WHC-MR-0391

Field Trip Guide to the Hanford Site

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Prepared for the U.S. Department of Energy
Office of Environmental Restoration
and Waste Management

Westinghouse
Hanford Company Richland, Washington

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U.S. Department of Energy

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FIELD TRIP GUIDE TO THE HANFORD SITE

Stephen P. Reidel
Kevin A. Lindsey
Karl R. Fecht

INTRODUCTION

This report is designed to provide a guide to the key geologic and hydrologic features of the U.S. Department of Energy's Hanford Site located in south-central Washington. The guide is divided into two parts. The first part is a general introduction to the geology of the Hanford Site and its relation to the regional framework of south-central Washington. The second part is a road log that provides directions to important geologic features on the Hanford Site and descriptions of the locality. The exposures described were chosen for their accessibility and importance to the geologic history of the Hanford Site and to understanding the geohydrology of the Site.

REGIONAL GEOLOGIC SETTING

The Hanford Site lies within the Columbia Plateau, a broad plain situated between the Cascade Range to the west and the Rocky Mountains to the east (Fig. 1) and constructed from the Miocene Columbia River Basalt Group. The Columbia Plateau is often called the Columbia Basin because it forms a broad lowland surrounded on all sides by mountains. In the central and western parts of the Columbia Plateau, the basalt is underlain predominantly by Tertiary continental sedimentary rocks and overlain by late Tertiary and Quaternary fluvial and glaciofluvial deposits.

The Columbia Plateau covers four general structural-tectonic regions or subprovinces, each of which has a distinctly different structural style: the Yakima Fold Belt; the Palouse Slope; the Blue Mountains; and the Clearwater, St. Maries, and Weiser embayments (Fig. 2). The Hanford Site lies in the eastern portion of the Yakima Fold Belt and adjacent to the Palouse Slope. The Yakima Fold Belt consists of a series of anticlinal ridges and synclinal valleys with generally east-west trends (ranging from N 50° W to N 50° E) (Fig. 3). The Palouse Slope is the least deformed region with only minor faults and low amplitude, long-wavelength folds on an otherwise gently westward dipping paleoslope (Swanson et al. 1980). The Palouse Slope marks the eastern boundary of the Yakima Fold Belt and has been a relatively stable feature since at least the middle Miocene (Swanson and Wright 1976). The Blue Mountains are a northeast-trending anticlinorium extending 250 km from the Cascades to the eastern part of the Plateau and forming the southern boundary of the Yakima Fold Belt.

Two major regional features crosscut the Columbia Plateau: the Olympic-Wallowa lineament (OWL) and the Hog Ranch-Naneum Ridge (HR-NR) anticline (Fig. 3). The segment of the OWL that crosses the Yakima Fold Belt is referred to as the Cle Elum-Wallula deformed zone (CLEW) (Keinle et al. 1977) and is marked by a rather diffuse zone of anticlines with a N 50° W orientation. The CLEW is one of the major geologic features that occurs on the Hanford Site. It has been an important feature with respect to design and construction of nuclear facilities.

The HR-NR anticline is a basement-controlled anticline that extends southward from the North Cascades (Tabor et al. 1984) and forms the western boundary of the Pasco Basin (Fig. 3) (Reidel 1984). Although the HR-NR anticline does not cross the Hanford Site, uplift along the structure has influenced the geologic development of the Site.

PHYSIOGRAPHIC SETTING OF THE HANFORD SITE

The Hanford Site lies within the Columbia Basin and Central Highlands subprovinces of the Columbia Intermontane Province (Fig. 1). The Columbia Intermontane Province is the product of Miocene continental flood basalt volcanism and regional deformation that occurred over the past 17 million years. The Columbia Plateau is that portion of the Columbia Intermontane Province that is underlain by the Columbia River Basalt Group.

The physiography of the Hanford Site (Fig. 4) is dominated by low-relief between anticlinal ridges of the Yakima Fold's physiographic region. Synclinal valleys

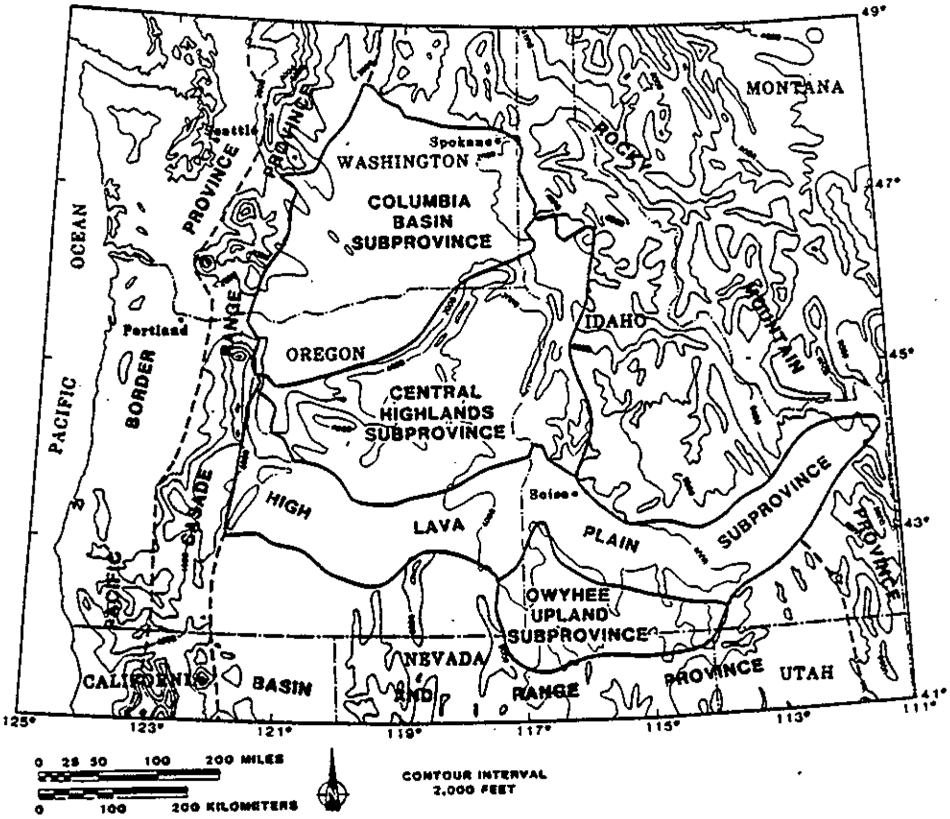


Figure 1. Subdivisions of the Columbia Intermontane Physiographic Province and adjacent provinces (after Freeman et al. 1945, Thornbury 1965).

were alluviated by rivers and streams during the late Miocene to early Pleistocene. Surface topography has been modified within the past several million years by Pleistocene cataclysmic flooding, Holocene eolian activity, and landsliding. Cataclysmic flooding of the Hanford Site occurred when ice dams in western Montana and northern Idaho were breached, allowing large volumes of water to spill across eastern and central Washington. Much of the landscape in the path of the flood water was stripped of sediments, and basalt bedrock was scoured, forming "scabland" topography. The last major flood occurred about 13,000 years ago, during the late Pleistocene Epoch. Anastomosing flood channels, giant current ripples, bergmounds, and giant flood bars are among the landforms created by the floods and readily seen on the Hanford Site.

Since the end of the Pleistocene, winds have locally reworked the flood sediments, depositing dune sands in the lower elevations and loess (windblown silt) around the margins of the Pasco Basin. Sand dunes have generally been stabilized by anchoring vegetation except where they have been reactivated where vegetation is disturbed and in the barchan dune complex in the west-central Hanford Site.

STRATIGRAPHY

The generalized stratigraphy of the Yakima Fold Belt is shown in Figure 5. The dominant rocks of the area are the Columbia River Basalt Group and intercalated sedimentary rocks of the Ellensburg Formation. These are overlain by younger sedimentary rocks of the Ringold Formation and the Pleistocene cataclysmic flood deposits of the Hanford formation (informal). Sedimentary and volcanic units of the Naches, Ohanapecosh, and Fifes Peak formations underlie the basalt along the western margin and extend under the basalt (Campbell 1989).

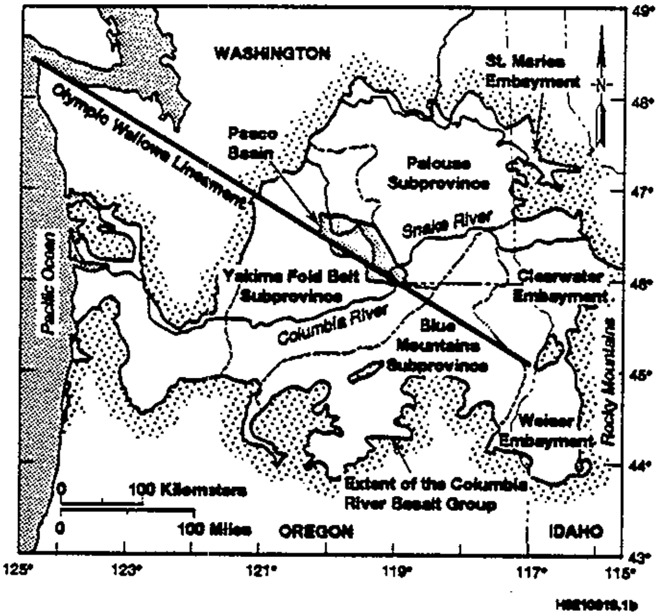


Figure 2. The Columbia Plateau and areal extent of the Columbia River Basalt Group. Shown are the four major structural-tectonic subprovinces and the Pasco Basin.

COLUMBIA RIVER BASALT GROUP

The Columbia River Basalt Group, the principal rock unit in the Yakima Fold Belt and the Hanford Site, is a sequence of tholeiitic flood basalt flows erupted between 17 and 6 MA. This covers approximately 164,000 km^2 and consists of 174,000 km^3 of basalt (Tolan et al. 1989). The flows were erupted from north-northwest-trending fissures or linear vent systems in north-central and northeastern Oregon, eastern Washington, and western Idaho (Swanson et al. 1979b).

The Columbia River Basalt Group is divided into five formations (Swanson et al. 1979a); only the Grande Ronde Basalt, the Wanapum Basalt, and the Saddle Mountains Basalt are exposed on the Hanford Site.

The basalt flows of the Columbia River Basalt Group are recognized using a combination of lithology, chemistry, and paleomagnetic data (Swanson et al. 1979a). Chemical composition and paleomagnetic data have proven to be the most reliable criteria for flow recognition and correlation; lithology is reliable for many flows primarily within the Wanapum and Saddle Mountains Basalts, but chemical compositions are still used to confirm identifications.

Chemical composition and paleomagnetic data are most important in identifying flows within the Grande Ronde Basalt because of the similarity of lithology. In the field, the Grande Ronde Basalt has been divided into four magnetostratigraphic units (MSU) which, from oldest to youngest are Reversed 1 (R_1), Normal 1 (N_1), Reversed 2 (R_2), and Normal 2 (N_2) (Swanson et al. 1979a). Based on concentrations of MgO (Swanson et al. 1979a) the composition has been broadly subdivided into two groups: high MgO and low MgO. Recent studies, however, have provided more detailed compositional subdivisions (Reidel et al. 1989b).

The younger basalt flows on the Hanford Site have been locally eroded to various degrees. Uplift along anticlinal ridges has resulted in erosion to different depths along the margin of the Pasco Basin and Cold Creek syncline. Within the synclines where the basalt surface is covered by sediment fill, the upper basalt flows have been locally eroded by fluvial activity and proglacial flooding. North of the 200 Areas near Gable Gap, the Saddle Mountains Basalt has been eroded down to the Umatilla Member. The Elephant Mountain Member is suspected of being eroded near the northeast corner of 200 East Area (Graham 1984).

LATE NEOGENE SEDIMENTS

Two main Late Neogene sedimentary units occur in the region: the Ellensburg Formation and the Ringold Formation (Fig. 5). The Ellensburg Formation consists of a series of sedimentary units that are interbedded between many of the basalt flows of the Columbia River Basalt Group. Ringold strata overlie the youngest basalt flows in the region.

