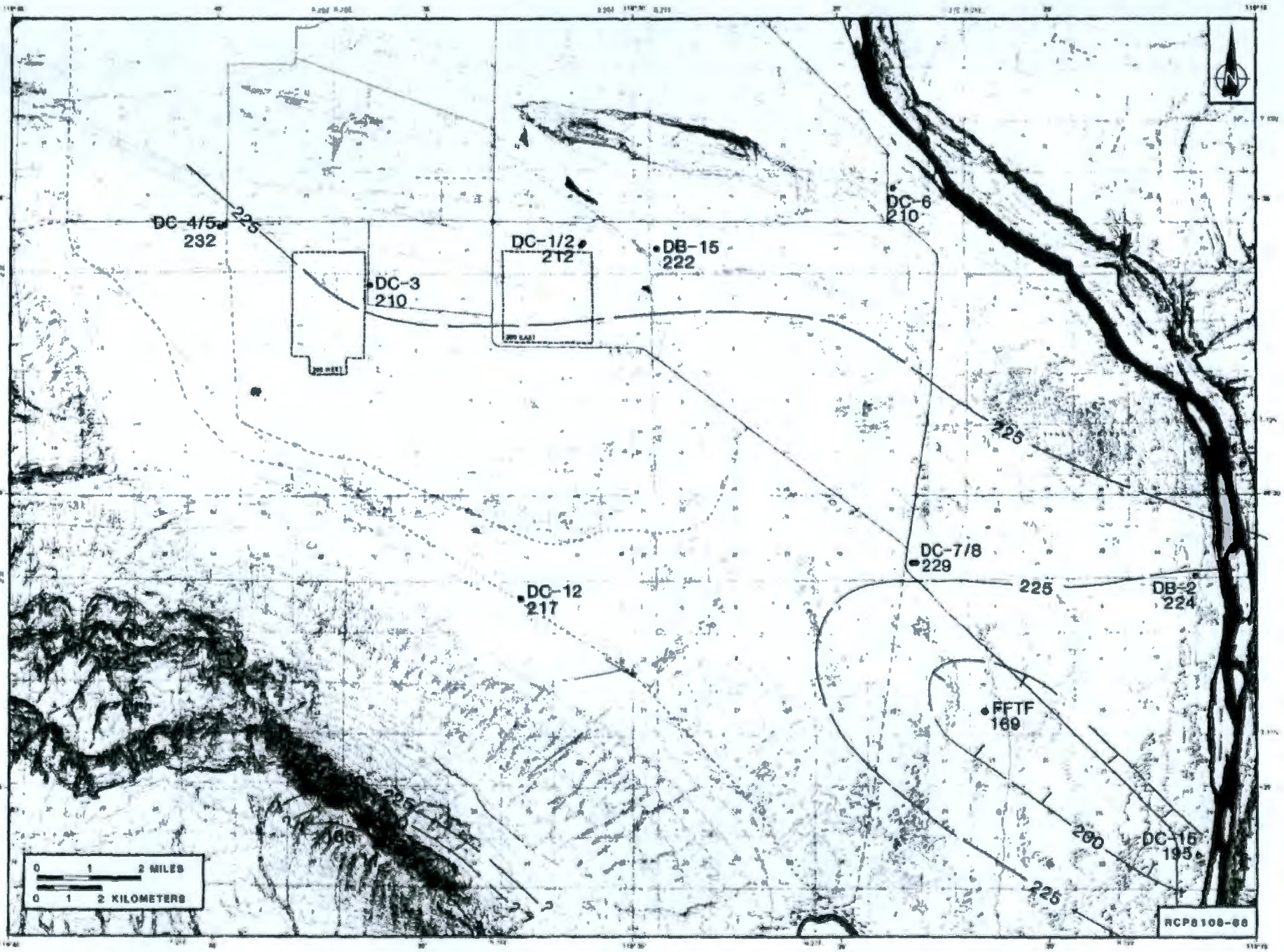

FIGURE 3-7. Isopach Map, Priest Rapids Member, Cold Creek Syncline. Contour interval is 25 ft. See Figure 3-2 for location of structural features and Table 3-1 for explanation.

The Lolo flow is also thicker on the southern margin of the Cold Creek syncline and thins across the Umtanum Ridge-Gable Mountain structure and Rattlesnake Mountain structure. The maximum thickness occurs in a northwest-southeast zone that parallels the present axis of the Cold Creek syncline. Evidence for ponding and slow cooling along the north side of Rattlesnake Mountain is apparent from areas where the basalt has a diabasic texture. The Lolo flow also pinches out on the east side of the Pasco Basin beyond the limits of the Cold Creek syncline (Reidel and others, 1980).

SADDLE MOUNTAINS BASALT

The Saddle Mountains Basalt consists of seven members (Fig. 3-1) in the Pasco Basin: (1) Umatilla, (2) Wilbur Creek, (3) Asotin, (4) Esquatzel, (5) Pomona, (6) Elephant Mountain, and (7) Ice Harbor. With the exception of the Wilbur Creek, all members are present in the Cold Creek syncline area. The Saddle Mountains Basalt in the Pasco Basin ranges in age from 13.5 to 8.5 mybp (Watkins and Baksi, 1974; McKee and others, 1977; ARHCO, 1976).

The Saddle Mountains Basalt flows were erupted over a much greater interval of time than the flows of any other formation of the Columbia River Basalt Group (Swanson and others, 1979b) and contain a wide diversity of petrographic characteristics, chemical types, and magnetic inclinations. Vents for the Saddle Mountains Basalt have been recognized in eastern Washington, northeastern Oregon, and western Idaho (Taubeneck, 1970; Price, 1977; Ross, 1978; Camp, in Swanson and others, 1979a).

Thickness variations in the Saddle Mountains Basalt (Fig. 3-8) are greater and more complex than in the Wanapum Basalt because of (1) thinning over structures, (2) a greater time between eruptions, and (3) the limited extent of many flows. Variations could also be attributable, in part, to the greater amount of information available for the Saddle Mountains Basalt than for other formations (Reidel and others, 1980).

UMATILLA MEMBER

The Umatilla Member consists of two flows in the Pasco Basin. Based upon chemical correlations with the type localities described by Laval (1956), the younger flow is the Sillusi flow and the older flow is the Umatilla flow (Fig. 3-1). The member varies in thickness from 35 to 85 m in the Cold Creek syncline (Fig. 3-9).

Both flows are fine grained to glassy with rare microphenocrysts of plagioclase and olivine and even rarer silicic xenoliths of basement rock. The flows are predominantly entablature with a small basal colonnade or pillowed base.

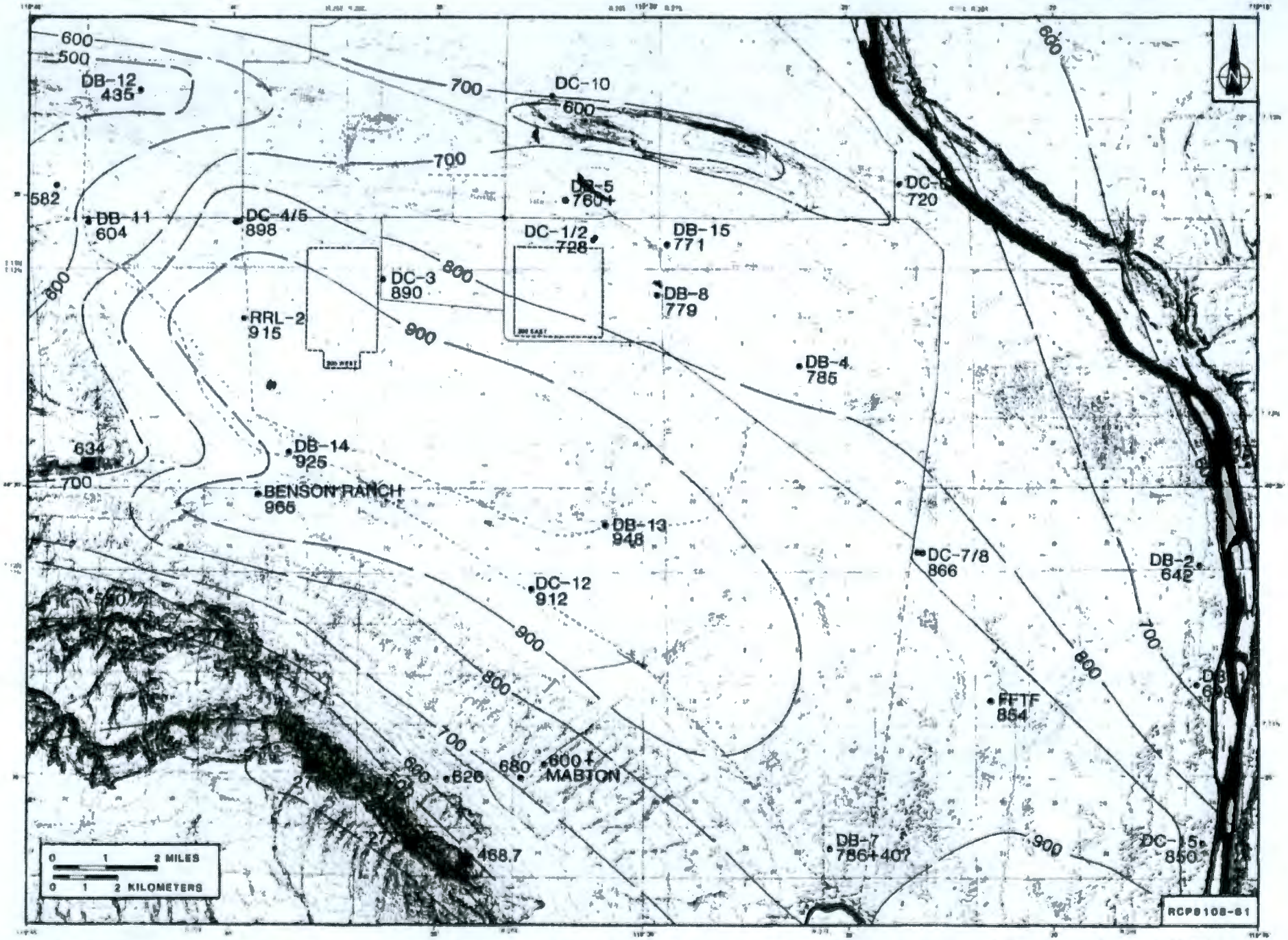

FIGURE 3-8. Isopach Map, Wanapum Basalt, Cold Creek Syncline. Data points shown on the map are thicknesses measured from boreholes and field sections Contour interval is 100 ft. See Figure 3-2 for location of structural features and Table 3-1 for explanation.

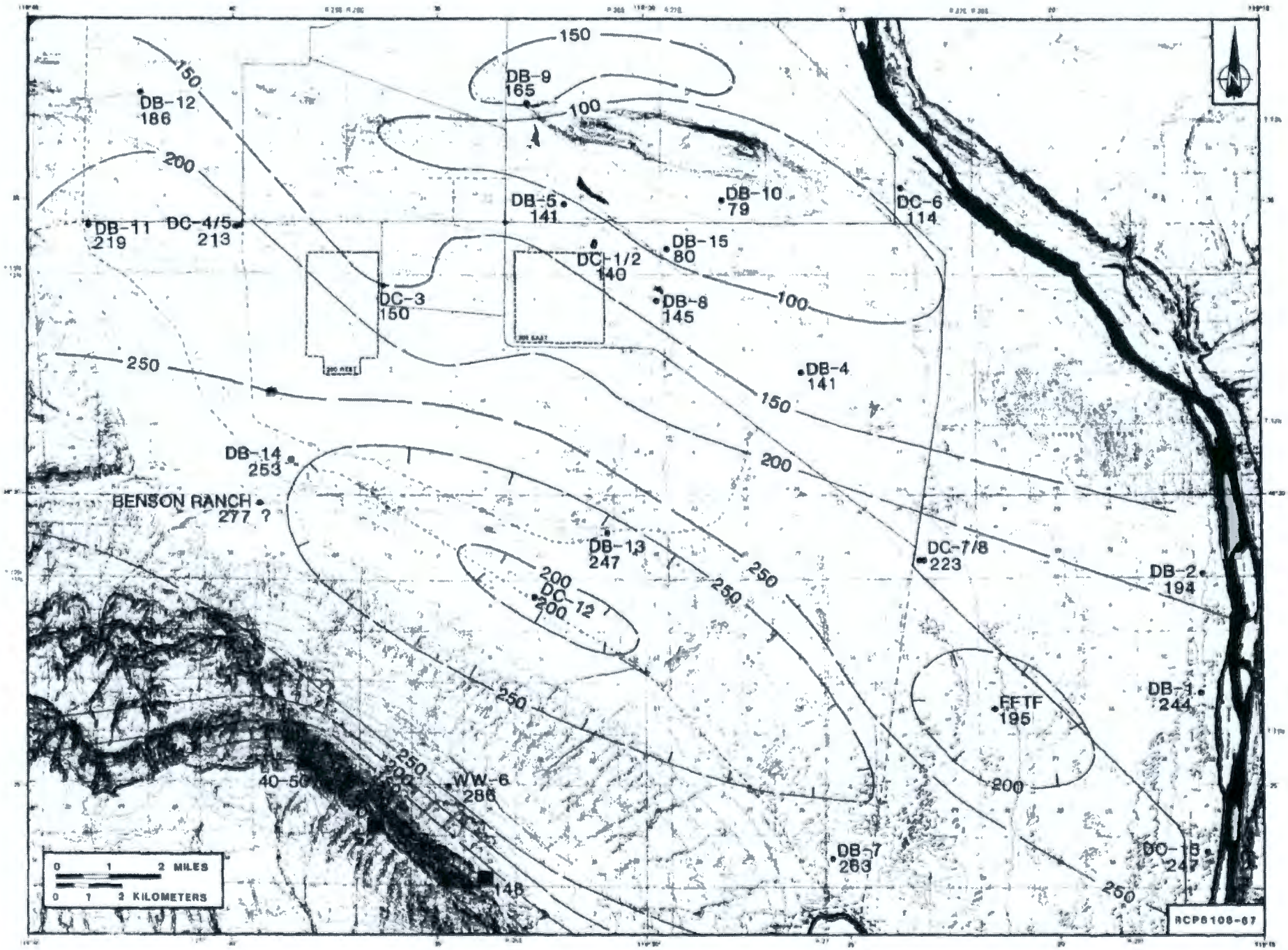

FIGURE 3-9. Isopach Map, Umatilla Member, Cold Creek Syncline. Contour interval is 50 ft. See Figure 3-2 for location of structural features and Table 3-1 for explanation.