Ellensburg Formation

The Ellensburg Formation includes epiclastic and volcaniclastic sedimentary rocks that are intercalated with and overlie the Columbia River Basalt Group (Waters 1961, Swanson et al. 1979a). The Ellensburg stratigraphy of the Hanford Site has been discussed by Reidel and Fecht (1981) and by Fecht et al. (1987). At the Hanford Site, the Ellensburg Formation consists of a mix of sediments deposited by the ancestral Clearwater and Columbia Rivers (Fecht et al. 1982, 1987). The Ellensburg Formation occurs only intercalated with the Columbia River Basalt Group.

Most volcaniclastic material in the Ellensburg Formation was produced by volcanic events in the Cascade Range. Along the western margin of the plateau, deposition was primarily by volcanic debris flows (lahars) and related stream and sheet floods. Some airfall and

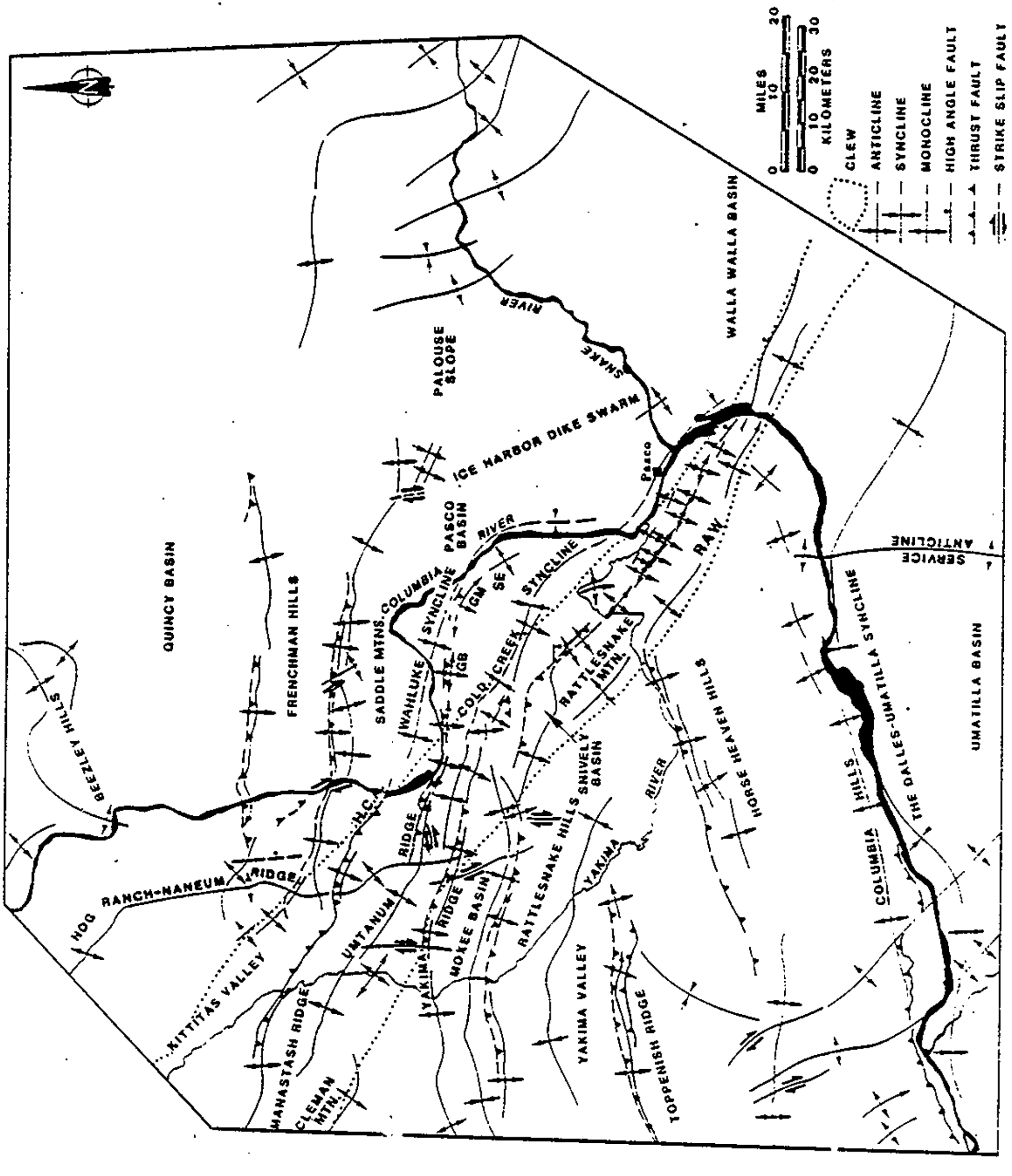


Figure 3. Major faults and folds in the central part of the Yakima Fold Belt and the western part of the Palouse Slope (from Reidel et al. 1989a).

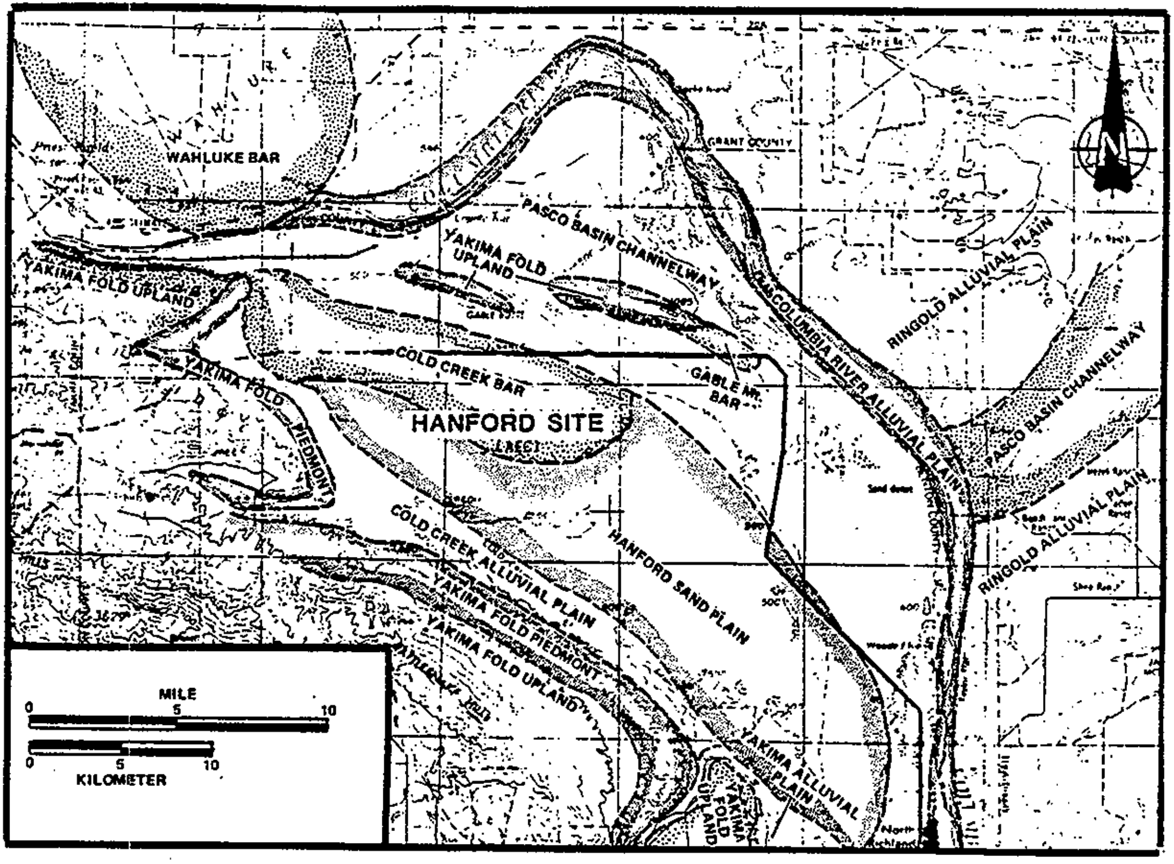


Figure 4. Map showing the major geomorphic features of the Hanford Site and vicinity.

pyroclastic-flow deposits are also present. Airfall tuff is the dominant volcaniclastic material at the Hanford Site; no volcanic debris flows have been identified at the Site as yet. The age of the formation along the western margin in the Naches drainage is between 16.5 and 7.4 Ma (Smith et al. 1988).

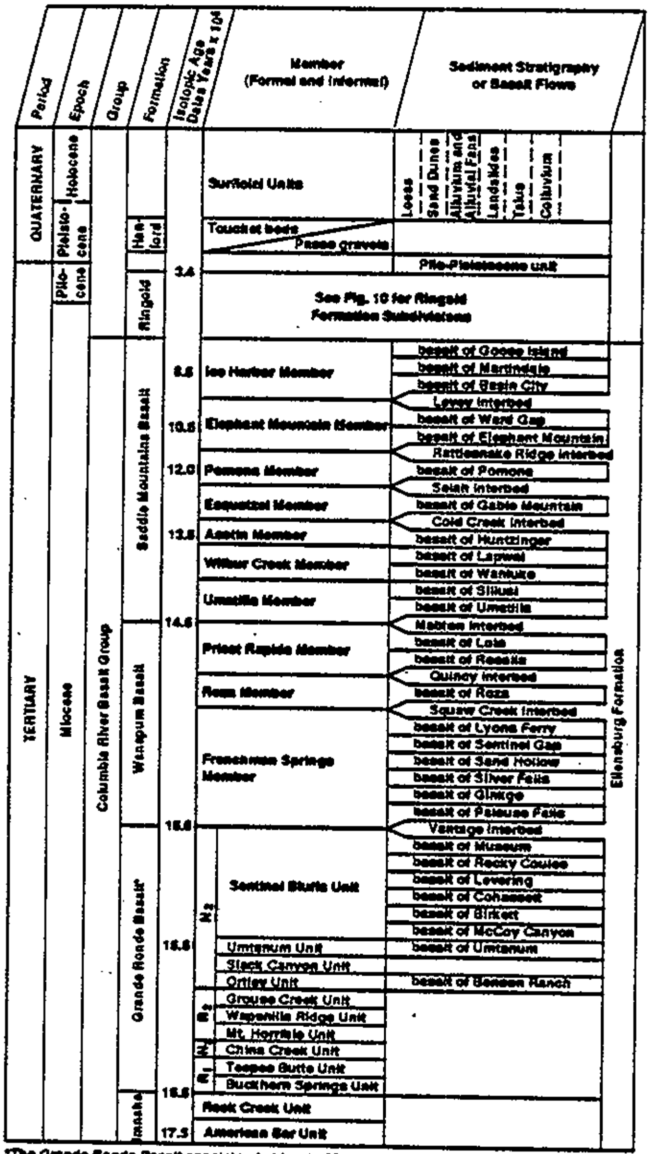
Snipes Mountain Conglomerate

The Snipes Mountain Conglomerate forms a thin veneer of gravels over the Saddle Mountains east of Sentinel Gap and on the east end of Umtanum and Yakima Ridges. The Snipes Mountain Conglomerate consists of epiclastic gravels such as are found in the Ellensburg Formation and Ringold Formation on the Hanford Site. The unit primarily overlies the Elephant Mountain Member of the Saddle Mountains Basalt and is in part equivalent to the Levy interbed of the Ellensburg Formation and the gravels of Ringold unit A.

Ringold Formation

Sediments continued to be deposited in most synclinal valleys of the central Columbia Basin long after the eruptions of the Columbia River Basalt Group. Although exposures of the Ringold Formation are limited to the White Bluffs on the east side of the Hanford Site, five isolated localities between Rattlesnake Mountain and Wallula Gap, and the Smyrna and Taunton Benches within the Othello Basin, extensive data on the Ringold Formation are available from boreholes at the Hanford Site.

The Ringold Formation at the Hanford Site is up to 185 m thick in the deepest part of the Cold Creek syncline south of the 200 West Area and 170 m thick in the western Wahluke syncline near the 100-B Area. The Ringold Formation pinches out against the Gable Mountain, Yakima Ridge, Saddle Mountains, and Rattlesnake Mountain anticlines. It is largely absent in the northern and northeastern parts of the 200 East Area and adjacent areas to the north.



*The Grande Ronde Basalt consists of at least 120 major basalt flows. Only a few flows have been named. N_2, R_2, N_1 and R_1 are magnetostratigraphic units.