Both the Umatilla and Sillusi flows have similar overall chemical compositions and fall into the Umatilla chemical type of Wright and others (1973). There are distinct differences in chemical composition, however, that allow the flows to be distinguished: The Umatilla has higher TiO_2, magnesium oxide (MgO), and lower phosphorus pentoxide (P_2O_5) than the Sillusi (Table 3-2).

Rietman (1966) found that the Umatilla Member has normal magnetic polarity. Van Alstine and Gillett (in press) found the Umatilla and Sillusi flows have nearly identical mean declinations of 324.3° and 321.7° and mean inclinations of +31.7° and +32.2°, respectively (Table 3-3). They suggested that this indicates the flows were erupted nearly contemporaneously.

Vent areas for the Umatilla Member have been located in eastern Washington and northeastern Oregon by Waters (1961), Price (1977), and Ross (1978). The flows of the Umatilla Member entered the Pasco Basin from the south and filled the Cold Creek syncline. The overall geometry of the Umatilla Member is that of a wedge that thins to the north (Fig. 3-10). The member pinches out just north of the Umtanum Ridge-Gable Mountain trend and just east of the Cold Creek syncline (Reidel and others, 1980). It is much thinner on the crest of Rattlesnake Mountain and on the extension of Yakima Ridge (Fig. 3-9). Thinning is also apparent across the subsurface extensions of Gable Mountain, Gable Butte, and an apparent southeast extension of a similar structure from Umtanum Ridge to DC-3. The subsurface extension of Yakima Ridge resembles the en echelon nature of the Gable Mountain and Gable Butte structures based upon thickness variations observed in the Umatilla Member.

Both the Umatilla and Sillusi flows are present throughout most of the Cold Creek syncline (Fig. 3-10). The Umatilla flow is the thicker flow in the western and southern parts of the syncline, but the Sillusi flow is the only flow present in the eastern part and is the thicker flow in the northern part of the syncline. In Figure 3-10, it is apparent that the western part of the Cold Creek syncline was covered first by the Umatilla flow. The Sillusi flow was later directed along the northern and eastern margins of the Umatilla flow, which it also onlapped. This distribution was probably a result of the Sillusi flow filling the low area formed between the gently westward-dipping, regional paleoslope and the northward-tapering margin of the Umatilla flow.

WILBUR CREEK MEMBER

The Wilbur Creek Member in the Pasco Basin consists of one flow, the Wahluke flow, and is generally <30 m thick. It is typically fine grained to glassy and aphyric with sparse microphenocrysts of plagioclase.

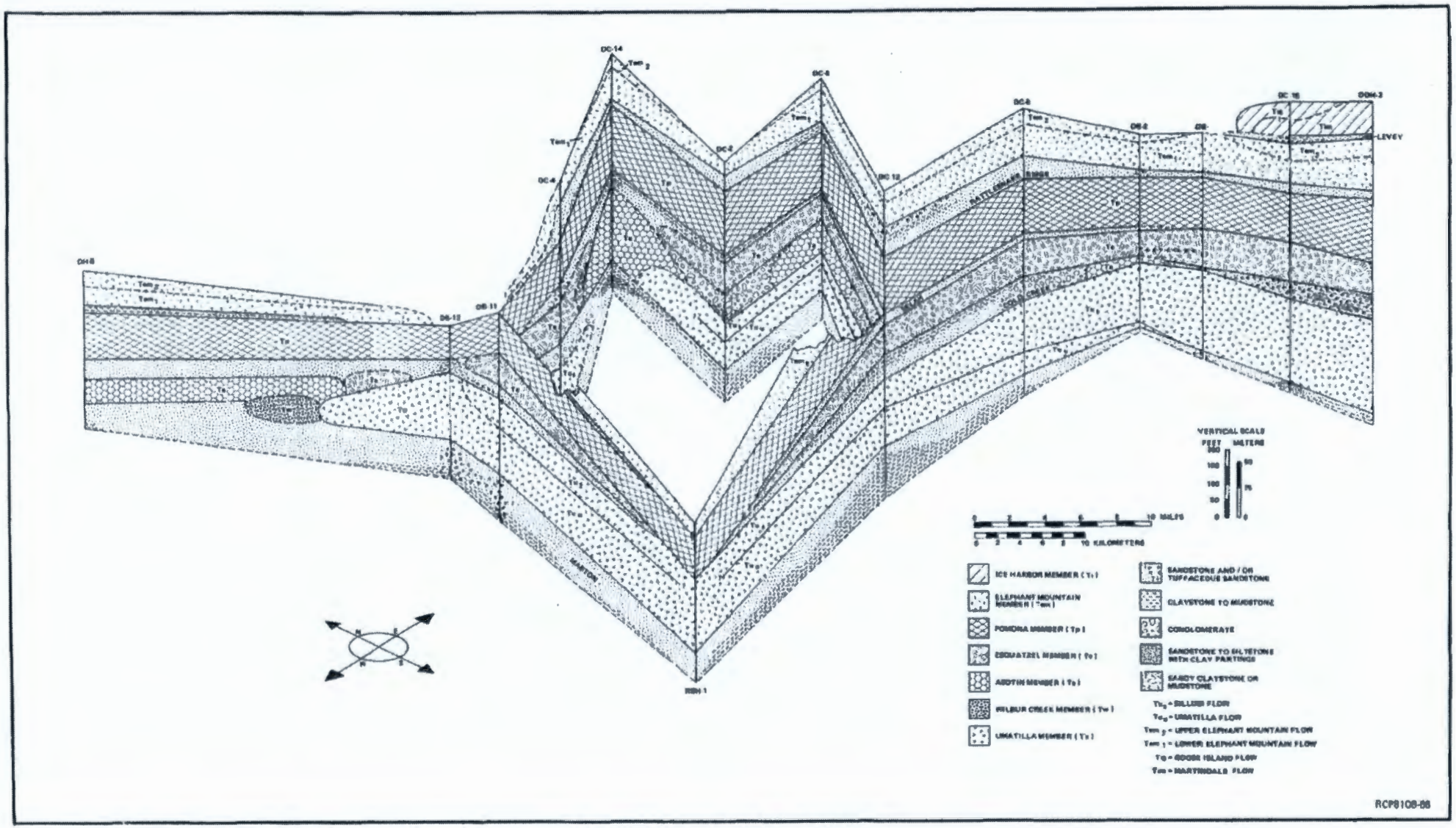

FIGURE 3-10. Fence Diagram, Saddle Mountains Basalt, Cold Creek Syncline. See Figure 3-2 for location of boreholes.

The chemical composition of the Wilbur Creek Member from the Pasco Basin falls within the Wilbur Creek chemical type of Swanson and others (1979b). The Wahluke flow has a mean magnetic declination of 345.7° and a mean inclination of +72.1° (Table 3-3; Van Alstine and Gillett, in press). The Wahluke flow was also sampled from core in DH-4 in the northeast part of the Pasco Basin by Packer and Petty (1979) who reported a 6° shallower inclination angle.

The Wahluke flow of the Wilbur Creek Member is not present in the Cold Creek syncline area of the Pasco Basin. This flow entered the Pasco Basin from the northeast and flowed southwest toward Umtanum Ridge. Just northwest of the Cold Creek syncline, the course of the Wahluke flow was partly controlled by the leading edge of the Umatilla Member (Reidel and others, 1980) (Fig. 3-10, DB-12 to DH-5).

ASOTIN MEMBER

The Asotin Member occurs as a single flow in the Pasco Basin. This was called the Huntzinger flow by Mackin (1961), Myers and Brown (1973), and ARHCO (1976). The flow varies from 23 to 66 m in thickness (Fig. 3-11) and is best exposed in the northern part of the basin along the Saddle Mountains (Reidel, 1978a).

The texture of the Huntzinger flow varies considerably throughout the Pasco Basin. The flow has abundant olivine, but sparse plagioclase, and its texture varies from fine grained and glassy to ophitic.

The chemical composition of the Asotin Member varies considerably throughout the Pasco Basin (Table 3-2). This extreme variation was first recognized by Myers (1973) and Ward (1976). The Asotin Member contains chemical compositions from two types defined by Swanson and others (1979b): (1) Asotin and (2) Lapwai. In Figure 3-12, the chemical composition of samples from a typical section of the Asotin Member (DH-4; Fig. 3-2) is shown and the approximate mean and range of the Lapwai and Asotin chemical types (from Wright and others, 1980) are plotted. It is apparent from this diagram that the Lapwai chemical type occurs at the top and bottom of the flow with Asotin chemical type in between and a complete gradation from one to the other. This indicates that the two chemical types are probably related by differentiation occurring in the flow at the surface. Myers (1973) related the chemical variation to olivine abundance and suggested that fractional crystallization of olivine is at least partly responsible. Based on sampling of surface exposures, Van Alstine and Gillett (in press) determined a mean declination of 23.7° and a mean inclination of +80.6° for the Asotin Member (Table 3-3).

The Asotin Member was erupted from an as yet undiscovered fissure, probably in eastern Washington or western Idaho (Camp, in Swanson and others, 1979a). The Asotin Member is confined to the northern part of the Cold Creek syncline and Pasco Basin (Reidel and others, 1980). As shown in Figure 3-10, the front of the Umatilla Member was a major factor controlling the edge of the Huntzinger flow. The Huntzinger flow is

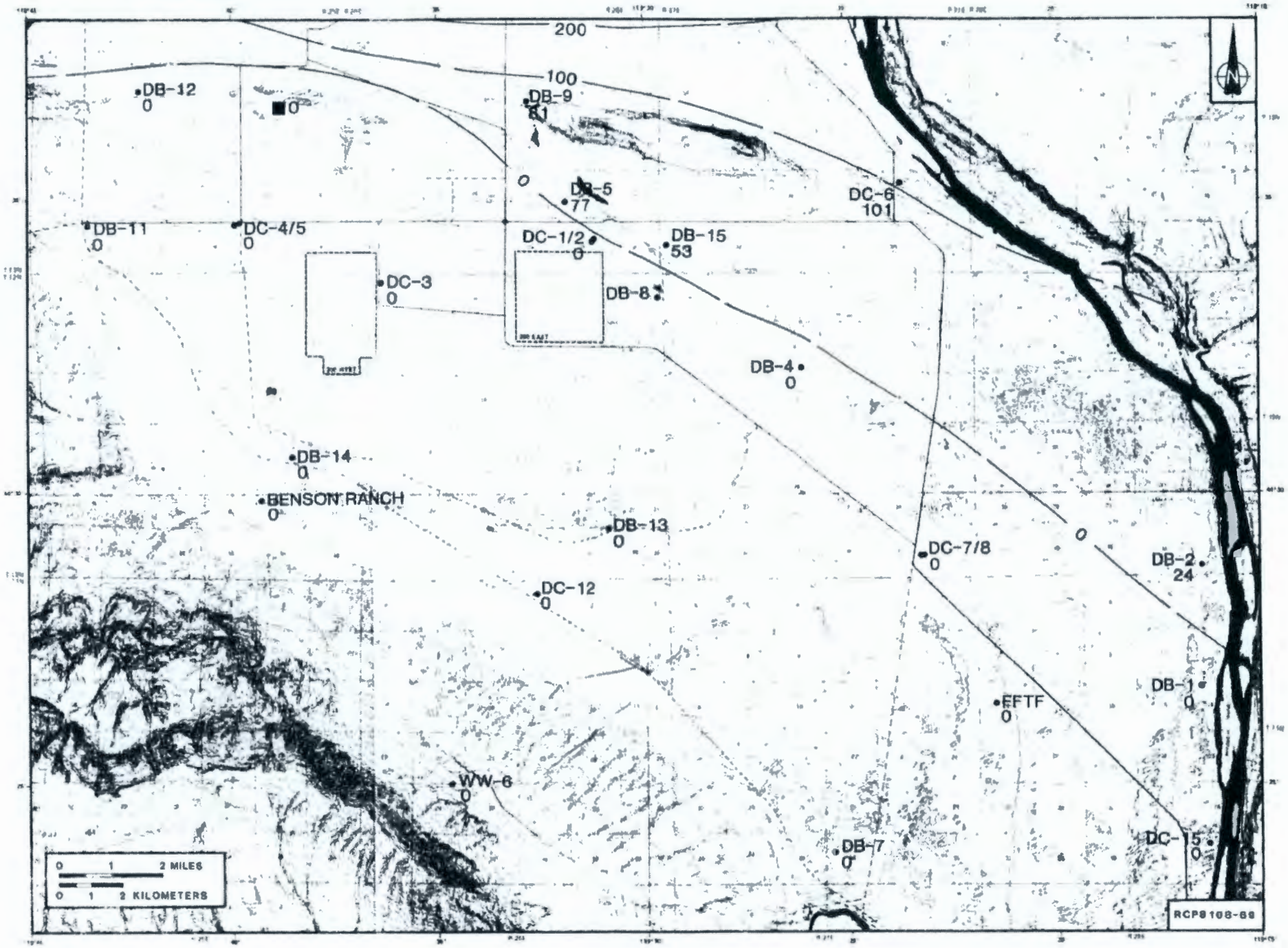

FIGURE 3-11. Isopach Map, Asotin Member, Cold Creek Syncline. Contour interval is 100 ft. See Figure 3-2 for location of structural features and Table 3-1 for explanation.

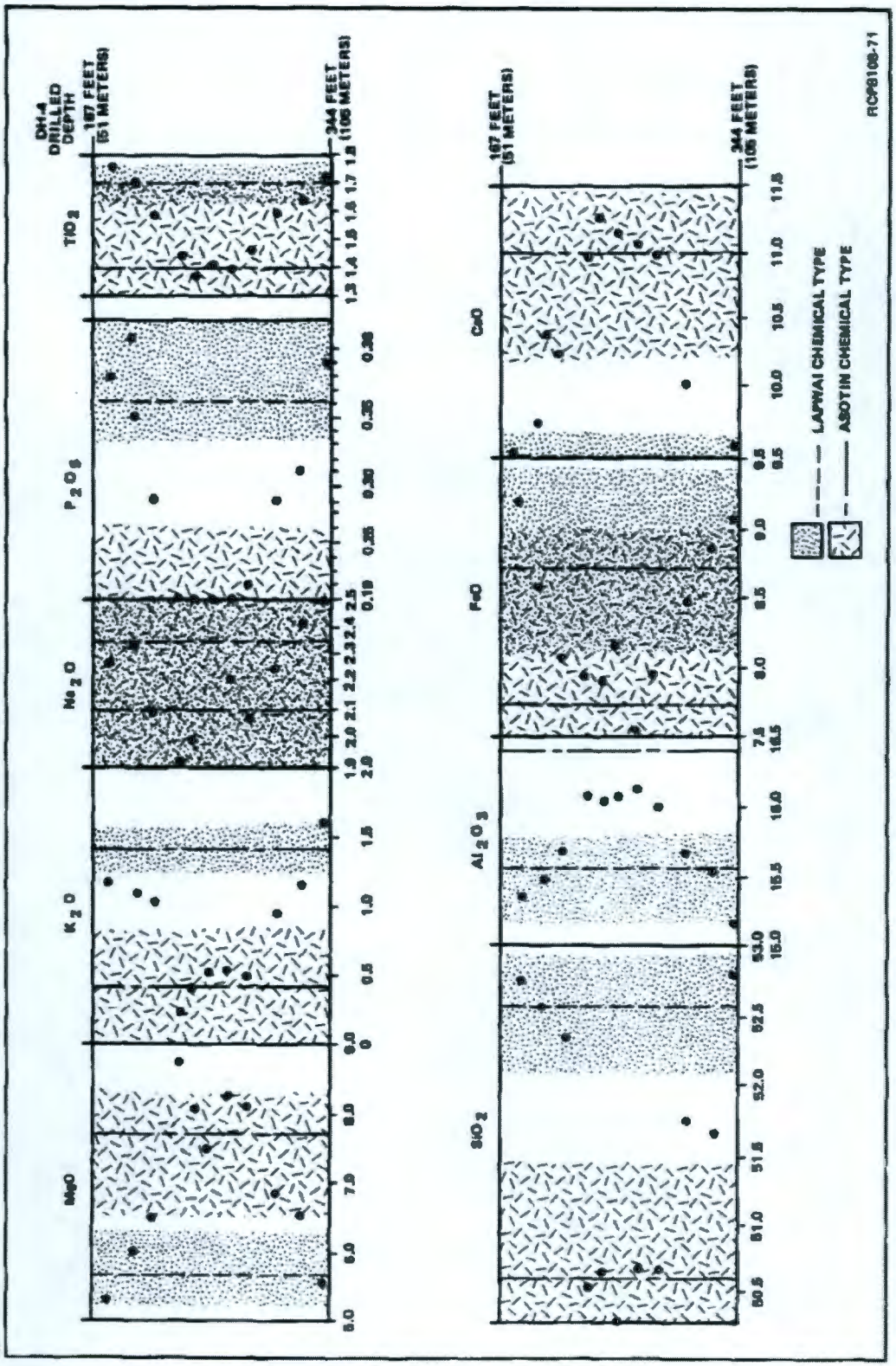

FIGURE 3-12. Chemical Variation of the Asotin Member, Borehole DH-4. Dots represent an analysis from a particular depth in the core. Dashed line represents the mean of the Lapwai chemical type and dotted pattern is the range (from Wright and others, 1980). Long dashed line is the mean of the Asotin chemical type and pattern is the range (from Swanson and others, 1979b).

interpreted (Reidel and others, 1980) to have entered from the east near Mesa and spread into the northern Pasco Basin. As it flowed south, a topographic low between the northward-tapering flow front of the Umatilla Member and the westward-dipping paleoslope channeled the Huntzinger flow. The Huntzinger flow lapped onto the Umatilla Member and pinched out on the slope formed by the flow front. The Umtanum Ridge-Gable Mountain structure also contributed to controlling the southern extent of the Huntzinger flow.

ESQUATZEL MEMBER

The Esquatzel Member in the Pasco Basin consists of one to two flows or flow lobes and varies in thickness from 21 to 38 m (Fig. 3-13) across the Cold Creek syncline. In the eastern Cold Creek syncline, there are two Esquatzel flows or flow lobes that occur locally with a vitric tuff between them (in core from DB-1 and DB-2).

The Esquatzel Member is plagioclase-phyric to glomerophyric and contains microphenocrysts of clinopyroxene. The abundance of phenocrysts is variable throughout the Cold Creek syncline area, with some localities completely void of phenocrysts.

The average chemical composition of the Esquatzel Member is given in Table 3-2 and falls within the Esquatzel chemical type of Swanson and others (1979b). Van Alstine and Gillett (in press) indicated that flows of the Esquatzel Member have normal polarity with a mean declination of 348.4^{0} and a mean inclination of $+64.8^{0}$ (Table 3-3). These results are similar to those determined by Choinier and Swanson (1979) for the Esquatzel Member.

Flows of the Esquatzel Member entered the Pasco Basin from the east near Mesa in a channel that was cut into the Priest Rapids Member (Swanson and others, 1979a; Reidel and others, 1980). It is confined to the south and east parts of the Pasco Basin and pinches out along and north of the Umtanum Ridge-Gable Mountain structure. It is thicker in the western Cold Creek syncline area north of the Yakima Ridge subsurface extension. It also thins across the subsurface extension of the Yakima Ridge and Rattlesnake Mountain structures and pinches out just south of the present crest of Rattlesnake Mountain. Flows of the Esquatzel, Asotin, and Wilbur Creek Members exited the Pasco Basin in channels to the west (Goff, 1981; Goff and Myers, 1978; Reidel and others, 1980).

Several factors probably controlled the distribution of the Esquatzel Member in the Cold Creek syncline. First, the margin of the Huntzinger flow of the Asotin Member formed a barrier that prevented the Esquatzel flow from spreading across the northern Pasco Basin. The channel that the Esquatzel flows occupies near Mesa is probably part of the same channel that is now filled by sediments along the southern margin of the Huntzinger flow in the Cold Creek syncline. The Umtanum Ridge-Gable Mountain structure was a structural high that influenced the spread of the Esquatzel flows to the west, as indicated by the absence of the Esquatzel Member west of Gable Butte and in DB-12 (Fig. 3-10). Rattlesnake Mountain was also important in controlling flows of the Esquatzel Member, as evidenced by its pinchout near the present crest.

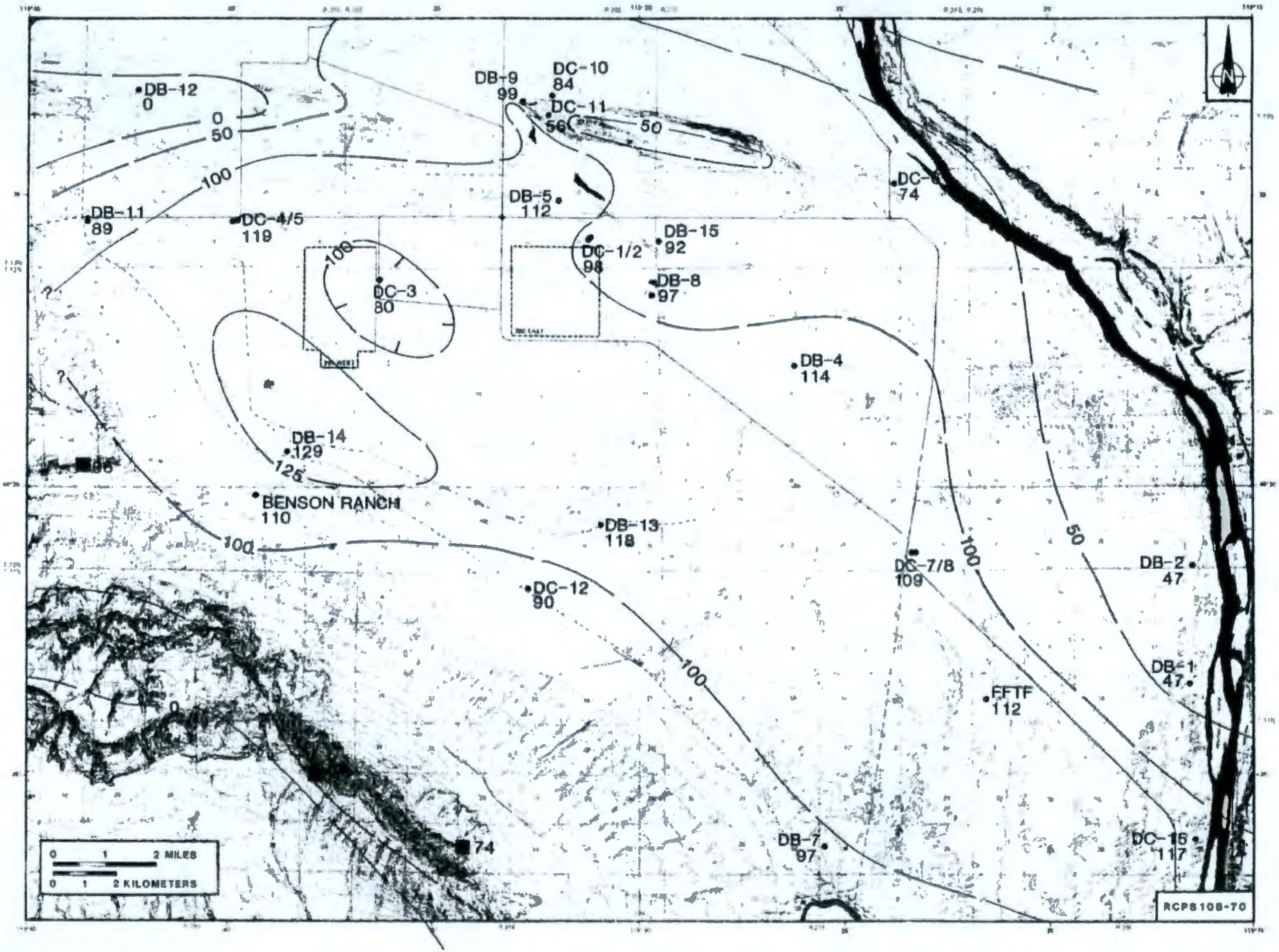

FIGURE 3-13. Isopach Map, Esquatzel Member, Cold Creek Syncline. Contour interval is 25 ft. See Figure 3-2 for location of structural features and Table 3-1 for explanation.