Figure 5. Generalized stratigraphy of the Hanford Site.

The Ringold Formation consists of semi-indurated clay, silt, pedogenically altered sediment, fine- to coarse-grained sand, and granule-to-cobble gravel. Ringold strata typically are situated below the water table. The Ringold Formation historically has been divided into a variety of units, facies types, and cycles (Newcomb 1958, Newcomb et al. 1972, Myers et al. 1979, Tallman et al. 1979, Bjornstad 1984, DOE 1988). However, these terminologies have proven to be of limited use because they are too generalized to account for significant local stratigraphic variation or they were defined in detail for relatively small areas and do not account for basinwide stratigraphic variation (Lindsey and Gaylord 1989, Lindsey 1991).

Recent studies of the Ringold Formation in the Pasco Basin indicate that significant, previously undocumented stratigraphic variation occurs (Lindsey and Gaylord 1989, Lindsey 1991). The Ringold Formation is best described on the basis of sediment facies associations and their distribution. The following sediment facies associations in the Ringold Formation are defined on the basis of lithology, stratification, and pedogenic alteration.

1. Fluvial gravel--Clast-supported granule-to-cobble gravel with a sandy matrix dominates the association (Fig. 6). Intercalated sands and muds also are found. Clast composition is variable, with basalt, quartzite, porphyritic volcanics, and greenstone being the most common types. Silicic plutonic rocks, gneisses, and volcanic breccias also are found. Sands in the association generally are quartzo-feldspathic, with basalt content usually ranging between 5% and 25%. Low angle to planar stratification; massive bedding; wide, shallow channels; and large-scale cross-bedding are found in outcrops. The association was deposited in a gravelly fluvial braidplain characterized by wide, shallow, shifting channels.

2. Fluvial sand--Quartzo-feldspathic sands displaying cross-bedding and cross-lamination in outcrops dominate this association (Fig. 7). These sands usually contain less than 15% basalt lithic fragments, although basalt contents as high as 50% may be encountered. Intercalated strata consist of lenticular silty sands and clays up to 3 m thick and thin (<0.5 m) gravels. Fining upwards sequences less than one meter to several meters thick are common in the association. Strata that constitute the association were deposited in wide, shallow channels.

3. Overbank deposits and paleosols--This association (Fig. 8) dominantly consists of laminated to massive silt, silty fine-grained sand, and paleosols containing variable amounts of pedogenic calcium carbonate. Overbank deposits occur as thin (<0.5 to 2 m) lenticular interbeds in the fluvial gravel and fluvial sand associations and as thick (up to 10 m) laterally continuous sequences. These sediments record deposition in proximal levee to more distal floodplain conditions.

Figure 6. Outcrop of the pebble-cobble gravel and minor interbedded sand typical of the fluvial gravel facies association of the Ringold Formation. Outcrop located at the base of the White Bluffs at the north end of the Taylor Flats.

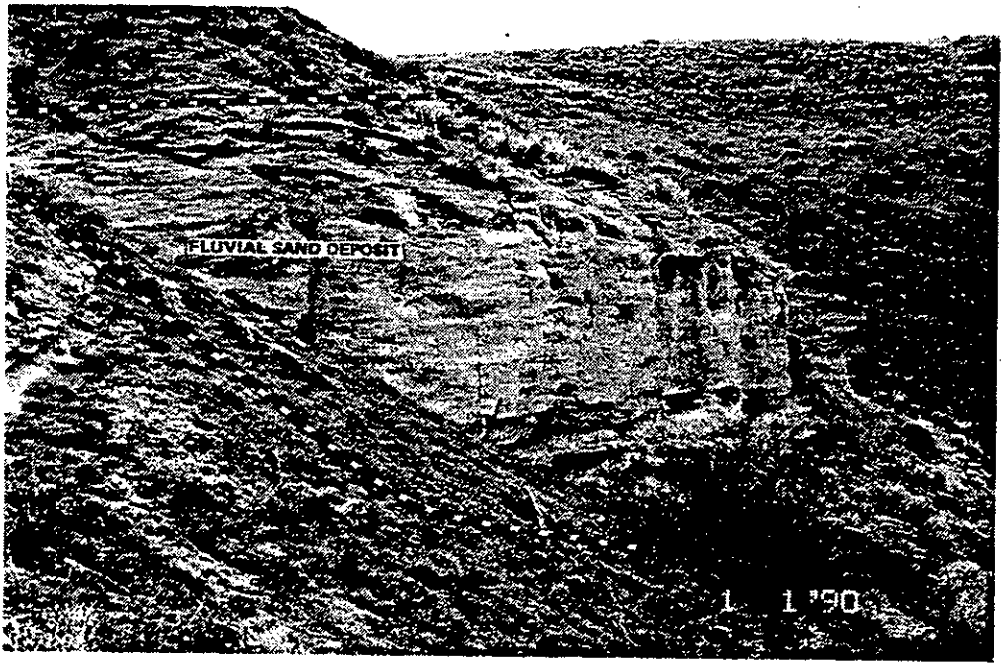


Figure 7. Outcrop of cross-stratified sands typical of the fluvial sand facies association of the Ringold Formation. Outcrop located in the White Bluffs opposite the north end of Taylor Flats.

Figure 8. Typical exposure of interstratified silt and clay of the overbank facies association of the Ringold Formation. Outcrop located in the White Bluffs opposite the north end of Savage Island.

4. Lacustrine deposits—Plane laminated to massive clay with thin silt and silty sand interbeds displaying some soft-sediment deformation characterize this association (Fig. 9). Coarsening upwards packages less than 1 m thick to 10 m thick are common in the association. Strata composing the association were deposited in a lake under standing water to deltaic conditions.

5. Alluvial fan—Massive to crudely stratified, weathered to unweathered basaltic detritus dominates this association. These basaltic deposits generally are found around the periphery of the basin. The association records deposition by debris flows in alluvial fan settings and in sidestreams draining into the Pasco Basin.

The lower half of the Ringold Formation contains five separate stratigraphic intervals dominated by fluvial gravels. These gravels, designated units A, B, C, D, and E (Fig. 10), are separated by intervals containing deposits typical of the overbank/paleosol and lacustrine facies associations (Lindsey 1991). The lowermost of the fine-grained sequences overlying unit A is designated the lower mud sequence. The uppermost gravel unit, unit E, grades upwards into interbedded fluvial sand and overbank deposits that are in turn overlain by lacustrine-dominated strata (Figs. 10 and 11).

Fluvial gravel units A and E correspond to the lower basal and middle Ringold units respectively as defined by DOE (1988). Gravel units B, C, and D do not correlate to any previously defined units (Lindsey 1991). The lower mud sequence corresponds to the upper basal unit and lower unit as defined by DOE (1988). The upper basal and lower units are not differentiated in this report. The sequence of fluvial sands, overbank deposits, and lacustrine sediments overlying unit E corresponds to the upper unit as originally defined by Newcomb (1958) along the White Bluffs in the eastern Pasco Basin.

QUATERNARY STRATIGRAPHY OF THE PASCO BASIN

Quaternary sediments as much as 100 m thick within the Pasco Basin are differentiated on the basis of texture, composition, and sedimentary structure, and to a lesser extent on their sedimentologic features (Baker et al. 1991). This section, based largely on Baker et al. (1991), focuses on deposits associated with cataclysmic flood, fluvial, and eolian deposits. For the purpose of discussing Quaternary geology, the Pasco

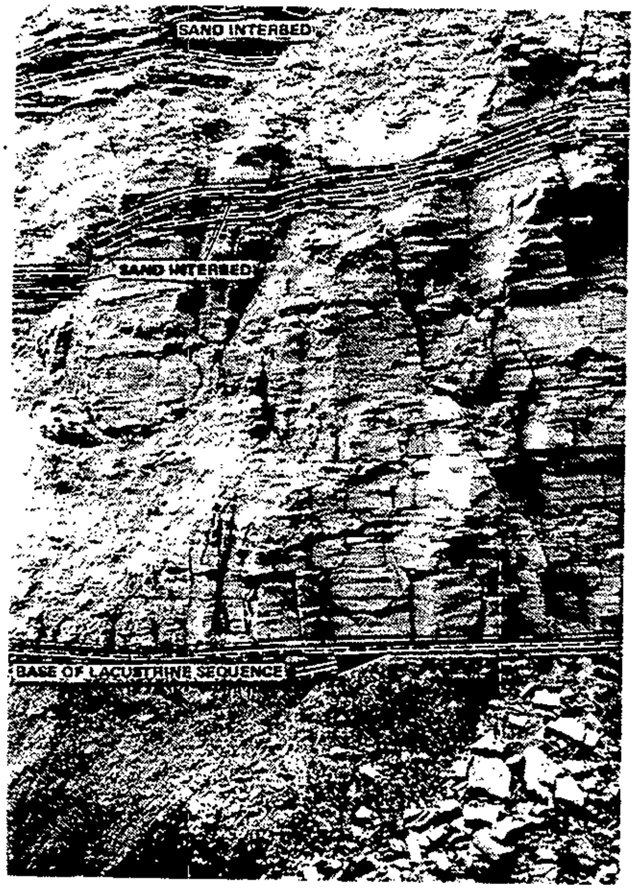


Figure 9. Exposure consisting of thinly bedded sand, silt, and clay typical of the lacustrine facies association of the Ringold Formation.

Basin is subdivided into three stratigraphic subprovinces: (1) central basin, (2) basin margin, and (3) ridge terrain.

Several informal units comprise the Quaternary Section at the Hanford Site. The most extensive of these is the Pleistocene-aged Hanford formation (Fig. 11). Locally the Hanford formation and underlying Ringold Formation are separated by several laterally discontinuous and informally defined units. They are the Plio-Pleistocene unit, the pre-Missoula gravels, and the early "Palouse" soil (Fig. 11).

Quaternary Alluvium

Alluvial deposits from major rivers (Yakima, Snake, and Columbia) in addition to localized sidestreams are represented in the Pasco Basin, dating since at least the late Tertiary (Baker et al. 1991). In the central Pasco Basin, mainstream alluvium lies stratigraphically between the Ringold Formation and the Hanford formation. Mainstream alluvium of probable early Pleistocene age is exposed along Cold Creek and the Yakima Bluffs and underlies much of the south-central Hanford Site. The mainstream alluvium is informally referred to as pre-Missoula gravels and was deposited during relatively long time intervals separating major cataclysmic flood episodes. However, these deposits rarely are preserved within the Pasco Basin, probably because of the scouring by cataclysmic floods that removed most of the mainstream channel alluvium deposited between floods.

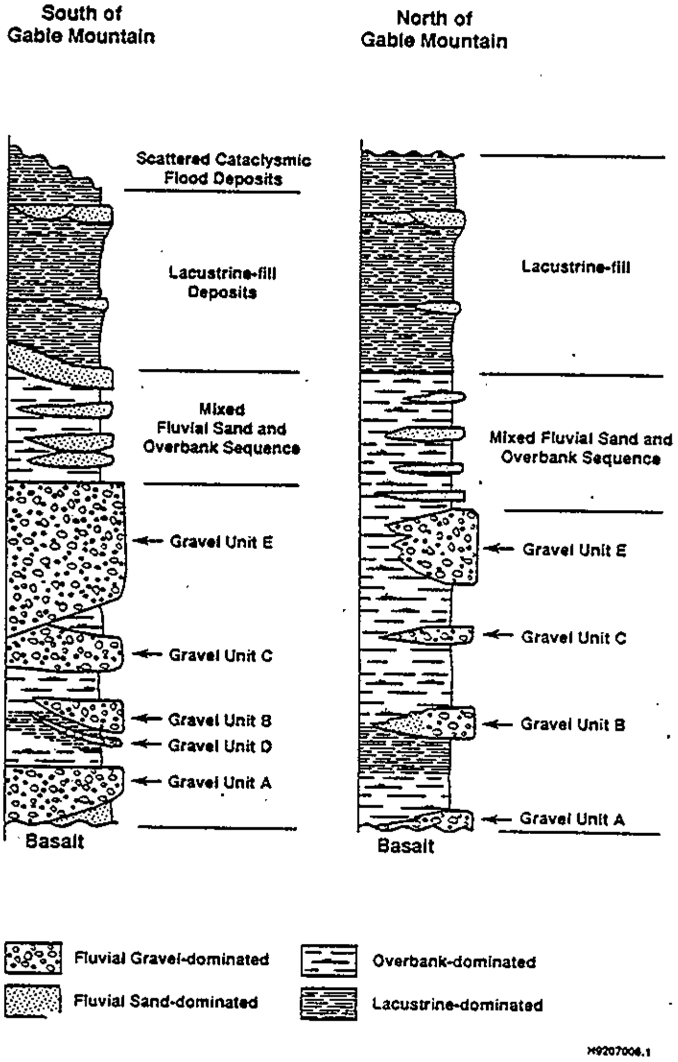


Figure 10. Idealized stratigraphy of the Ringold Formation north and south of Gable Mountain.