POMONA MEMBER

The Pomona Member was erupted from dikes near Orofino, Idaho (Camp, in Swanson and others, 1979a) and has been dated at 12 mybp (McKee and others, 1977). The member consists of one to two flows or flow lobes in the Pasco Basin and varies in thickness from 37 to 56 m (Fig. 3-14) in the Cold Creek syncline area.

The texture of the Pomona Member is relatively uniform across the Pasco Basin. It typically is fine grained to glassy with wedge-shaped plagioclase phenocrysts and rare olivine.

The Pomona Member has a distinct chemical composition (Pomona chemical type of Wright and others, 1973) with little overall variance (Table 3-2). The member has reversed magnetic polarity (Rietman, 1966; Choinier and Swanson, 1979). This polarity was corroborated by Van Alstine and Gillett (in press) who also found the Pomona has the tightest inclination and declination grouping of any flow analyzed from the Columbia River Basalt Group. The Pomona Member has a mean declination of 193.5^{o} and a mean inclination of -52.7^{o} (Table 3-3). It is proposed that the Pomona Member within the Pasco Basin may be comprised of two separate flows rather than two flow lobes. This premise is supported by the fact that the two distinct and separate flows of the Umatilla Member also have nearly the same chemical compositions and magnetic declinations and inclinations.

The Pomona Member is present throughout most of the Pasco Basin and reaches its greatest thickness in the southeast portion of the Cold Creek syncline and just north of Gable Mountain (DC-14; Fig. 3-2) in the Wahluke syncline. The Pomona Member thins over the Umtanum Ridge-Gable Mountain structure, Rattlesnake Mountain, and the subsurface extension of Yakima Ridge.

The volume of Pomona lava that was flowing into the Pasco Basin was considerably greater than that of the Umatilla, Wilbur Creek, Asotin, and Esquatzel Members. This volume overcame any effects of flow edges and topography, and the Pomona flow buried the topography of the Cold Creek syncline and much of the Pasco Basin.

ELEPHANT MOUNTAIN MEMBER

The Elephant Mountain Member consists of two separate flows: (1) Elephant Mountain flow of Waters (1955) and (2) Ward Gap flow of Schmincke (1967b). It varies in thickness from 0 to almost 46 m in the Cold Creek syncline area (Fig. 3-15).

The texture of the flows is medium to fine grained with abundant microphenocrysts of plagioclase. Where lava ponded, the flows exhibit a coarse-grained texture. Both flows (Table 3-2) fit the Elephant Mountain chemical type of Wright and others (1973).

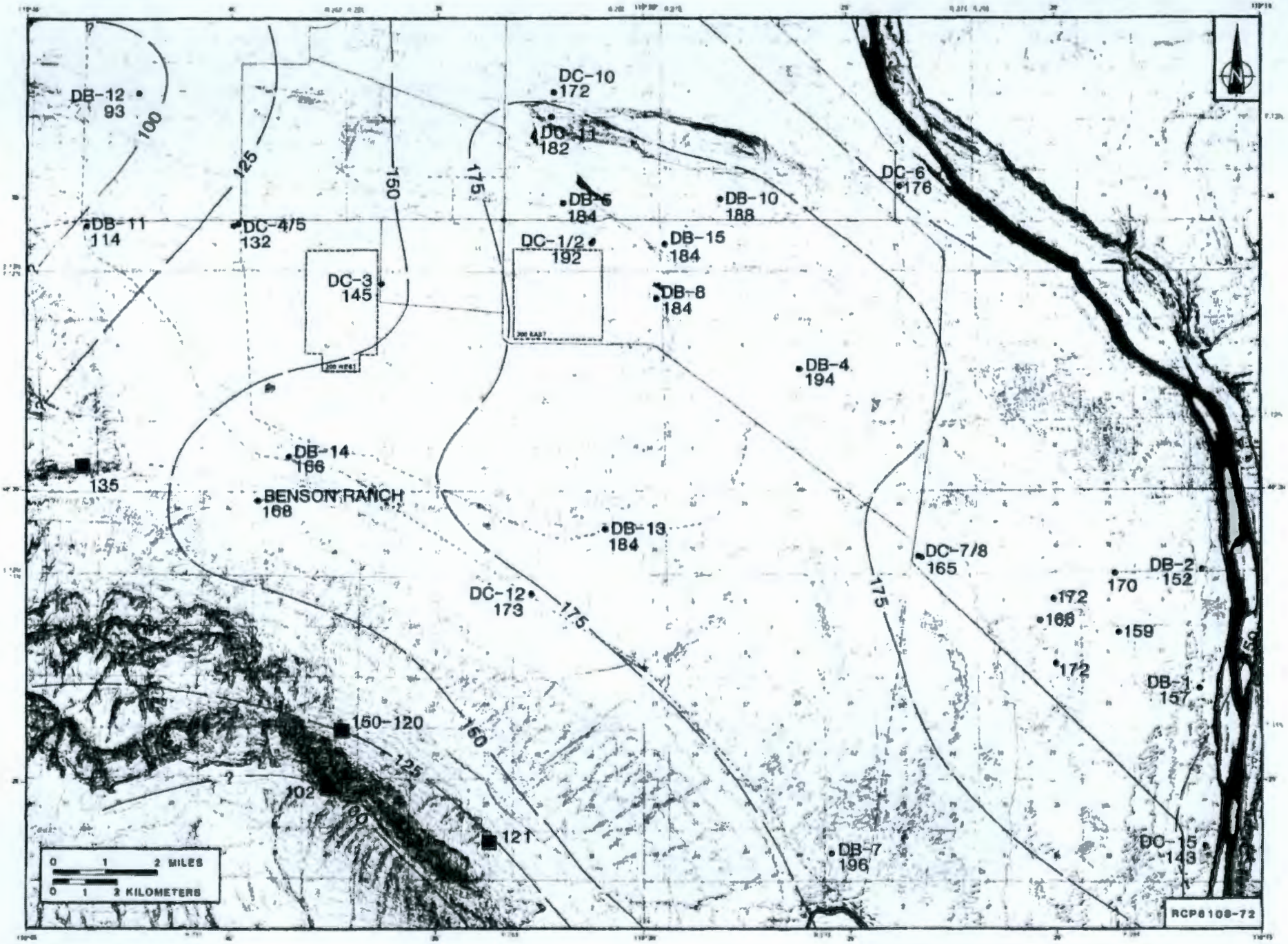

FIGURE 3-14. Isopach Map, Pomona Member, Cold Creek Syncline. Contour interval is 25 ft. See Figure 3-2 for location of structural features and Table 3-1 for explanation.

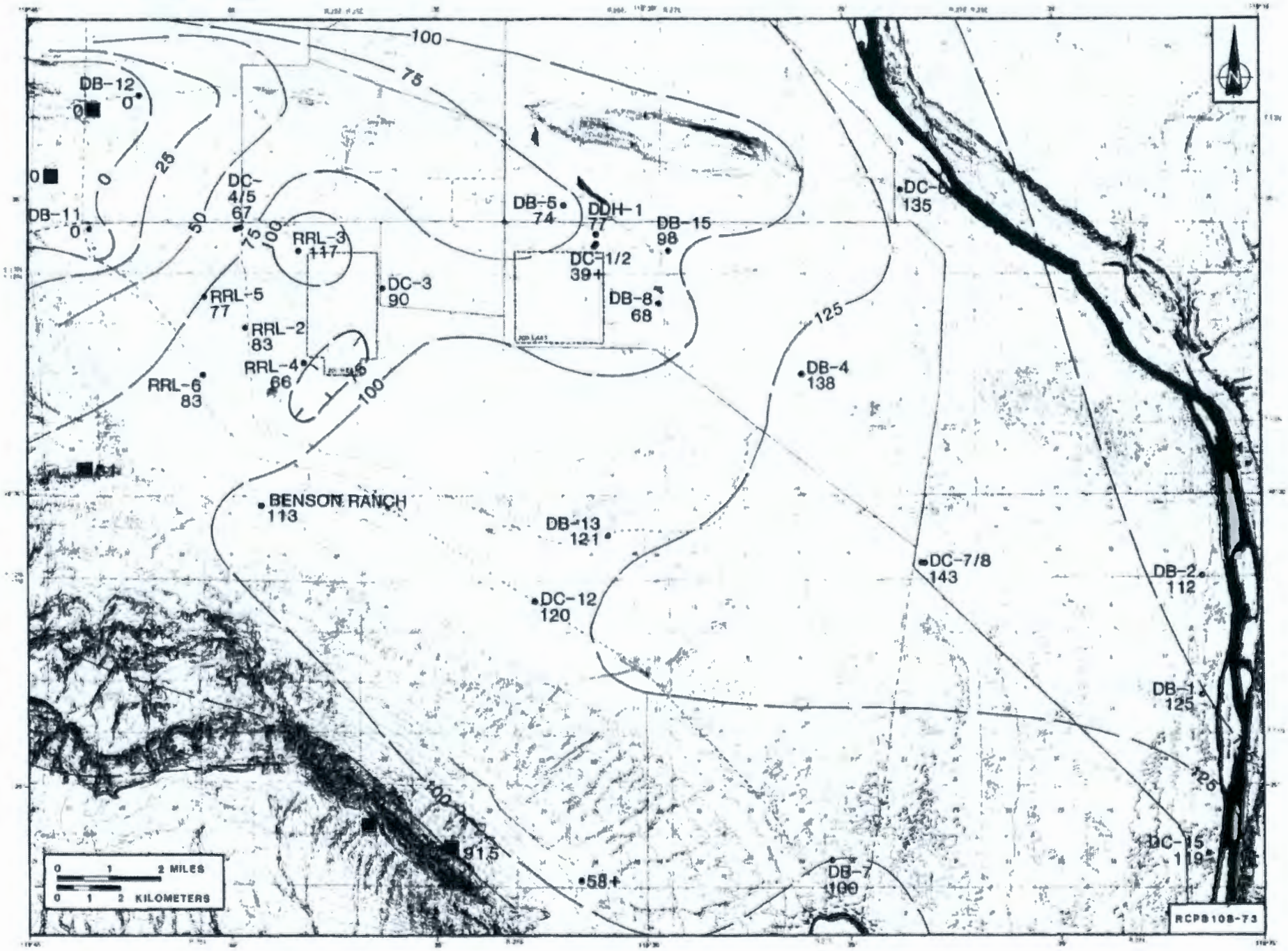

FIGURE 3-15. Isopach Map, Elephant Mountain Member, Cold Creek Syncline. Contour interval is 25 ft. See Figure 3-2 for location of structural features and Table 3-1 for explanation.

Choinier and Swanson (1979) and Rietman (1966) reported that the Elephant Mountain Member has transitional to normal magnetic polarity. Van Alstine and Gillett (in press) sampled surface exposures and found that both flows yielded a mean declination of 133.2° and a mean inclination of -39.2° (Table 3-3).

The Elephant Mountain Member is stratigraphically younger than the Rattlesnake Ridge interbed, but in many areas, an invasive relationship between basalt and sediment has been observed. Both Elephant Mountain Member flows pinch out in the northwest part of the Cold Creek syncline (Fig. 3-10). The member is thicker in the eastern part of the Cold Creek syncline area and thins toward Rattlesnake Mountain. The lower Elephant Mountain flow has a greater lateral extent than the upper flow (Ward Gap flow), but pinches out before reaching the DB-11/DB-12 area (Fig. 3-10). The Elephant Mountain Member defines the top of basalt (TOB) in the western Cold Creek syncline area.

ICE HARBOR MEMBER

The Ice Harbor Member is the youngest member of the Saddle Mountains Basalt present in the Pasco Basin and was erupted from vents on the east side of the basin 8.5 mybp (McKee and others, 1977). The member consists of three flows (Fig. 3-1): (1) Basin City, (2) Martindale, and (3) Goose Island. The flows of the Ice Harbor Member are generally no >30 m thick.

The flows are typically fine to medium grained with glomerocrysts and phenocrysts of olivine, plagioclase, and clinopyroxene. The overall petrography of the flows varies. Olivine occurs primarily in the Martindale and Basin City flows, while the Goose Island flow contains glomerocrysts of pyroxene and plagioclase. The average chemical compositions for flows of the Ice Harbor Member from the Pasco Basin are given in Table 3-2. These flows comprise three chemical types for the Ice Harbor Member (Swanson and others, 1979b).

Choinier and Swanson (1979) sampled flows of the Ice Harbor Member for remanent magnetic polarity. They found that the Goose Island and Basin City flows have normal magnetic polarity, while the Martindale flow has reversed polarity (Table 3-3).

Two flows of the Ice Harbor Member are present in the extreme southeast portion of the Cold Creek syncline: (1) Martindale and (2) Goose Island. The Martindale flow is present in DDH-3 and DC-15 (Fig. 3-10), but the Goose Island flow is present only in the most northern one, DC-15. The older, Martindale, flow front controlled the younger, Goose Island flow, forcing it along the lower topographic area between the Martindale flow front and the regional paleoslope.

ELLENSBURG FORMATION

Intercalated with and overlying the flows of the Columbia River Basalt Group in the western and central Columbia Plateau in Washington are sedimentary beds of the Ellensburg Formation (Smith, 1901; Schmincke, 1964, 1967a; Swanson and others, 1979b). As a unit, these sediments are relatively thick along the western margin of the plateau and thin eastward onto the central Columbia Plateau. Within the Pasco Basin, Ellensburg sediments are primarily interbedded in the Wanapum and Saddle Mountains Basalts. The lateral extent and thickness of the sediments generally increase upward in the section.

The Ellensburg Formation of the central plateau is composed of two, major, and distinct lithologies of different provenance (Schmincke, 1964, 1967a; Swanson and others, 1979b). One includes volcaniclastic sediments deposited as ashfall and by tributary rivers flowing onto the central plateau. The other includes clastic, plutonic, and metamorphic rock derived from Rocky Mountain terrain that was carried onto the plateau by westward-flowing, ancestral rivers. These two, major lithologies occur either as distinct or mixed deposits within the Ellensburg Formation of the Pasco Basin.

The nomenclature used for the individual interbeds within the Ellensburg Formation in the Cold Creek syncline is informal and is based on upper- and lower-bounding basalt flows (Fig. 3-1). Therefore, discussions of individual units are restricted to those units with consistent upper- and lower-bounding flows.

VANTAGE INTERBED

The Vantage interbed is comprised of sediments lying between the Frenchman Springs Member of the Wanapum Basalt and the Sentinel Bluffs sequence of the Grande Ronde Basalt in the Pasco Basin. This interbed is the lowest, relatively continuous, Ellensburg unit in the Pasco Basin. The Vantage interbed is ∿24 m thick in the northwestern Pasco Basin, but thins to the southeast and locally pinches out (Fig. 3-16). The northwestern area probably represents a low that formed between the regional paleoslope and the Hog Ranch structure, which was a topographic high during Grande Ronde time. Saprolite formed on the Grande Ronde Basalt beyond the area of sedimentation during this time.

The thicker sequences of Vantage consist of arkosic sandstone locally containing thin, clay stringers with a clay cap. The thinner sequences of Vantage consist of clays which are altered tuffs.

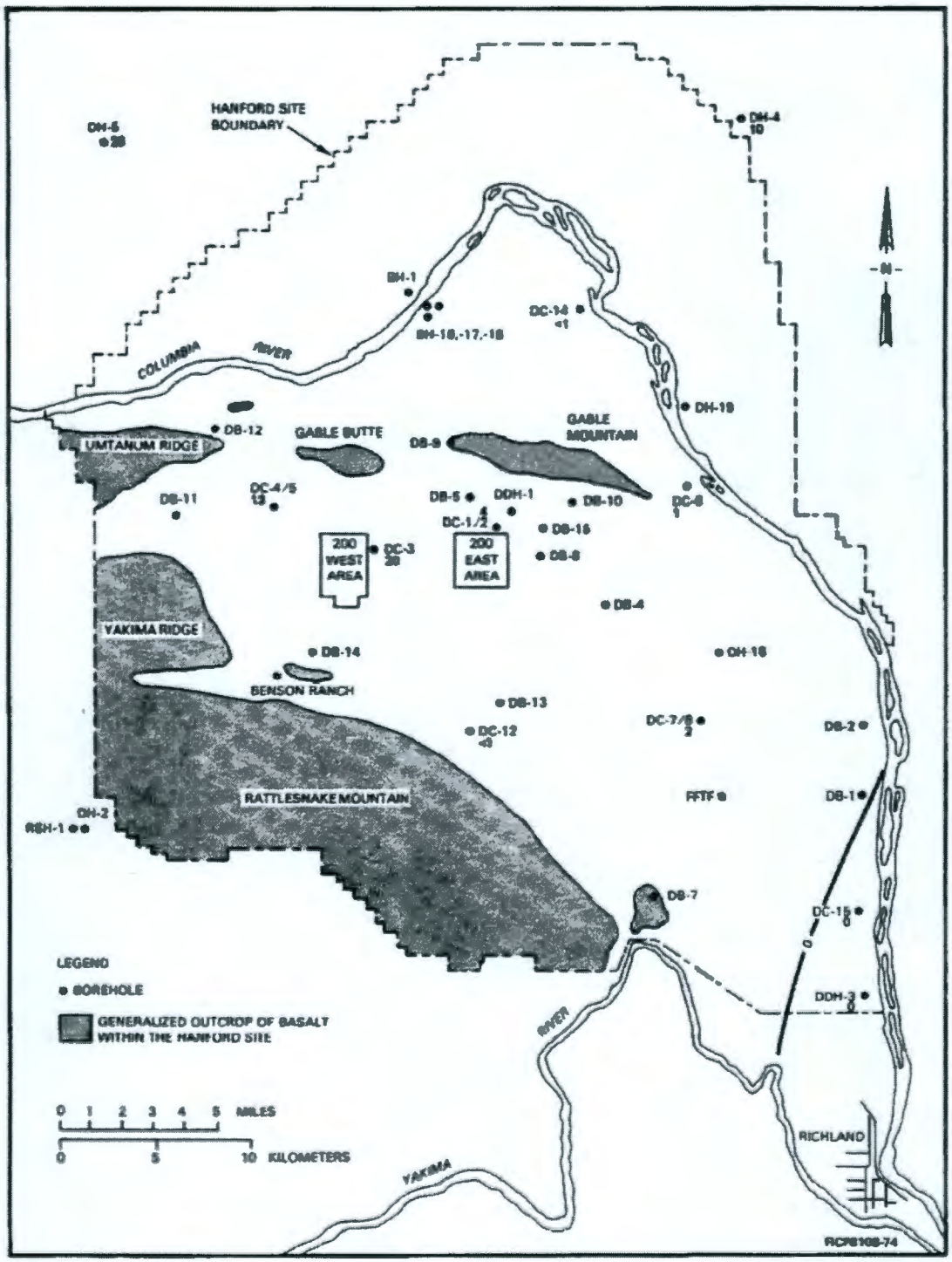

FIGURE 3-16. Isopach Map, Vantage Interbed. Contour interval is 50 ft. Thickness variations are less than contour interval. Thicknesses are shown for only those boreholes that penetrate the Vantage interbed.

MABTON INTERBED

The Mabton interbed is stratigraphically below the Umatilla Member and above the Priest Rapids Member in the Pasco Basin. The Mabton interbed is thickest in the central Pasco Basin area and thins in all directions (Fig. 3-17). Vertical lithologic and textural changes in the Mabton interbed are relatively uniform. From top to bottom, the interbed generally consists of (1) a well-indurated, lapilli tuffstone, locally baked; (2) a fine-grained, tuffaceous, clayey quartzitic sandstone; (3) a quartzitic to arkosic sandstone with interlayered, tuffaceous sandstones and siltstones; and (4) commonly a thin, basal, silty clay.

COLD CREEK INTERBED

The Cold Creek interbed refers to the sequence of Ellensburg sediments that occur stratigraphically between the Esquaztel and Umatilla Members of the Saddle Mountains Basalt. The Asotin Member partially controlled the distribution of part of the Cold Creek interbed. Three separate units of the interbed are identified on the basis of bounding flows. These intervals are the Umatilla-Esquaztel, Umatilla-Asotin, and Asotin-Esquatzel intervals.

Umatilla-Esquatzel Interval

The Umatilla-Esquatzel interval is the thickest interbed and has the largest areal extent (Fig. 3-18). This interval is divided into two textural facies: (1) a finer grained, tuffaceous sandstone facies and (2) a coarser sandstone and conglomerate facies with tuffaceous siltstone and clays. The coarser grained facies follows an arcuate trend that is subparallel to the flow front of the Asotin Member. The coarser grained facies represents the high-energy, main channel of a fluvial system which is interpreted to have flowed parallel to the flow front of the Asotin Member.

Umatilla-Asotin Interval

The Umatilla-Asotin interval which has a small, lateral extent (Fig. 3-19) is generally thin, <6 m, or not present. Where present, the unit is composed chiefly of tuffaceous siltstones and tuffaceous claystones.

Asotin-Esquatzel Interval

The Asotin-Esquatzel interval is generally thin (<3 m), but in the vicinity of DB-15 along the southern margin of the interval, it thickens to 29 m (Fig. 3-20). North and south of Gable Mountain the interval consists of tuffs and clay, arkosic to quartzose sandstones, and basaltic conglomerates. The interbed is not present along the Gable Mountain structure.

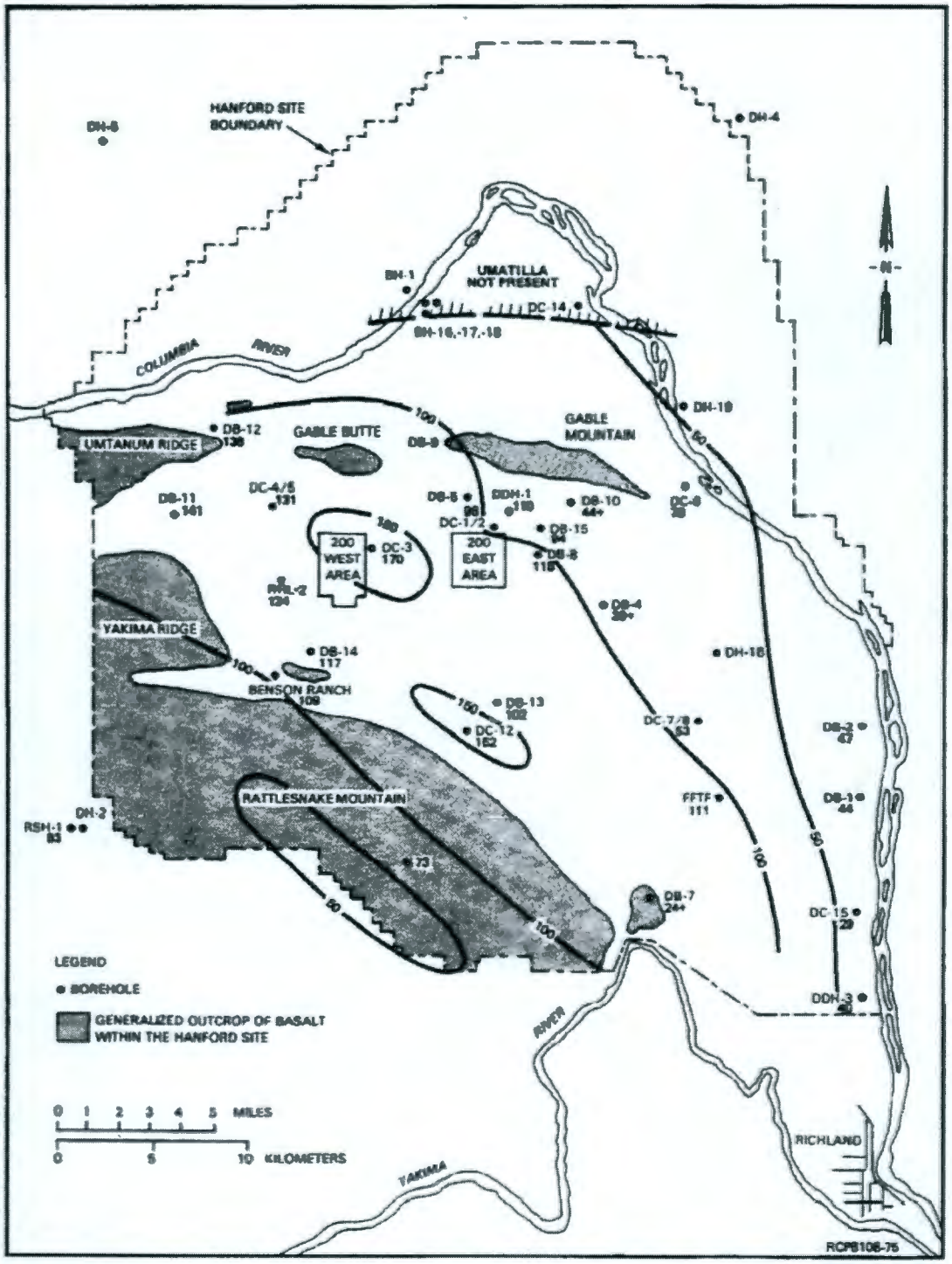

FIGURE 3-17. Isopach Map, Mabton Interbed. Contour interval is 50 ft. Thicknesses are shown for only those boreholes that penetrate the Mabton interbed. See Table 3-1 for explanation.