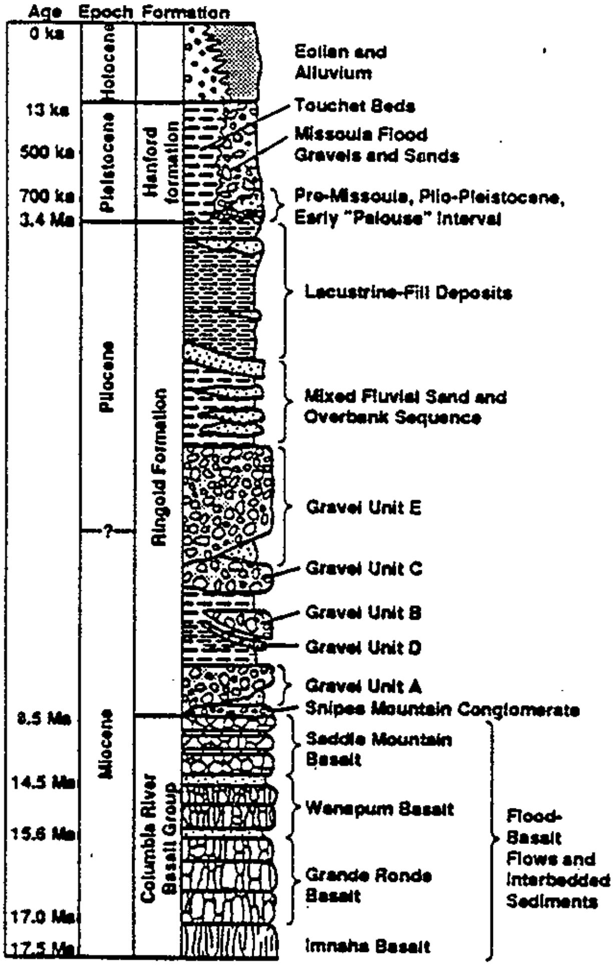


Figure 11. Generalized stratigraphy of the suprabasalt sediments and Columbia River Basalt Group of the Hanford Site.

Unconformably overlying the Ringold Formation in the western Cold Creek syncline in the vicinity of 200 West Area is the laterally discontinuous Plio-Pleistocene unit (DOE 1988). The unit is up to 25 m thick and separated into two facies: basaltic detritus and pedogenic calcrete (Stage III and Stage IV of Machette [1985]). Depending on location, one or both facies may be present. The calcrete facies generally consists of interfingering carbonate-cemented silt, sand, and gravel, and carbonate-poor silt and sand. The basaltic detritus facies consists of weathered and unweathered basaltic gravels deposited as locally derived slope wash, colluvium, and sidestream alluvium. The Plio-Pleistocene unit appears to be correlative to other sidestream alluvial and pedogenic deposits found near the base of the ridges bounding the Pasco Basin on the north, west, and south. These sidestream alluvial and pedogenic deposits are inferred to have a late Pliocene to early Pleistocene age on the basis of stratigraphic position and magnetic polarity of interfingering loess units.

<u>Pre-Missoula Gravels</u>

Quartzose to gneissic clast-supported pebble-to-cobble gravel with a quartzo-feldspathic sand matrix separates the Hanford formation and the Ringold Formation in the east-central Cold Creek syncline and at the east end of Gable Mountain anticline east and south of 200 East Area. These gravels, called the pre-Missoula gravels (PSPL 1982), are up to 25 m thick, contain less basalt than underlying Ringold gravels and overlying Hanford deposits, have a distinctive white or bleached color, and sharply truncate underlying strata. The nature of the contact between the pre-Missoula gravels and the overlying Hanford formation is not clear. In addition, it is unclear whether the pre-Missoula gravels overlie or interfinger with the early "Palouse" soil and Plio-Pleistocene unit. Magnetic polarity data indicate the unit is no younger than early Pleistocene in age (>1 Ma). The pre-Missoula gravels are interpreted as mainstream deposits of the Columbia River.

<u>Sidestream Alluvium</u>

Thin (<10 m) deposits of sidestream alluvium occur along basin margins where ephemeral streams eroded into basalt ridges and/or the Ringold Formation. Sidestream alluvium, consisting dominantly of basaltic gravel mixed with varying amounts of sand and silt (mostly reworked loess) was deposited in alluvial fans and/or floodplains.

At least two ages of sidestream alluvium can be differentiated on the basis of paleosol development, interstratified tephra, and stratigraphic position. The oldest sidestream unit, rarely exposed and only in ridge terrain, is weathered, subangular to subrounded basaltic alluvium capped by silcrete. The silcrete formed in late Pliocene and/or early Pleistocene time, perhaps under more humid conditions. A second, coarse-grained sidestream alluvial unit is locally present along exposed basin margins. Unlike the silcrete-cemented unit, this unit consists of angular, unweathered basalt clasts cemented with one or more carbonate horizons. This unit is estimated to be early to late Pleistocene in age, based on correlation with intertonguing loess units having both reversed and normal magnetic polarity.

Eolian Deposits

Loess deposits at the Hanford Site contain a detailed Quaternary record; five units are represented with the Pasco Basin. These units are informally referred to as L1 through L5 and differentiated on the basis of (1) position relative to other stratigraphic units, (2) color, (3) soil development, and (4) paleomagnetic polarity. The oldest loess unit (L1) is distinctively very compact, reddish yellow, and usually capped by silcrete. Its inferred age is late Pliocene to early Pleistocene, based on the siliceous character of the paleosol it bears and its geomorphic position with respect to the overlying unit (L2). The chemical nature and stratigraphic position of the silcrete suggest that it predates the calcic paleosols of the Quaternary.

Loess L2 consists of compact, brownish-yellow silt capped by a K horizon with as much as 4 m of platy (Stage III to IV) pedogenic carbonate. L2 is present in Snively Basin, where it overlies L1, and in isolated outcrops at Vernita Grade and Radar Hill. Based on its predominantly reversed polarity, L2 is interpreted to be early Pleistocene. Minor normal polarity intervals within L2, at Vernita grade for example, may represent either the Jaramillo or Olduvai normal polarity subchrons within the Matuyama chron.

Unit L2 may correlate with reversely magnetized loess at lower exposed stratigraphic levels in the Palouse region. Also, a well-sorted, massive, pale brown loess, described from boreholes in the west-central Pasco Basin, may correlate with L2. This unit, called the early "Palouse" soil, lies between a highly weathered Ringold surface and cataclysmic flood deposits.

Loess unit L3 is a compact, yellowish-brown loess, as much as 7 m thick. It contains multiple paleosols that have well-developed argillic B horizons and platy, carbonate-plugged (Stage II to IV) K horizons. This unit, commonly exposed in ridge terrain, is probably equivalent to the middle-to-late Pleistocene Palouse Formation that lies east of the Pasco Basin. Normal magnetic polarity, along with thorium/uranium age dates on the pedogenic carbonate, suggest an age of 75 to 79 ka.

Unit L4 consists of multiple cycles of loose-to-weakly compact, pale brown loess. This unit bears weak to moderately well-developed B horizons with thin coatings, filaments, and nodules of carbonate (Stage I to II). At least one tephra, the Mount St. Helens set M couplet (18 to 20 ka), is associated with L4. Based on tephra and carbonate ages, unit L4 is middle to late Wisconsin (18 to 75 ka).

The youngest loess unit in the Pasco Basin, L5, includes loess deposited during and since late Wisconsin time (about 20 ka). Characteristically, it is loose, well sorted, and pale brown. Soil profiles atop or within unit L5 normally have only weak A to C horizons. Carbonate development is limited to filaments and thin particle coatings (Stage I). Tephra from three sources is associated with this unit: the Mount St. Helens set S couplet (or triplet) (13 ka), Glacier Peak (layers G and B), and Mount Mazama (6.6 ka).

The main eolian unit in the subsurface at the Hanford Site is referred to as the early "Palouse" soil. This Palouse soil consists of up to 20 m of massive, brown-yellow, compact, loess-like silt and minor fine-grained sand (Tallman et al. 1979, 1981; DOE 1988). Granule-sized grains consisting primarily of basalt commonly occur in this unit. These deposits overlie and possibly interfinger with the Plio-Pleistocene unit (Fig. 5) in the western Cold Creek syncline around the 200 West Area. The unit is differentiated from overlying graded rhythmites (Hanford formation) by greater calcium carbonate content, massive structure in core, and high natural gamma response in geophysical logs (DOE 1988). The upper contact of the unit is poorly defined, and it may grade up-section into silty strata commonly found in the lower part of the Hanford formation. Based on a predominantly reversed polarity, the unit is inferred to be early Pleistocene in age.

Hanford Formation

The Hanford formation consists of pebble-to-boulder gravel, fine- to coarse-grained sand, and silt. These deposits are divided into three facies: (1) gravel-dominated, (2) sand-dominated, and (3) silty (Figs. 12, 13, and 14). These facies are referred to as coarse-grained deposits, plane-laminated sand facies, and rhythmite facies respectively in Baker et al. (1991). The rhythmites also are referred to as the "Touchet Beds" or slackwater deposits. The Hanford formation is thickest in the vicinity of the 200 West and 200 East Areas where it is up to 65 m thick. Hanford deposits are absent on ridges more than approximately 385 m above sea level, the highest level of cataclysmic flooding in the Pasco Basin (Baker et al. 1991).

1. Gravel-Dominated Facies--This facies generally consists of coarse-grained basaltic sand and granule-to-boulder gravel (Fig. 12). These deposits display massive bedding, plane to low-angle bedding, and large-scale planar cross-bedding in outcrop. These gravels usually are matrix-poor and display an open-framework texture. Lenticular sand and silt beds

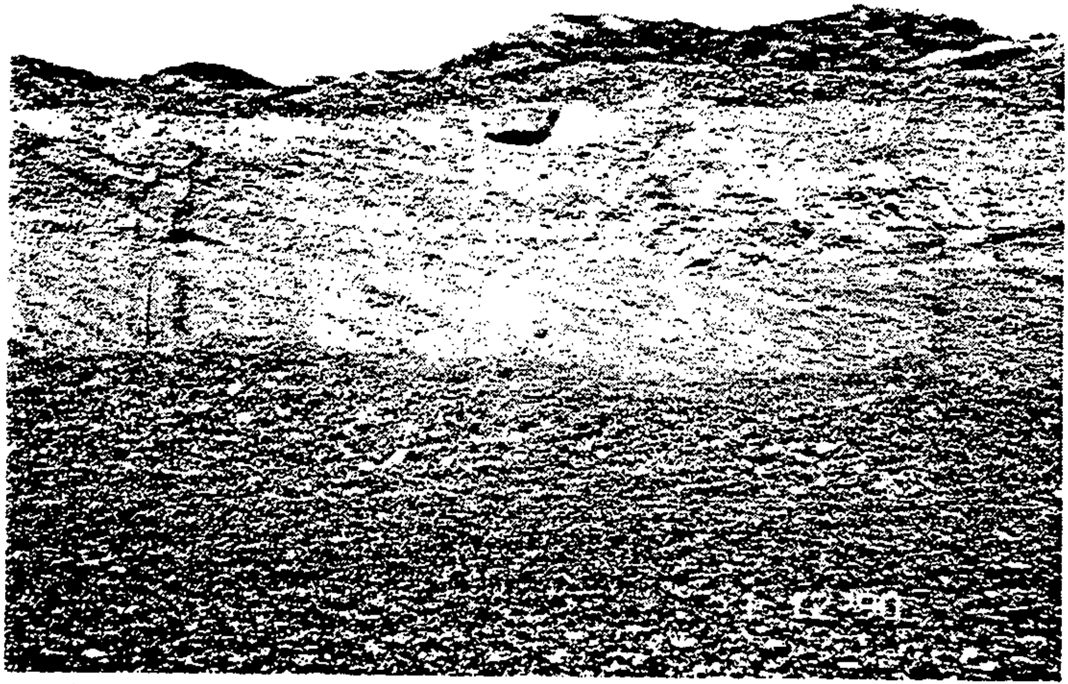


Figure 12. Outcrop of the gravel-dominated facies of the Hanford formation. Exposure is located at the Hanford Site Batch Plant gravel pit.