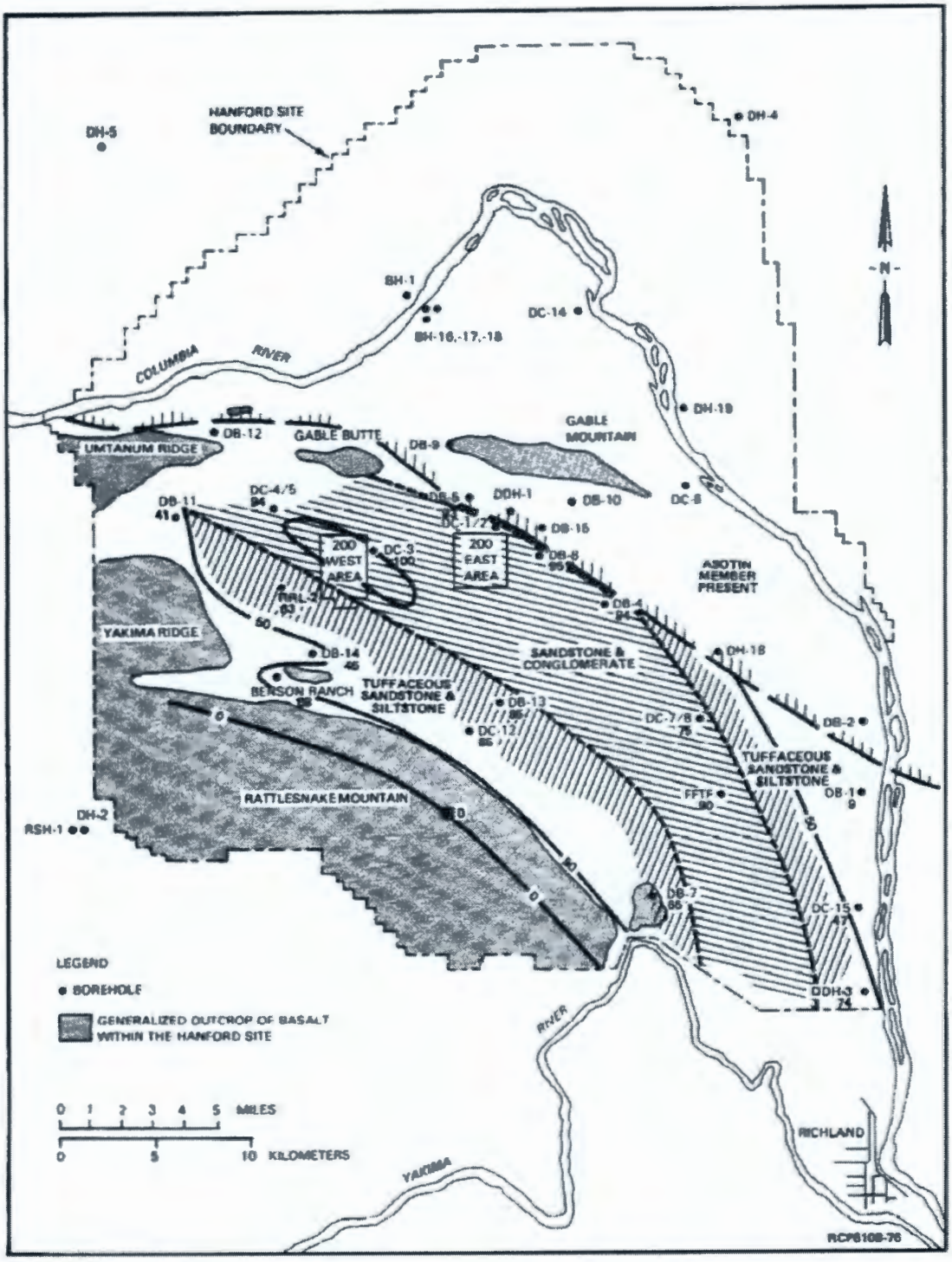

FIGURE 3-18. Isopach Map, Umatilla-Esquatzel Interval, Cold Creek Interbed, Cold Creek Syncline. Contour interval is 50 ft. Thicknesses are shown for only those boreholes that penetrate the sedimentary interval. See Table 3-1 for explanation.

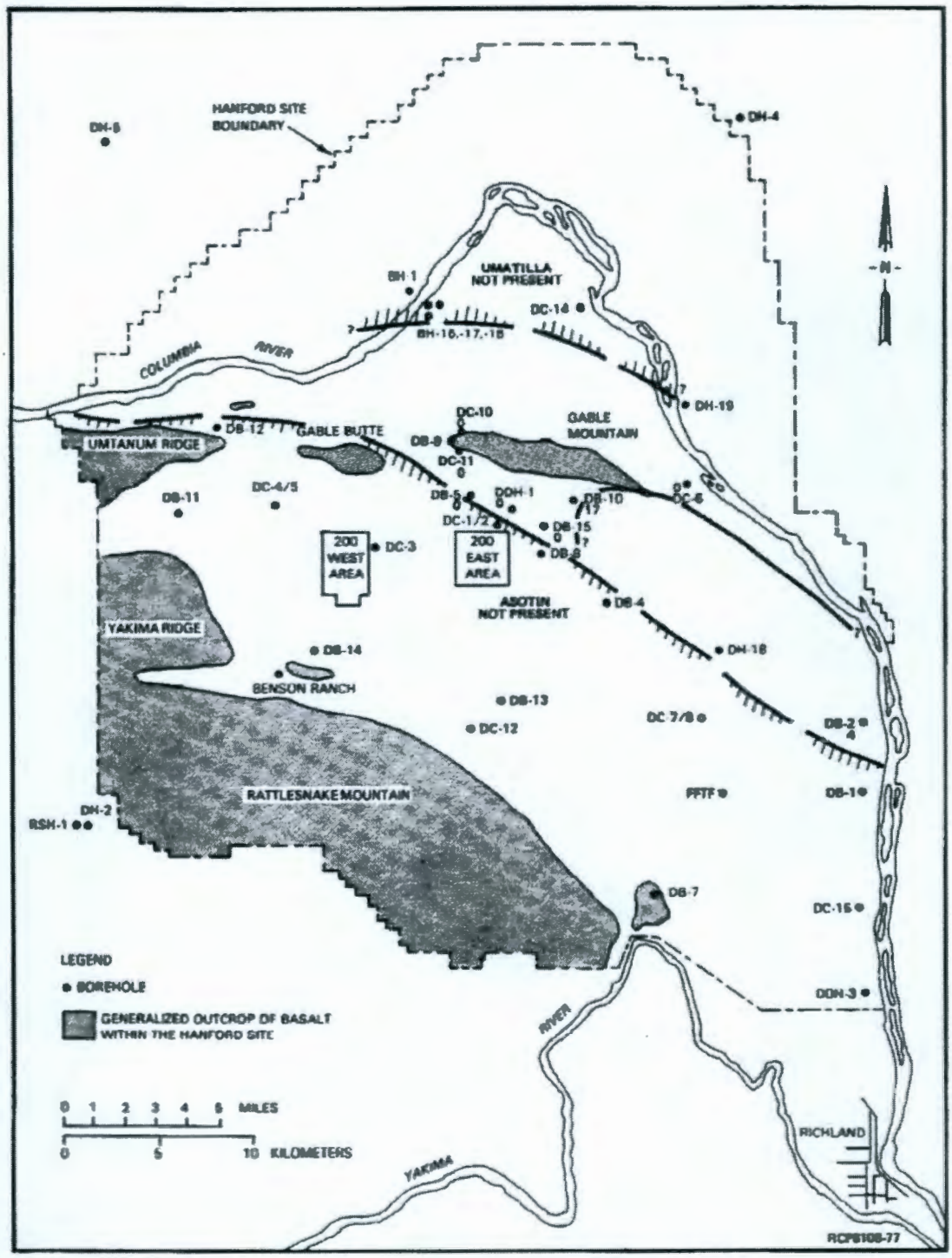

FIGURE 3-19. Isopach Map, Umatilla-Asotin Interval, Cold Creek Interbed, Cold Creek Syncline. Contour interval is 50 ft. Thicknesses are shown for only those boreholes that penetrate the sedimentary interval. See Table 3-1 for explanation.

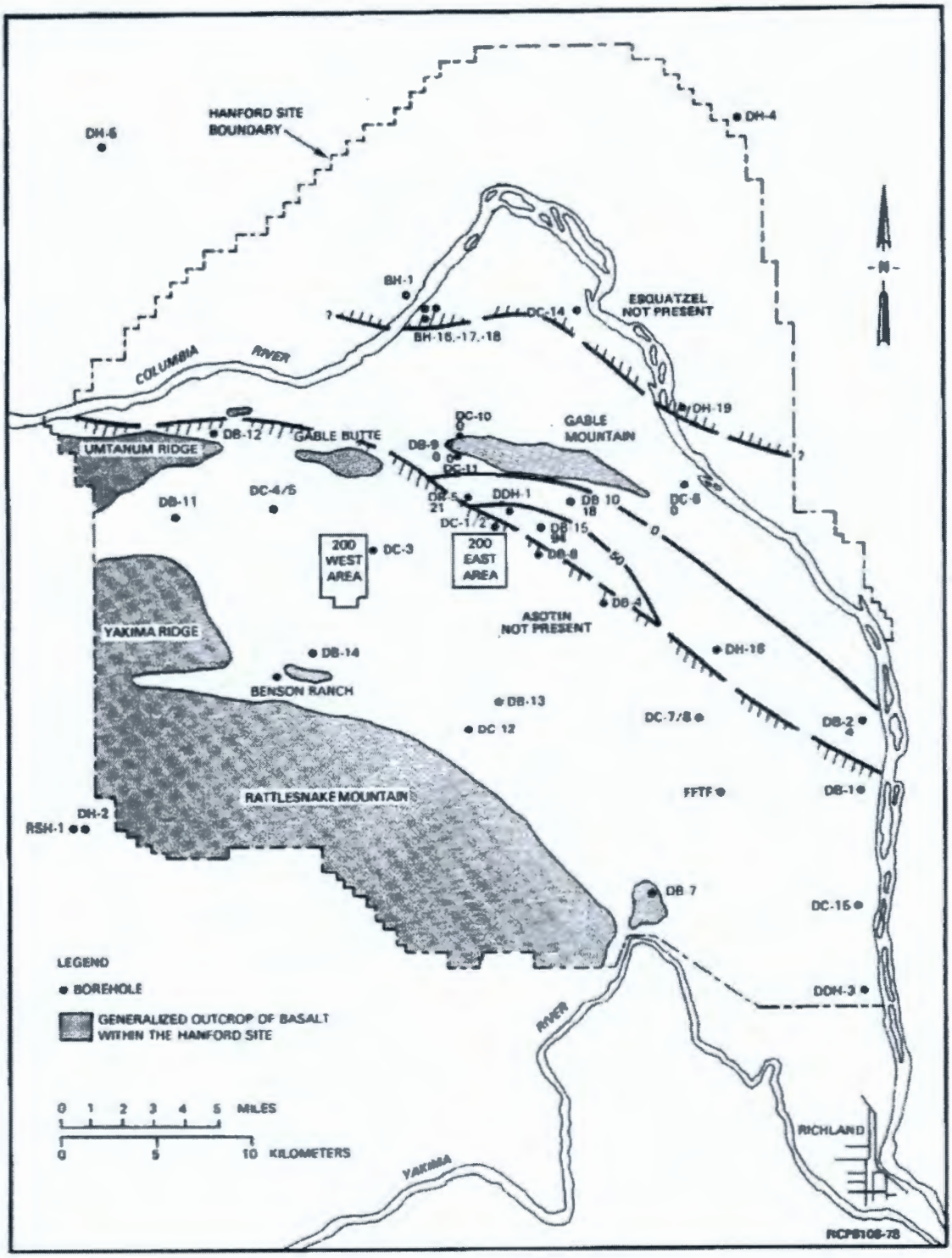

FIGURE 3-20. Isopach Map, Asotin-Esquatzel Interval, Cold Creek Interbed, Cold Creek Syncline. Contour interval is 50 ft. Thicknesses are shown for only those boreholes that penetrate the sedimentary interval. See Table 3-1 for explanation.

SELAH INTERBED

Interbedded between the Esquatzel and Pomona Members of the Saddle Mountains Basalt is the Selah interbed (Fig. 3-21). The lateral extent of the Selah interbed is restricted by the lateral extent of the Esquatzel Member. Lithologically and texturally, the interbed is a variable mixture of silty or sandy, vitric tuff, arkosic sands, tuffaceous clays, and locally thin stringers of predominantly basaltic gravels. The upper portion of the Selah interbed is a vitric tuff commonly fused to a perlitic vitric tuff by the overlying Pomona Member. Opaline silica and pepperite are common at the Pomona contact. In the northwestern Pasco Basin, sediments judged to be equivalent in age to the Selah of the central Pasco Basin consist of conglomerates containing plutonic and metamorphic clasts.

RATTLESNAKE RIDGE INTERBED

The Rattlesnake Ridge interbed (Fig. 3-22) is bounded by the overlying Elephant Mountain Member and the underlying Pomona Member. The interbed is present throughout the Pasco Basin, except locally on portions of structural ridges. In the Pasco Basin, the Rattlesnake Ridge interbed varies up to 33 m in thickness and can be divided into three facies based on lithology and texture. The first facies occurs in the central Cold Creek syncline area and generally consists of three units: (1) a lower clay or tuffaceous sandstone; (2) a middle, micaceous-arkosic and/or tuffaceous sandstone; and (3) an upper, tuffaceous siltstone or tuffaceous sandstone. The second facies is a single, tuffaceous, sandstone-to-siltstone unit and occurs where the interbed is relatively thin. The third facies occurs on the northwestern margin of the Pasco Basin. Here, the Rattlesnake Ridge interbed generally consists of three units. The upper two units are similar in texture and lithology to the first facies. The lower unit, however, is a conglomerate with plutonic and metamorphic clasts. On Yakima Ridge, the Rattlesnake Ridge interbed thins with only the upper tuffaceous unit and, locally, the conglomerate unit present.

LEVEY INTERBED

The Levey interbed is defined as the sediments between the Ice Harbor and Elephant Mountain Members of the Saddle Mountains Basalt. These sediments are the youngest Ellensburg sediments in the Pasco Basin and are found throughout the southeastern Pasco Basin from DC-15 to Wallula Gap and from Ice Harbor Dam to Red Mountain (Fig. 3-23). Along its northern extent, the Levey interbed is a tuffaceous sandstone which is known to be 5 to 9 m thick. Exposures of Levey interbed along the southern and western margins of the Pasco Basin are <6 m thick and consist of a fine-grained, typically tuffaceous silt or siltstone. The Levey interbed has been locally oxidized by the overriding Ice Harbor flow(s).

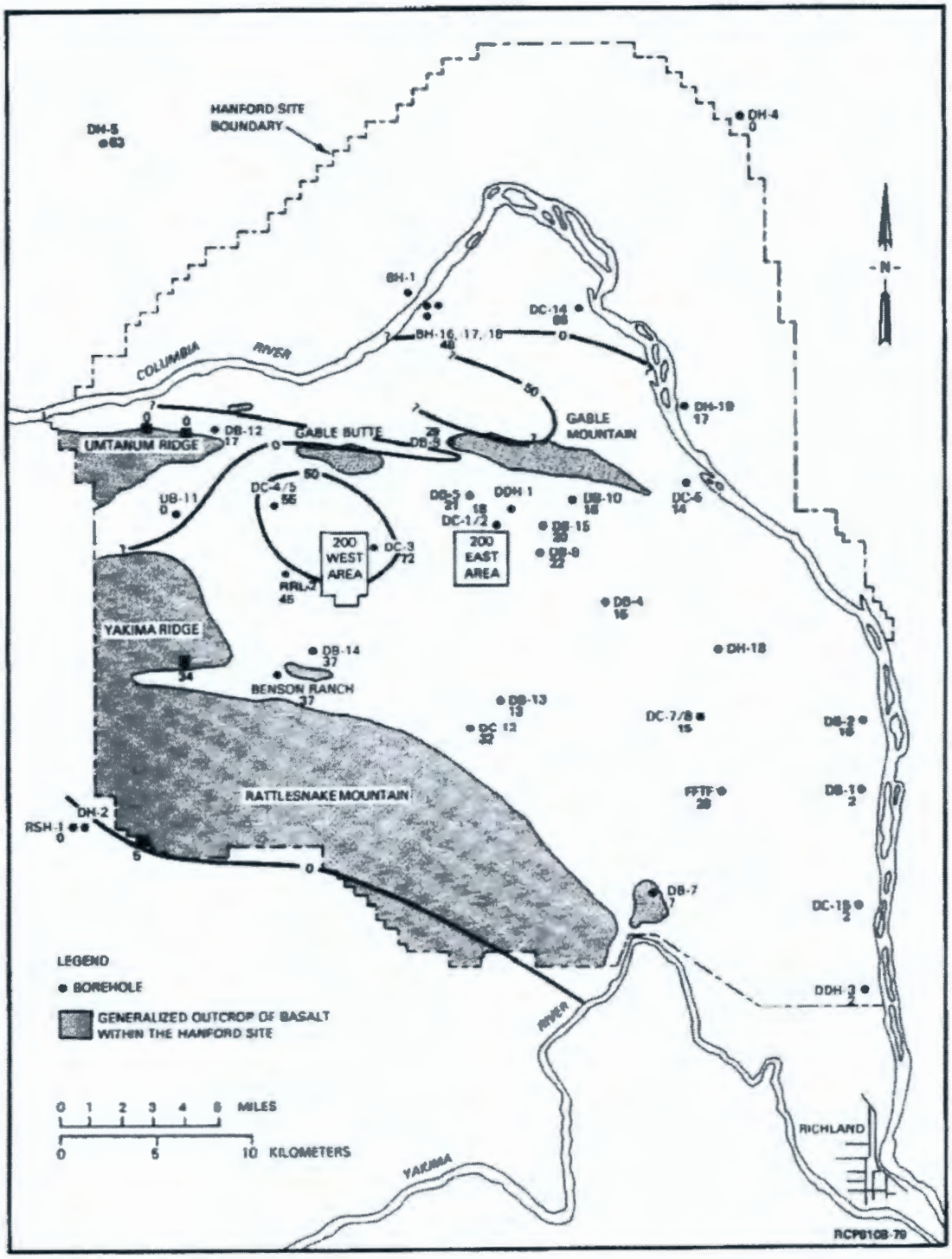

FIGURE 3-21. Isopach Map, Selah Interbed, Cold Creek Syncline. Contour interval is 50 ft. Thicknesses are shown for only those boreholes that penetrate the sedimentary interval. See Table 3-1 for explanation.

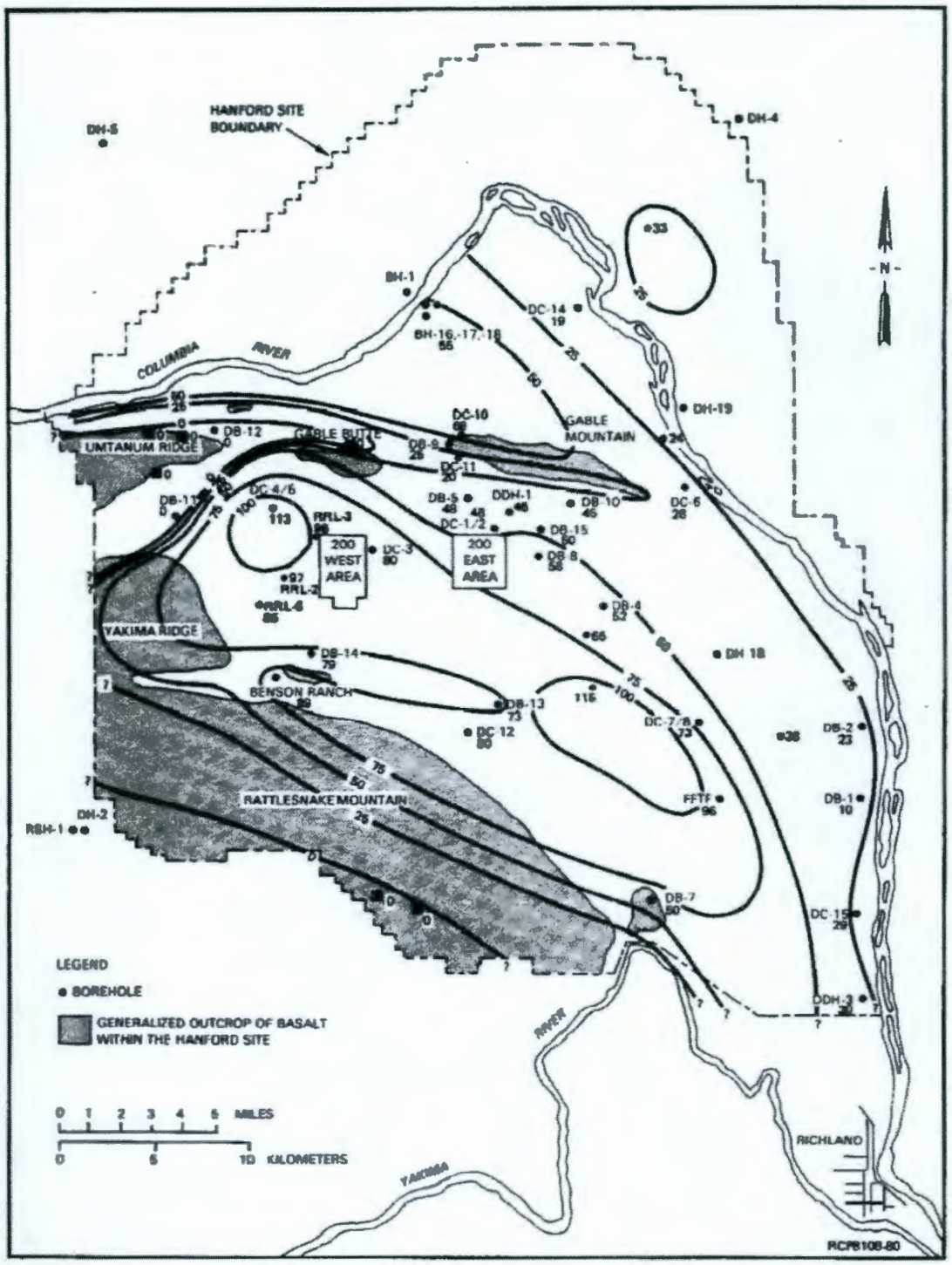

FIGURE 3-22. Isopach Map, Rattlesnake Ridge Interbed, Cold Creek Syncline. Contour interval is 50 ft. Thicknesses are shown for only those boreholes that penetrate the sedimentary interval. See Table 3-1 for explanation.