Figure 13. Exposure of the sand-dominated facies of the Hanford formation in the U.S. Ecology pit.

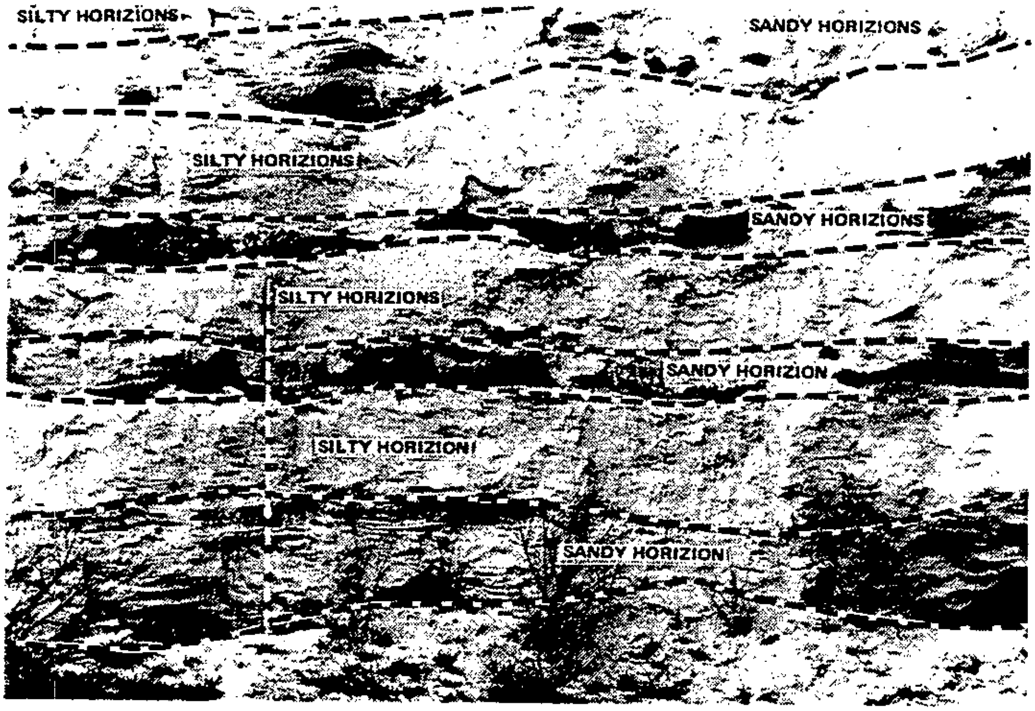


Figure 14. Silty strata of the silt-dominated facies of the Hanford formation exposed in Cold Creek Valley.

are intercalated throughout the facies. Gravel clasts in the facies generally are dominated by basalt (50% to 80%). Other clast types include Ringold and Plio-Pleistocene rip-ups, granite, quartzite, and gneiss. The gravel facies dominates the Hanford formation in the 100 Areas north of Gable Mountain, the northern part of 200 East and West Areas, and the eastern part of the Hanford Site including the 300 Area. The gravel-dominated facies was deposited by high-energy flood waters in or immediately adjacent to the main cataclysmic flood channelways.

2. Sand-Dominated Facies--This facies consists of fine- to coarse-grained sand and granule gravel displaying plane lamination and bedding and less commonly plane bedding and channel-fill sequences in outcrop (Fig. 13). These sands may contain small pebbles and rip-up clasts in addition to pebble-gravel interbeds and silty interbeds less than 1 m thick. The silt content of these sands is variable, but where it is low, a well-sorted and open framework texture is common. These sands typically are basaltic, commonly referred to as black, gray, or salt-and-pepper sands. This facies is most common in the central Cold Creek Syncline in the central to southern parts of the 200 East and 200 West Areas and in the vicinity of the Washington Public Power Supply System facilities. The laminated sand facies was deposited adjacent to main flood channelways during the waning stages of flooding and as water spilled out of channelways, losing competence. The facies is transitional between the gravel-dominated facies and the rhythmite facies.

3. Silty Facies--This facies consists of thinly bedded, plane-laminated and ripple cross-laminated silt and fine- to coarse-grained sand (Fig. 14) that commonly displays normally graded rhythmites a few centimeters to several tens of centimeters thick (Myers et al. 1979, Bjornstad et al. 1987, DOE 1988). This facies is found throughout the central, southern, and western Cold Creek syncline within and south of the 200 East and West Areas. These sediments were deposited under slackwater conditions and in back-flooded areas (DOE 1988).

HISTORY OF CATACLYSMIC FLOODING IN THE PASCO BASIN

The following discussion of cataclysmic flood episodes is summarized from Baker et al. (1991). Cataclysmic floods inundated the Pasco Basin several times during the Pleistocene (Fig. 15). Net erosion by these floods was minimal and probably associated with only the earliest floods; later floods only partially incised into older flood deposits before backfilling. During the three major flood episodes distinguished by stratigraphic criteria discussed below, there were probably numerous individual flood events. Deciphering the history of cataclysmic flooding in the Pasco Basin is complicated not only by floods from multiple sources, but also because the paths of Missoula floodwaters migrated and changed course with the advance and retreat of the Cordilleran Ice Sheet. The best preserved record is that of the last Missoula flood, which apparently came down the Columbia River.

Other evidence for cataclysmic flooding in the Pasco Basin includes high-water marks and faint strandlines along the basin margins. These were created because of the hydraulic damming and formation of Lake Lewis behind Wallula Gap. Formation of this lake and its overflow may have initiated in the Columbia Gorge, as indicated by similar high water marks both upstream and downstream of Wallula Gap. High water mark elevations for Lake Lewis are inferred from ice-rafted erratics on ridges and range from 370 to 385 m above sea level. Several weak strandlines are interpreted from photolineaments between 245 and 305 m above sea level along the northeastern flank of Rattlesnake Mountain. A flood origin is inferred based on exposures in trenches that cross these features. The lack of well-developed strandlines and the absence of typical lake deposits overlying flood deposits suggest that Lake Lewis was short-lived.

The gravel-dominated flood facies is generally confined to relatively narrow tracts within or near flood channelways. The sand-dominated facies, on the other hand, occurs as a broad sheet over most of the central basin. Paleocurrent indicators within beds of plane-laminated sands are unidirectional, generally toward the south and east, within the Pasco Basin.

Silty facies occur in slackwater areas around the margins of the basin and were deposited by multidirectional currents, including upvalley currents. Individual rhythmites become finer and thinner both laterally and vertically. Locally within late Pleistocene fine-grained flood sequences, rhythmites overlie plane-laminated sand facies, but not vice versa. Multiple floods may be recognized where evidence for subaerial exposure (e.g., tephra, paleosols, bioturbation, and/or eolian sand) lies between rhythmites. In contrast, similar evidence for subaerial exposure is rarely observed within plane-laminated sand facies. Poorly sorted flood-gravel units lie both above and below slackwater deposits, whereas the well-sorted flood gravel units generally are present only above slackwater deposits.

Three episodes of cataclysmic flooding are recognized in the Pasco Basin. Based on reversed magnetic polarity, the oldest cataclysmic flood deposits antedate the Matuyama-Brunhes magnetic reversal, 770 ± 20 ka. Reversed-polarity flood gravels are exposed at Marengo, Revere, Macall, and Old Maid Coulee in the Channeled Scabland and at Poplar Heights, Vernita Grade, and Yakima Bluffs within the Pasco Basin.

At least one middle Pleistocene episode of cataclysmic flooding is indicated by poorly sorted gravel (with normal polarity) capped by platy to massive carbonate-plugged K horizons, characteristic of Stage III to Stage IV pedogenic carbonate development. A minimum age for the calcrete cap determined by thorium/uranium dating is about 200 ka. Fine-grained deposits inferred to be of this age contain paleosols with weakly developed B horizons. Flood deposits assigned to the middle Pleistocene episode occur along the top of a prominent flood terrace at approximately 140 m elevation in the southern Pasco Basin northwest of Wallula Gap. Flood deposits of this age also are exposed at the Oak Creek, South Bombing Range Road, Kiona Quarry, and Leslie Road localities.

Gravels associated with the last (late Wisconsin) episode of cataclysmic flooding are widespread throughout the basin. These gravels are characterized by little or no soil development. Where pedogenic alteration has occurred, it is limited to thin coatings of carbonate on the undersides of gravel clasts (Stage I carbonate development). Fine-grained deposits associated with the last flood commonly contain the Mount St. Helens set S tephra couplet, dated at approximately 13 ka.

Several large floods confined to the immediate Hanford Reach of the Columbia River have occurred since the last cataclysmic flooding from Glacial Lake Missoula. The largest of these floods is marked by the planar-laminated sands located in a pit south of 100-D Area. The deposits are older than 6,300 years b.p. The remaining flood deposits were deposited by high

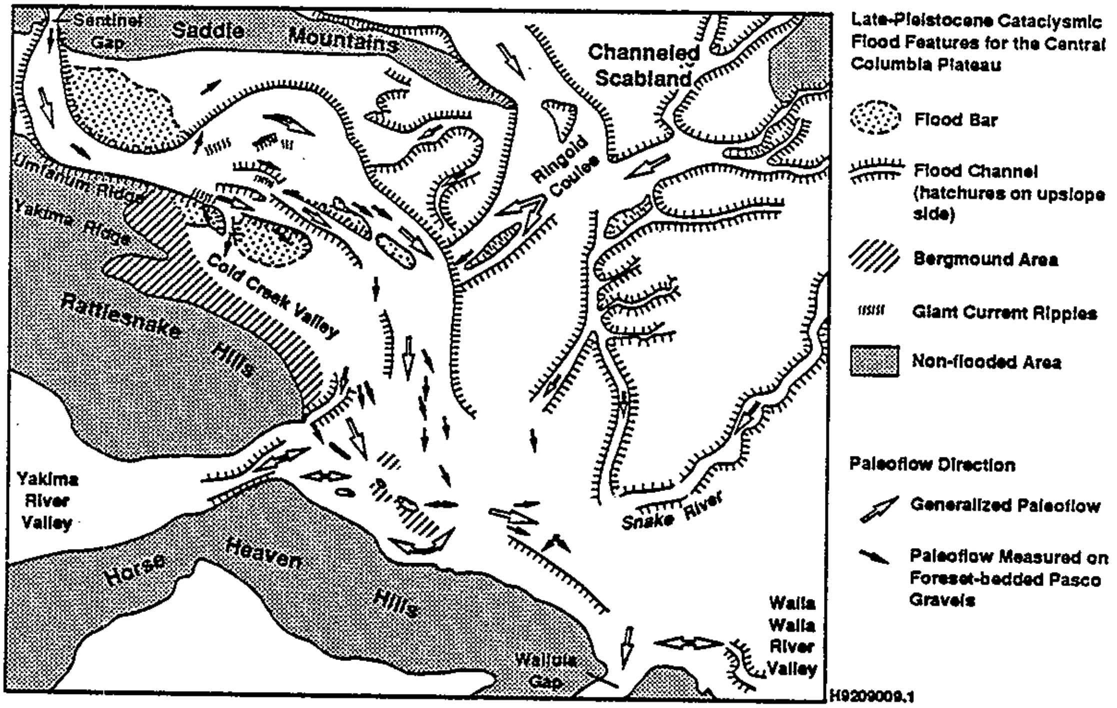


Figure 15. Paleoflow directions and landforms associated with proglacial cataclysmic flooding in the central Columbia Basin (from DOE 1988).

stages of the Columbia River. Similar deposits also occur along the Yakima River near the boundary of the Hanford Site.

HANFORD SITE STRUCTURAL GEOLOGY

INTRODUCTION

The Hanford Site lies in the Pasco Basin (Fig. 16), one of the larger structural basins near the eastern limit of the Yakima Fold Belt. The Yakima Fold Belt gives the Hanford Site its principal physiographic features and has been the primary factor influencing the geohydrologic conditions at the Site. In this section we will discuss the structural framework of the Hanford Site.

CHARACTERISTICS OF THE YAKIMA FOLDS

Introduction

The Yakima Fold Belt consists of non-cylindrical, asymmetrical anticlinal ridges and synclinal valleys. The anticlines are typically segmented and usually have a north vergence, although some folds have a south vergence. Synclines are typically asymmetrical with a gently dipping north limb and a steeply dipping south limb. Fold length is variable, ranging from several kilometers to over 100 km; fold wavelengths range from several kilometers to as much as 20 km. Structural relief is typically about 600 m but varies along the length of the fold. The greatest structural relief along the Frenchman Hills, the Saddle Mountains, Umtanum Ridge, and Yakima Ridge occurs where they intersect the north-south trending HR-NR anticline (Fig. 3) (see Reidel et al. 1989a).

In general, the axial trends produce a crude "fanning" pattern across the fold belt. Anticlines on the southwestern side of the fold belt generally have a N 50° E trend (Swanson et al. 1979b). Anticlines in the central part of the fold belt have east-west trends except along the CLEW where a N 50° W trend predominates. The Rattlesnake Hills, Saddle Mountains, and Frenchman Hills have overall E-W trends across the fold belt, but Yakima Ridge and Umtanum Ridge change from E-W to N 50° W in the zone of the CLEW. In the central part of the fold belt, the Horse Heaven Hills (HHH), the Rattlesnake Hills, and the Columbia Hills have eastward terminations against the CLEW. There is no evidence for continuation of any anticline to the northeast across the CLEW.

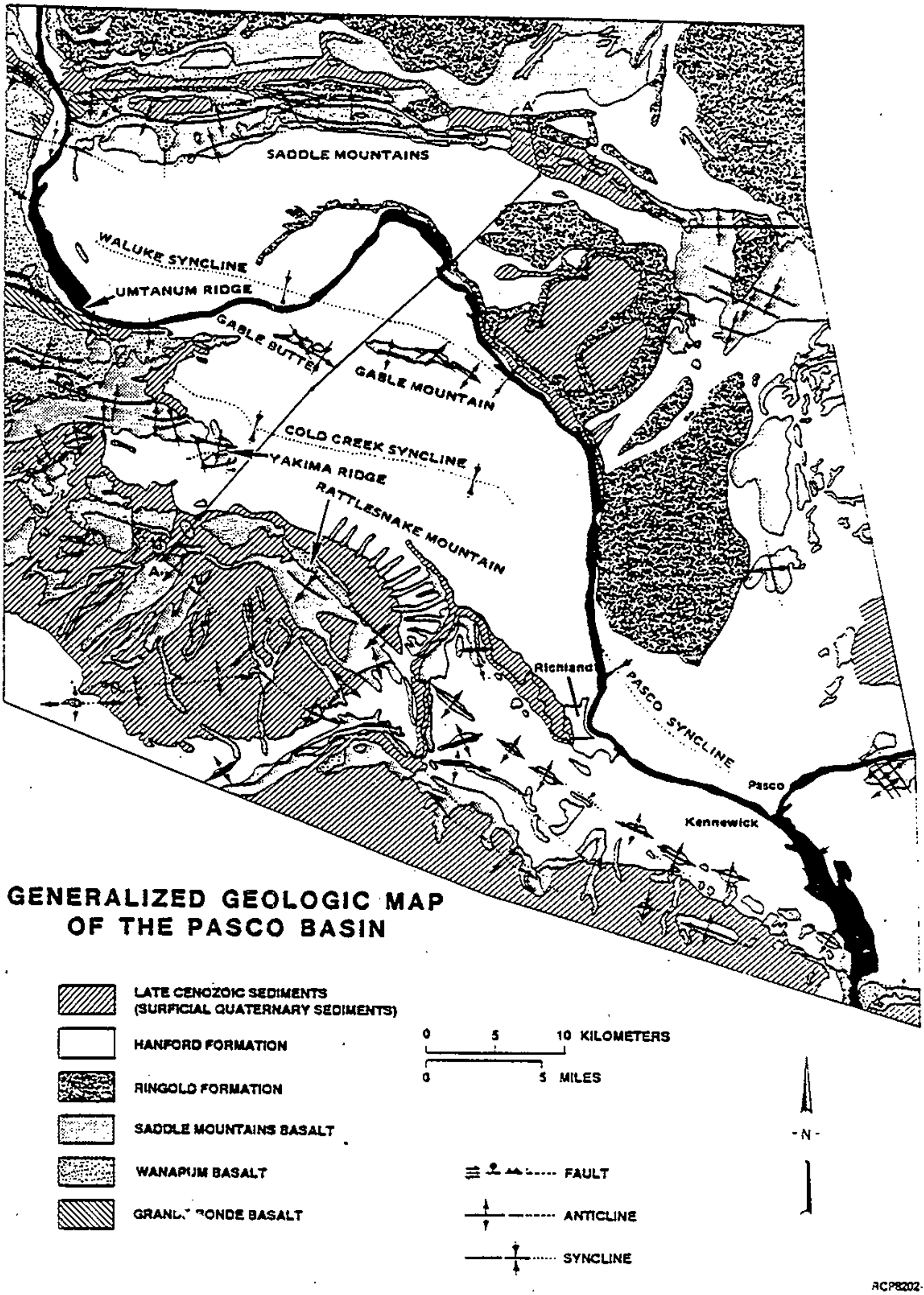


Figure 16. Generalized geologic map of the Hanford Site. Most faults and folds are not shown on the map. See Figure 3 for location of faults and folds.

Fold and Fault Geometry

Within the east-central fold belt, the fold geometry typically consists of steeply dipping to overturned north flanks and gently dipping (<5 degrees) south flanks (Fig. 17). Exceptions, however, include the doubly plunging anticlines within the Rattlesnake-Wallula alignment (RAW) of the CLEW (Fig. 3) and the conjugate box-fold geometry of parts of the anticlines such as the Smyrna segment of the Saddle Mountains (Reidel 1984). The main variable in fold profiles is the width of the gently dipping limb. The widths of the gently dipping limbs vary from as little 5 km to as much as 35 km.

Segmentation of the anticlines is common throughout the fold belt and is defined by abrupt changes in fold geometry or by places where regional folds die out and become a series of doubly plunging anticlines. Segment lengths are variable but average about 12 km (ranging from 5 to 35 km) in the central Plateau; some of the larger segments contain subtler changes in geometry such as different amplitudes that could also be considered segment boundaries. Segment boundaries are often marked by cross or tear faults that trend N 20° W to north and display a principal component of strike-slip movement (e.g., Saddle Mountains [Reidel 1984]). In the central Columbia Plateau, these cross faults are confined to the anticlinal folds and usually occur only on the steeper limb, dying out onto the gentler limb. In the southwest Plateau, some cross faults can be traced as far as 100 km (Swanson et al. 1979b).

Segment boundaries may also be marked by relatively undeformed areas along the fold trend where two fold segments plunge toward each other. For example, the Yakima River follows a segment boundary where it crosses the RAW at the southeast termination of Rattlesnake Mountain (Fig. 3).

The steep limb of the asymmetrical anticlines in the east-central fold belt is almost always faulted (Fig. 17). In the eastern portion of the Yakima Fold Belt, the steep limb is typically the northern flank, but elsewhere, as at the Columbia Hills (Swanson et al. 1979b), the south limb is faulted. Where exposed, these frontal fault zones have been found to be imbricated thrusts as, for example, at Rattlesnake Mountain, Umtanum Ridge near Priest Rapids Dam (Bentley 1977, Goff 1981, Bentley in Swanson et al. 1979b), the HHH near Byron Road (Hagood 1986), and the Saddle Mountains near Sentinel Gap (Reidel 1984).

Yakima folds of the central Columbia Plateau have emergent thrust faults at the ground surface (Fig. 17). The tops of the youngest lava flows at the earth's surface serve as a plane that becomes a low-angle thrust fault; the structural attitude of the surface flow controls the angle of the emergent fault plane. This type of apparent structural control led many investigators to conclude that faults associated with the Yakima Folds are low-angle thrust faults with detachment surfaces either within the Columbia River Basalt Group, in the sediments below the basalts, or at the basalt-sediment contact. Where erosion provides deeper exposures into the cores of folds, the frontal faults are observed to be reverse faults [e.g., the Columbia water gap in the Frenchman hills, 45 degrees south (Grolier and Bingham 1971); the Columbia Hills at Rock Creek, Washington, 50-70 degrees north (Swanson et al. 1979b)].

STRUCTURE OF THE HANFORD SITE

The Pasco Basin is bounded on the north by the Saddle Mountains anticline, on the west by the Umtanum Ridge, Yakima Ridge, and Rattlesnake Hills anticlines, and on the south by the Rattlesnake Mountain anticline (Fig. 3). The Palouse Slope, a west-dipping homocline, bounds the Pasco Basin on the east. The Pasco Basin is divided into the Wahluke and Cold Creek synclines by the Umtanum-Gable Mountain anticline.

The Cold Creek syncline (Fig. 3) lies between the Umtanum Ridge-Gable Mountain uplift and the Yakima Ridge uplift and is an asymmetrical and relatively flat-bottomed structure. The 200 Areas lie on the northern flank, and the bedrock dips gently (approximately 5°) to the south. The 300 Area lies at the eastern end of the Cold Creek syncline where it merges with the Pasco syncline.

The Wahluke syncline (Fig. 3) is the principal structural unit that contains the 100 Areas. The Wahluke syncline is an asymmetrical and relatively flat-bottomed structure similar to the Cold Creek syncline. The northern limb dips gently (approximately 5°) to the south. The steepest limb is adjacent to the Umtanum-Gable Mountain structure.

FIELD TRIP STOP DESCRIPTIONS

The following guidebook route begins at the Federal Building parking lot at the corner of Jadwin Avenue and Mansfield Street. All stops in this field trip guide are keyed to a geologic map (Fig. 16) of the Site and a field trip route map (Fig. 18). Mileage is given to the nearest tenth of a mile and is cumulative. Because there are several optional side trips, mileage for each optional trip begins at 0.0 where the trip leaves the primary route.

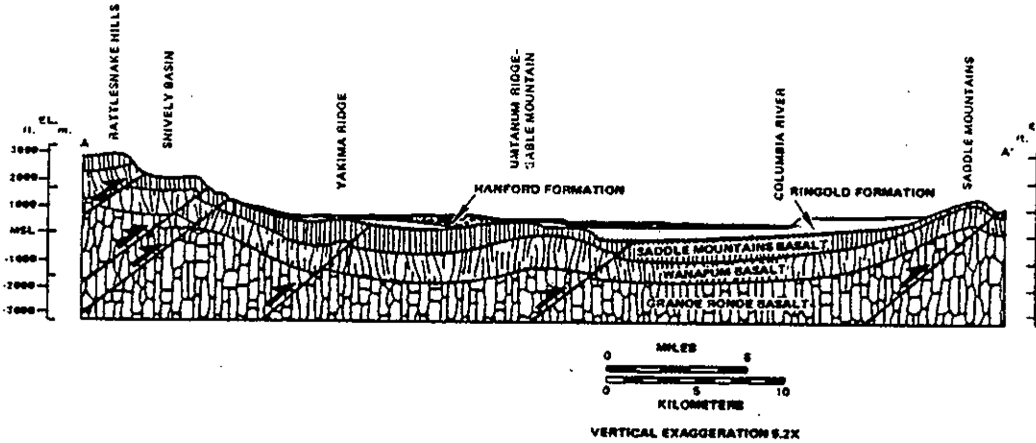


Figure 17. Schematic cross section of the Pasco Basin from Rattlesnake Mountain to the Saddle Mountains. (See Figure 16 for location of cross section.)