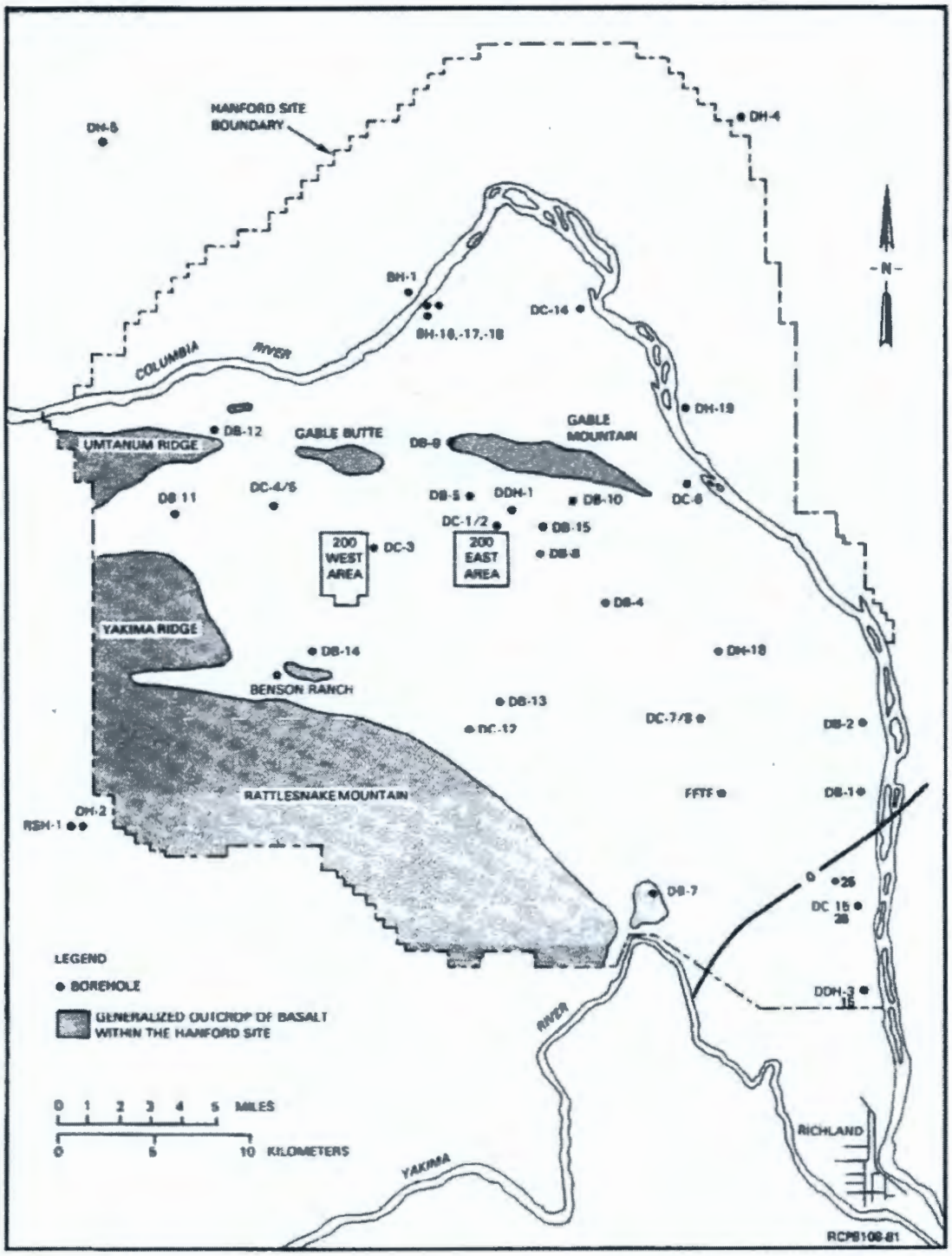

FIGURE 3-23. Isopach Map, Levey Interbed, Cold Creek Syncline. Thicknesses are shown for only those boreholes that penetrate the sedimentary interval. See Table 3-1 for explanation.

MEMBER THICKNESS VARIATIONS IN THE REFERENCE REPOSITORY LOCATION

The members of the Wanapum Basalt show very little thickness variation across the RRL (Fig. 3-2 and Table 3-4). Both the Roza and Priest Rapids Members have northwest-southeast thickness trends across the area, but the Frenchman Springs Member shows no apparent pattern. The total thickness variation for an individual member is <10 m, with the Frenchman Springs Member having the most (10 m) and the Roza Member having the least (3 m).

Considerably more variation in thicknesses of individual members occurs in the Saddle Mountains Basalt (Table 3-4) across the RRL. The Umatilla Member has 20 m of variation across the area, with an abrupt change along a northwest-southeast trend in the northeast part of the area. The thickness is relatively constant across the rest of the RRL. The Wilbur Creek, Asotin, and Ice Harbor Members are not present in this area. There is a 15-m-thickness variation in the Esquatzel Member along a northeast-southwest trend in the RRL. The Esquatzel Member is thicker in the northeast part of the RRL and thinner in the southwest. The Pomona Member has only 10 m of variation and this occurs along a northeast-southwest trend. There is an anomalous area of thinning near DC-3 (Fig. 3-2) which has an apparent northwest-southeast trend. The Elephant Mountain Member has a 21-m-thickness variation across the RRL, also with a northeast-southwest trend. The Elephant Mountain Member thickens across the zone of thinning in the Pomona Member near DC-3. This member is relatively consistent across the rest of the area.

TABLE 3-4. Variation of Member Thickness in the Reference Repository Location.

Member	Thickness trend	Maximum observed variation
Elephant Mountain	NE-SW	21 m (15 to 35 m)*
Pomona	NE-SW	10 m (36 to 46 m)*
Esquatzel	None	15 m (24 to 39 m)*
Asotin	None present	-
Wilbur Creek	None present	-
Umatilla	NW-SE	20 m (46 to 66 m)*
Priest Rapids	NW-SE	6 m (64 to 71 m)*
Roza	NS to NW-SE	1 to 3 m (51 to 53 m)*
Frenchman Springs	None apparent	10 m (219 to 229 m)*

*Thickness range

MODEL FOR THE EMPLACEMENT OF WANAPUM AND SADDLE MOUNTAINS BASALT FLOWS

The lateral extent and thickness variations among individual flows of the Wanapum and Saddle Mountains Basalts in the Pasco Basin are the product of the collective interplay of four factors: (1) volume of each flow that entered the basin, (2) location of flow margins of previously emplaced flows, (3) effect of uplift and subsidence, and (4) regional paleoslope. The flow eruption and emplacement rate and rate of uplift and subsidence are so closely related that a detailed evaluation of the flow history and structural development of the basin during the late Miocene is possible.

Based on the extent and thickness variations of the basalt flows, it is apparent that the Pasco Basin and Cold Creek syncline were active structural features by at least the beginning of Wanapum time. The combined rate of uplift and subsidence in the Pasco Basin was calculated for the period of time over which the Wanapum and Saddle Mountains Basalt flows were erupted (Reidel and others, 1980) and found to be <80 m/million years. An assessment of the contribution of uplift versus subsidence was made by extrapolating Swanson and others' (1975) regional paleoslope into the Pasco Basin, and using the extrapolated surface of this paleoslope as a datum. Based on this datum, both the rates of uplift and subsidence were found to be <40 m/million years. These low uplift and subsidence rates combined with a relatively rapid eruption rate for the Wanapum Basalt indicate that only a small amount of relief on the Yakima fold structures was present when flows of this formation were emplaced. These rates also indicate that any structural relief existing and developing in Grande Ronde time would have been obscured by the large volume of lava which was erupted over a short period of time. A much greater length of time occurred between the eruption of Saddle Mountains Basalt flows, allowing more relief to develop along the structures during periods of volcanic quiescence. Consequently, the topography exerted greater control on the thickness and distribution of Saddle Mountains Basalt flows (Fig. 3-10).

The westward-dipping, regional paleoslope also controlled the extent and thickness of the flows that entered the Pasco Basin. Typically, the thicknesses of flows with large volumes that entered the Pasco Basin and ponded against the Yakima fold structures were controlled more by the topographic relief on structures than by other flows. As a flow ponded against a structure, the eastern flow margin encroached on the paleoslope until the topography was buried and the lava could flow unhindered down the paleoslope.

The volume of the individual eruptions contributed significantly to their lateral extent. Flows of great volume were typically able to bury the topography, so their lateral extent was nearly unaffected. The extent of flows with volumes that could not fill the basin were significantly affected by the topography produced by growing structures and previous flows. The Wilbur Creek, Asotin, Esquatzel, and Ice Harbor Members were of such a sufficiently low volume that they were greatly affected by the topography. The margins of previous flows combined with the existing

structural relief to produce channels. These channels controlled stream drainage during the eruption of flows and after the flows were emplaced. As a result, each new flow ponded in low areas caused by the edges of previous flows, the structural relief, and the paleoslopes. The extent to which a flow spread beyond these low areas was controlled by the volume of lava available.

Unconformities between the basalt flows of the Cold Creek syncline are of two types: (1) angular unconformities and (2) paraconformities. The angular unconformities resulted from onlap of basalt flows onto structural ridges on the margins of the Cold Creek syncline. Gentle tilting of the basalt flows occurred as the ridges grew and, as younger flows were emplaced, they onlapped the ridges at relatively shallow angles. Angular unconformities ($<10^{o}$) were produced between successive flows. In the central part of the Cold Creek syncline, very little structural relief was produced, but other previously mentioned factors caused limitations on the extent of the flows. Here, paraconformities are the predominant unconformity; these occur predominantly between the Saddle Mountains Basalt flows.

The overall geometry of the voluminous flows fits the present geometry of the Cold Creek syncline. The present structural asymmetry of anticlines with steep north flanks and gentle south flanks is reflected in the thickness distribution of the large-volume flows that filled a similar shaped basin in Wanapum and Saddle Mountains time. The thickest parts of the flows are on the south side of the syncline, with thinning over Rattlesnake Mountain and the subsurface extension of Yakima Ridge, and with a gradual thinning toward the Umtanum Ridge-Gable Mountain trend. The westward-dipping paleoslope and the geometry of the flows suggest that the asymmetry of the present structural ridges is probably similar to the geometry of the ridges in Wanapum and Saddle Mountains time, except that the Miocene Cold Creek syncline had less relief.

SUMMARY AND CONCLUSIONS

Basic information on the stratigraphy of the Wanapum and Saddle Mountains Basalts has been derived from a study of surface exposures and core and chip samples from drill holes. The Wanapum Basalt consists of three members in the Pasco Basin: (1) Frenchman Springs, (2) Roza, and (3) Priest Rapids. The Vantage interbed separates this formation from the underlying Grande Ronde Basalt. The petrographic characteristics, combined with distinct chemical differences, permit easy distinction of the Wanapum Basalt from the Grande Ronde Basalt. The Wanapum Basalt (13.5 to 14.5 million years old) is thickest in the central area of the Cold Creek syncline, but thins from west to east and over both the Rattlesnake Mountain and Umtanum Ridge-Gable Mountain structures.

The Saddle Mountains Basalt consists of seven members in the Pasco Basin: (1) Umatilla, (2) Wilbur Creek, (3) Asotin, (4) Esquatzel, (5) Pomona, (6) Elephant Mountain, and (7) Ice Harbor. With the exception of the Wilbur Creek Member, all members are present in the Cold Creek syncline area. The Saddle Mountains Basalt in the Pasco Basin ranges in age from 13.5 to 8.5 mybp.

The Saddle Mountains Basalt flows were extruded over a much greater interval of time than the flows of any other formation of the Columbia River Basalt Group and contain a wide diversity of petrographic characteristics, chemical types, and magnetic inclinations. Thickness variations in the Saddle Mountains Basalt are greater and more complex than in the Wanapum Basalt because of: (1) thinning over structures, (2) greater time between eruptions, and (3) limited extent of many flows.

Intercalated with and overlying the flows of the Columbia River Basalt Group are sedimentary beds of the Ellensburg Formation. Within the Pasco Basin, Ellensburg sediments primarily occur interbedded in the Wanapum and Saddle Mountains Basalts. The lateral extent and thickness of the sediments generally increase upward in the section.

The Ellensburg Formation of the central plateau is composed of two major and distinct lithologies of different provenance. One includes volcaniclastic sediments deposited as ashfall and by tributary rivers flowing on the central plateau. The other includes clastic, plutonic, and metamorphic rock derived from Rocky Mountain terrain that was carried onto the plateau by westward-flowing ancestral rivers. These two major lithologies occur either as distinct or mixed deposits within the Ellensburg Formation of the Pasco Basin.

The lateral extent and thickness variations among individual flows of the Wanapum and Saddle Mountains Basalts in the Pasco Basin are the product of the collective interplay of four factors: (1) volume of each flow that entered the basin, (2) location of flow margins of previously emplaced flows, (3) effect of uplift and subsidence, and (4) regional paleoslope. The flow eruption and emplacement rate and rate of uplift and subsidence are so closely related that a detailed evaluation of the flow history and structural development of the basin during the late Miocene is possible.

Based on the extent and thickness variations of the basalt flows, it is apparent that the Pasco Basin and Cold Creek syncline were active structural features by at least the beginning of Wanapum time. The rates of uplift and subsidence in the Pasco Basin were calculated for the period of time over which the Wanapum and Saddle Mountains Basalt flows were erupted and the rates of uplift and subsidence were found to be <40 m/million years. These low uplift and subsidence rates, combined with a relatively rapid eruption rate for the Wanapum Basalt, indicate that only a small amount of relief on the Yakima fold structures was present when flows of this formation were emplaced. These rates also indicate that any structural relief existing and developing in Grande Ronde time would have been obscured by the large volume of lava which was erupted over a short

period of time. A much greater length of time occurred between the eruption of Saddle Mountains Basalt flows, allowing more relief to develop along the structures during periods of volcanic quiescence. Consequently, the topography exerted greater control on the thickness and distribution of Saddle Mountains Basalt flows.

The present structural asymmetry of anticlines with steep north flanks and gentle south flanks is reflected in the thickness distribution of the large-volume flows that filled a similar-shaped basin in Wanapum and Saddle Mountains time. The thickest parts of the flows are on the south side of the syncline, with thinning over Rattlesnake Mountain and the subsurface extension of Yakima Ridge and a gradual thinning toward the Umtanum Ridge-Gable Mountain trend. The westward-dipping paleoslope and the geometry of the flows suggest that the asymmetry of the present structural ridges is probably similar to the geometry of the ridges in Wanapum and Saddle Mountains time, except that the Miocene Cold Creek syncline has less relief.

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