Mileage

0.0 Start at the Federal Building Parking lot on the northeast side at the corner of Jadwin and Mansfield. Turn left on Jadwin and proceed north for 1.9 miles to the juncture of Jadwin and Stevens Drive. Proceed north on Stevens for 0.2 mile and turn left toward State Route 240. Cross the "By-pass highway" at the traffic light and proceed toward Vantage on Washington State Route (SR) 240.

From here to Horn Rapids Dam, the road crosses stabilized sand dunes and other eolian deposits. The Washington State Department of Transportation has placed crushed basalt on several road cuts to decrease blowing dust.

8.9 Horn Rapids Road.

10.3 Horn Rapids Dam. Between here and Horn Road, the trip route crosses the eroded trace of the north-trending Horn Rapids anticline. This anticline is reflected in the bedrock high on the south side of Horn Rapids Dam. Ice Harbor, Elephant Mountain, and Pomona Members are exposed along the trace of this north-trending anticline.

10.8 Turn left onto Horn Road (to Benton City). Between the road intersection and the turnoff to Rattlesnake Mountain, the Pomona Member is exposed at river level on the left; on the right forming the slopes is the Elephant Mountain Member.

12.4 Turn right onto Rattlesnake Mountain Road.

12.7 Go through locked gate (Gate 106) onto the U.S. DOE National Environmental Research Park, Arid Lands Ecology Preserve (ALE). The road follows the surface of the Elephant Mountain Basalt, which is the second oldest basalt flow in the area. Across the Yakima River, the Elephant Mountain Member is overlain by the 8.5-million-year-old basalt of the Ice Harbor Member.

15.1 Note the landslide at 1 o'clock along the north side of Rattlesnake Mountain (Fig. 19). This landslide occurred after the last Missoula flood (post 13,000 years). The basis for this age determination is that there are no sediments from the last major cataclysmic flooding on the landslide. This indicates that the landslide is younger than the flood; otherwise flood sediments would be found on the landslide. The landslide was probably triggered when the floodwaters removed basalt from along the base of Rattlesnake Mountain, allowing the basalt and sediment in the landslide area to slide. The slide plane is the Mabton interbed, which is about 15 m thick in the area. At the western edge of the landslide the upper and lower faults along the higher part of Rattlesnake Mountain merge into one fault zone. The structure is more complicated to the west but is also more broken up so a single large slide plane could not form. Thus, it appears that the landslide could only

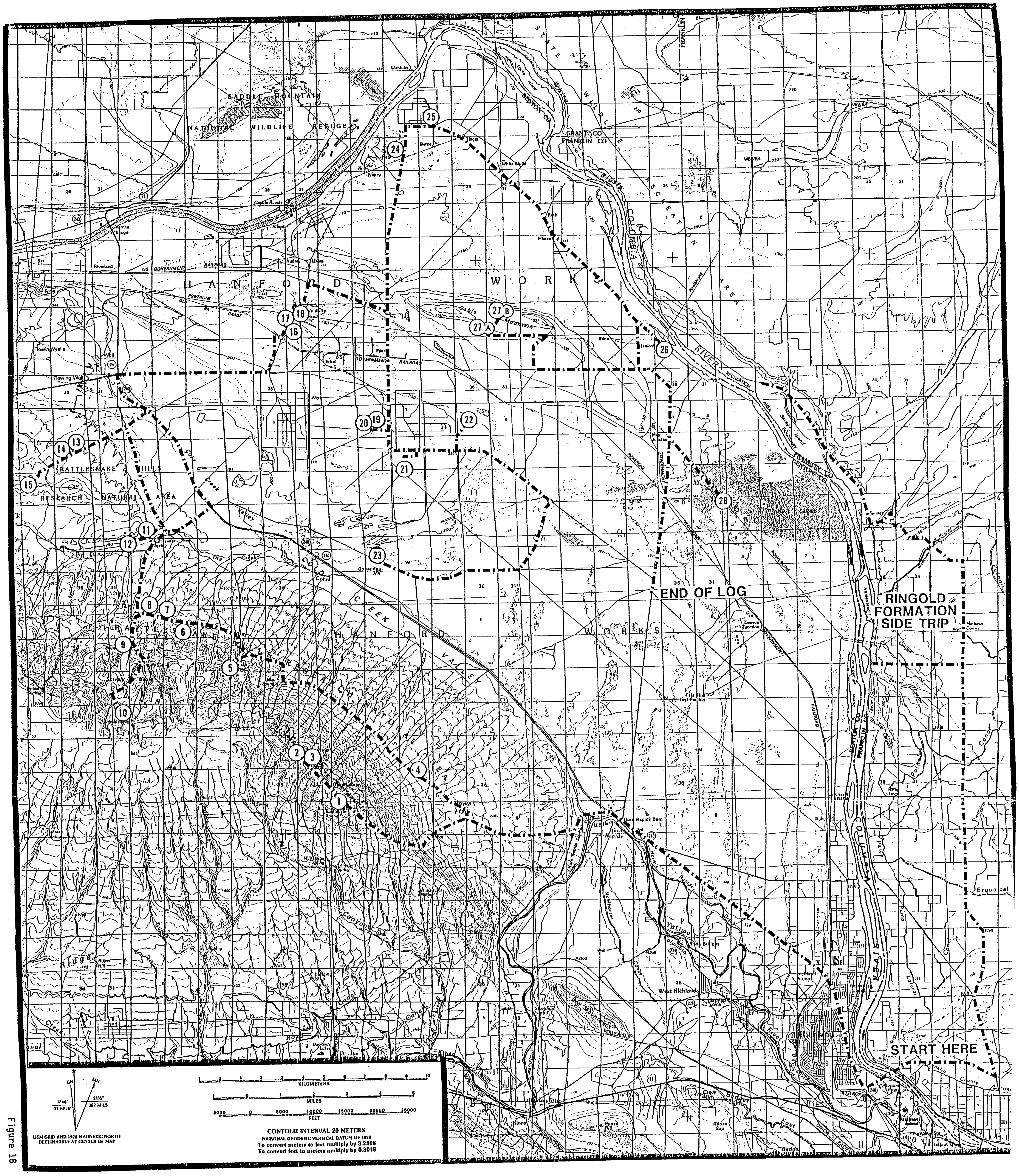

SADDLE MOUNTAIN
NATIONAL WILDLIFE REFUGE
HANFORD
WORKS
RATTLESNAKE HILLS
RESEARCH NATURAL AREA
COLD CREEK VALLEY
STATE WILDLIFE RECREATION AREA
COLUMBIA RIVER
GRANT CO
FRANKLIN CO
BENTON CO
Gable Mountain
Yakima
West Richland
Richland
END OF LOG
RINGOLD FORMATION SIDE TRIP
START HERE
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27A
27B
28
GN
MN
1°48'
32 MILS
21½°
382 MILS
UTM GRID AND 1978 MAGNETIC NORTH DECLINATION AT CENTER OF MAP
KILOMETERS
MILES
FEET
CONTOUR INTERVAL 20 METERS
NATIONAL GEODETIC VERTICAL DATUM OF 1929
To convert meters to feet multiply by 3.2808
To convert feet to meters multiply by 0.3048

Figure 18

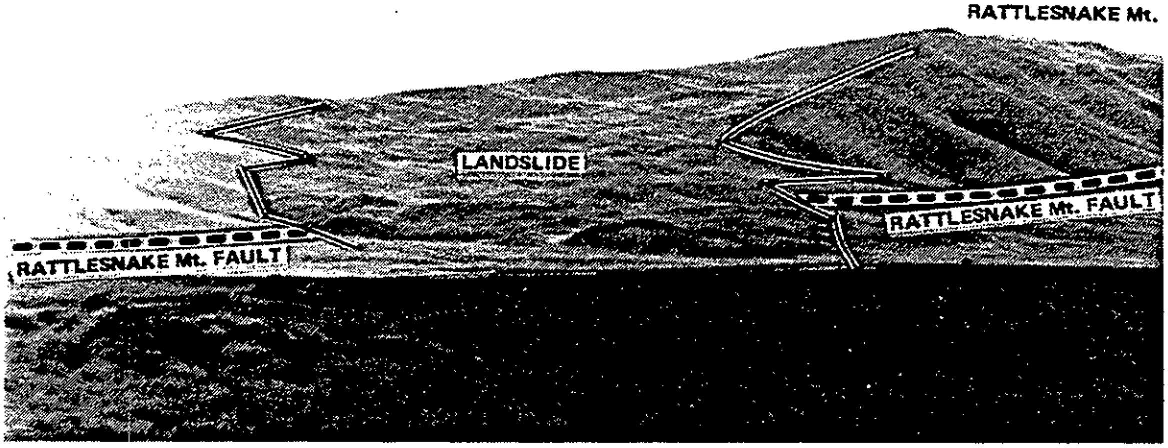


Figure 19. Rattlesnake Mountain landslide.

develop where the structure of Rattlesnake Mountain is an unfaulted dip slope.

15.9 Road forks; turn left.

17.4 Cross the approximate location of the Rattlesnake Mountain fault. The Rattlesnake Mountain fault is covered at this locality by colluvium, so its exact location can only be inferred. The age of the colluvium cover is not known, but farther west the 13,000-year-old landslide lies undisturbed above the fault. This indicates that movement on the fault is at least older than 13,000 years.

17.6 Road bends to the right; you are now climbing up the north side of Rattlesnake Mountain. The route is on basalt of the Pomona Member; some colluvium composed of basalt of the Elephant Mountain Member is also present.

18.8 Begin to climb up the plunging anticline that forms this part of Rattlesnake Mountain. The route follows the dip slope of the Pomona Member. Basalt of the Ice Harbor and Elephant Mountain Members is farther down the south slope.

The Ice Harbor Member basalt flow pinches out on the flank of the ridge, but the Elephant Mountain Member covered the mountain. The highest elevation of the Ice Harbor Member basalt is 366 m. This indicates that approximately 732 m of uplift has occurred on Rattlesnake Mountain since about 8.5 million years ago, the age of the Ice Harbor Member. Mount Adams can be seen in the distance at about 10 o'clock.

20.1 Crossing the highest point on the landslide.

20.6 Radio telescope observatory.

21.5 **STOP 1. OVERVIEW OF THE EASTERN PART OF THE YAKIMA FOLD BELT FROM THE CREST OF RATTLESNAKE MOUNTAIN (FIGURE 18).**

Pull over by the radio towers and support buildings.

This stop provides an overview of the Hanford Site, the central Columbia Basin and the Pasco Basin (Fig. 16 and Fig. 20). It is an excellent place to discuss the geologic history of the area and place the surrounding geographic features into a geologic perspective.

The view to the north allows one to see the main elements of the Palouse Slope (to the NE) and the Yakima Fold Belt (N and NW) and to contrast their main features. The Palouse Slope is marked by very gentle dips (1°) to the east-southeast into the area near Ice Harbor Dam where dikes that fed the basalts of the Ice Harbor Member (8.5 Ma) are found. Structural dips increase to several degrees westward from the Ice Harbor dike swarm into the Pasco Basin (Fig. 3). The Ice Harbor dikes generally mark the boundary between the Palouse Slope and the Yakima Fold Belt. The Ice Harbor dikes are the westernmost known dikes of the Columbia River

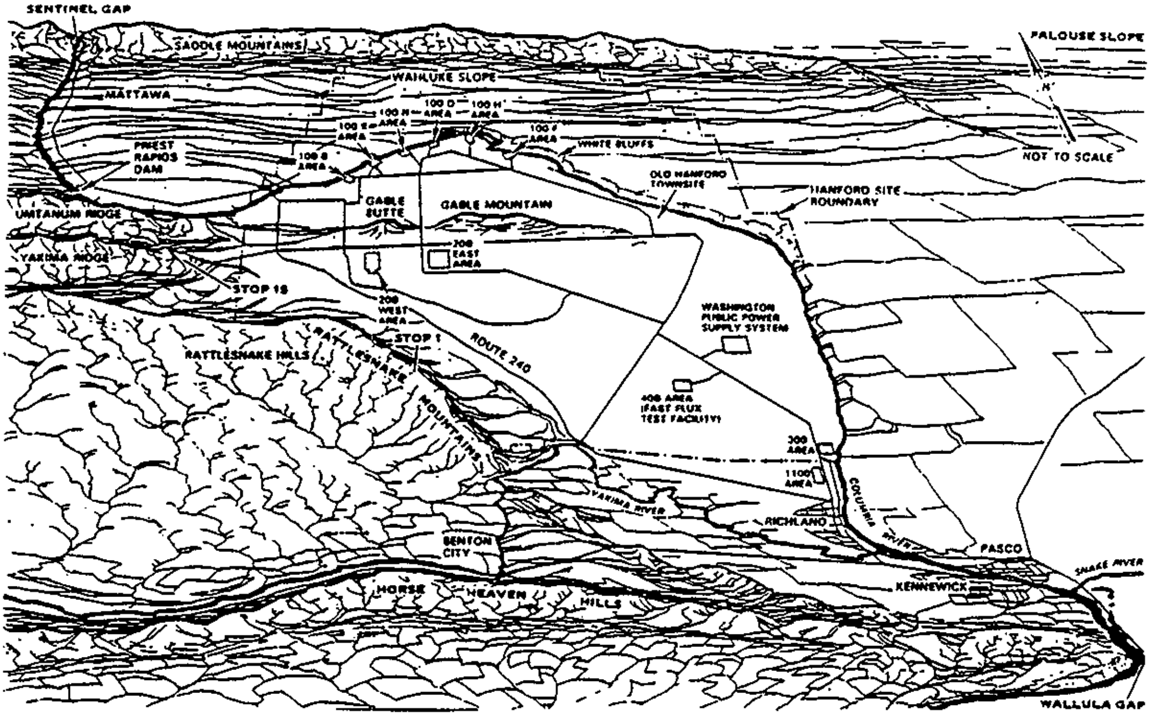


Figure 20. Oblique line drawing of the Pasco Basin and vicinity, Stop 1. View is from the south near the Oregon border looking to the north.

Basalt Group (excluding the Picture Gorge Basalt). The dikes occur on the western edge of the craton with accreted terrains lying to the west (Reidel et al. 1989a). The Pasco Basin lies within a graben that underlies almost the entire Yakima Fold Belt. The Hanford Site lies within the part of the graben where the basalts and underlying sediments are thickest. This thick sequence of basalt and sediments indicates that subsidence has been occurring over a long period of time. The area is still subsiding but at a very slow rate.

This vantage point also provides a good locality to see the typical geometry of a Yakima fold. Throughout much of the Columbia Basin, the topography is a direct reflection of the geometry of geologic structures because very little erosion has occurred. As we discuss geologic structural features, much of what we describe at a distance can be seen in the topographic shape.

Note that the north side of Rattlesnake Mountain is very steep while the south side has a very gentle slope. Also note the very abrupt change from a gentle south dip on the back slope to a steeper dip near the crest. This geometry is apparent on both Rattlesnake Mountain and the HHH (to the south). From our viewpoint we can see some of the doubly plunging anticlines that lie along the crest of the HHH. These anticlines tend to be east-west oriented and en echelon to the trend of the HHH, which is trending NE (see Hagood 1986 for a detailed study of the HHH).

The view to the south and southwest allows us to see the Blue Mountains anticlinorium. The Blue Mountains is one of the major mountain ranges of the Pacific Northwest that lies between the Cascade Range and the Rocky Mountains; it marks the southern boundary of the Palouse Slope and the Yakima Fold Belt. The Blue Mountains can be traced from the Cascade Range near Bend, Oregon to as far east as Lewiston, Idaho.

Southeast of Rattlesnake Mountain, the Rattlesnake Mountain structural trend continues to Wallula Gap where the Columbia River exits the Pasco Basin. This trend is blocked from our view at this locality but can easily be seen as we drive back down Rattlesnake Mountain. The trend is marked by a series of doubly plunging anticlines that have been called the "Rattles" in most geologic reports on the area. The Rattles and Rattlesnake Mountain form part of an alignment of topographic features called the Olympic-Wallowa lineament (OWL). This alignment of topographic features can be traced from the Olympic Mountains of Washington to the Wallowa Mountains of NE Oregon. The exact geologic nature of this alignment is not known. This portion of the alignment, the RAW, is the main portion of the OWL that can be tied to geologic structures.

The view to the southwest shows the continuation of the HHH anticline as a topographic high on the horizon. The HHH anticline can be traced as far as Portland, Oregon (Beeson et al. 1989). The highest elevation on the HHH occurs just north of Goldendale and can be seen from this point on a clear day. The high point is a result of magma intruding into the crust and inflating the crust below the HHH; this magma supplied the Simco volcanic field that lies on the south flank of the HHH. Farther in the distance is Mount Hood, one of the high-Cascade volcanoes.

To the NW the Saddle Mountains and Sentinel Gap, a water gap cut through the mountain by the Columbia River, can be seen. Beyond Sentinel Gap is the HR-NR anticline, which forms the western boundary of the Pasco Basin. This major anticlinal feature can be traced from the Mount Stuart area of the North Cascade Range onto the Columbia Plateau. On clear spring days, Mount Stuart and Glacier Peak can be seen from this viewpoint.

22.8 STOP 2. POMONA MEMBER (FIGURE 18).

The Pomona Member of the Columbia River Basalt Group is a fine-grained, sparsely plagioclase phyric basalt flow. One of the most distinctive features is the wedge-shaped plagioclase phenocrysts that are as much as 0.1 cm long. The flow forms distinctive columns exposed at this locality (Fig. 21a and b).

23.4 STOP 3. OBSERVATORY SPRING ON RATTLESNAKE MOUNTAIN (FIGURE 18).

The anticlinal ridges in and around the Hanford Site have uplifted and faulted the Columbia River Basalt Group, exposing many of the basalt flows and interbedded sedimentary units of the Ellensburg Formation. Between the basalt flows are aquifers that are confined by the lava flows. These aquifers are called the "confined aquifer system." Observatory Spring is just one of many similar springs around the Hanford Site and Columbia Basin where the confined aquifers have been exposed to form surface springs. These springs are a major source of water for the unconfined aquifer that overlies the upper surface of the Columbia River Basalt Group at the Hanford Site. These springs form small streams that flow year-round off the anticlinal ridges and into the unconfined aquifer system.

The spring at this stop emanates from the Priest Rapids Member of the Wanapum Basalt and produces several gallons of water per minute. The Priest Rapids Member is regionally the most important confined aquifer in the Columbia Basin. The watershed for this spring is about 71 ha on the north-facing slope of Rattlesnake Mountain and is spread over an elevation range of 760-1,060 m. This watershed has an estimated mean rainfall of 22 cm/year. Rainfall and snowmelt are the principal sources of recharge for this spring (Routson et al. 1977). Analyses of the water indicate that the spring is supplied primarily by rainfall and snowmelt that collects in this watershed. This spring differs from other springs around the Hanford Site in that it is supplied by recharge only on this ridge. Most other springs along the ridges, however, are supplied from a much greater recharge area that in some cases can extend as far away as the Cascade Range.

Retrace route to Stop 1.

25.5 Observatory.

26.0 View of doubly plunging anticlines along the RAW, Badger coulee, bend in HHH, Wallula gap, and Blue Mountains.

30.8 "Y" in road; bear left to ALE Headquarters. Gully and left bend.

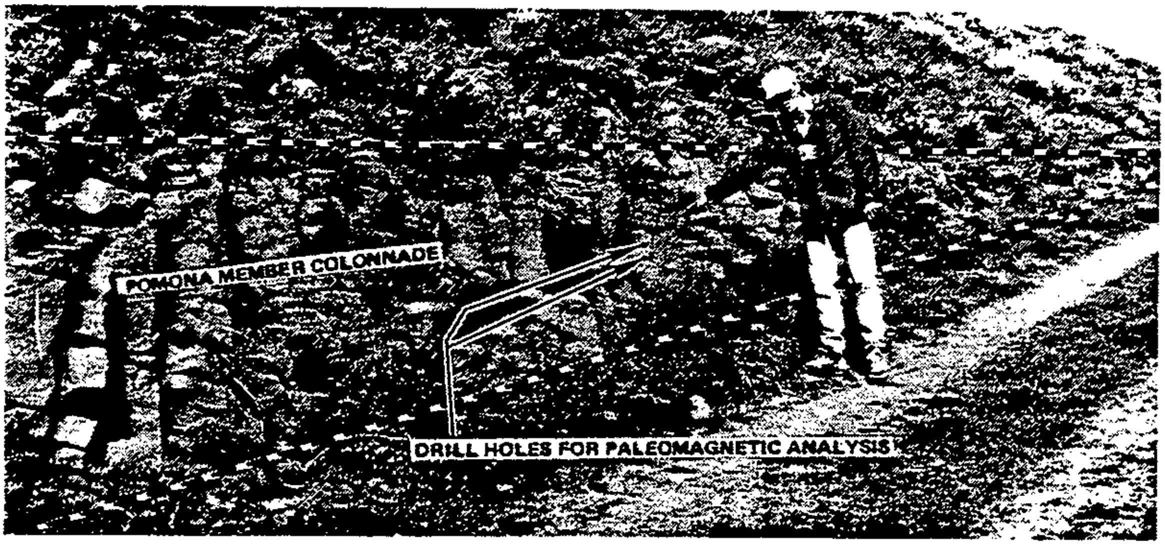


Figure 21a. Pomona Member, Columbia River Basalt Group, Stop 2. A. Colonnade of Pomona along road. Small 1-inch borehole sampling site for paleomagnetic analysis of the Pomona flow is shown.

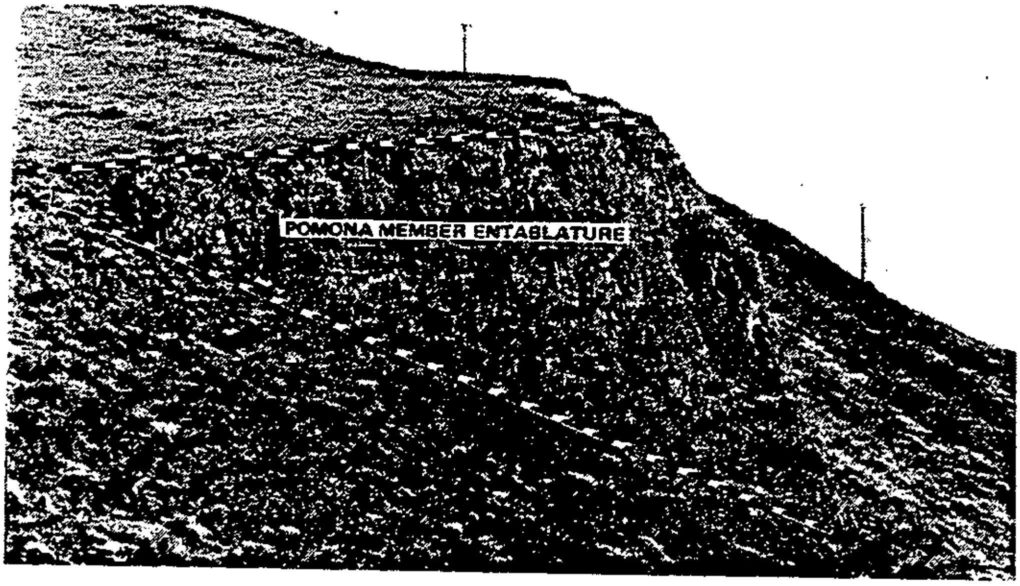


Figure 21b. Pomona Member, Columbia River Basalt Group, Stop 2. B. Entablature of the Pomona Member from exposure above A and on the crest of Rattlesnake Mountain.

32.1 Intersection - go straight
Leave pavement. The road traverses north-dipping Elephant Mountain Member.

32.6 **STOP 4. VIEW OF RATTLESNAKE MOUNTAIN (FIGURE 18).**

This locality provides an excellent view of the north flank of one of the largest of the Yakima anticlines, Rattlesnake Mountain (Fig 22). There is almost 1,219 m of structural relief on the basalt of the Elephant Mountain Member. All basalt flows encountered in boreholes at the Hanford Site thin onto Rattlesnake Mountain; we interpret this to mean that Rattlesnake Mountain was growing during the eruption of the Columbia River Basalt Group. The present relief developed in the last 10.5 million years, but geophysical data show that even more structural relief on Rattlesnake Mountain is buried by the younger flows (Reidel et al. 1989a).

The prominent bench just below the crest marks the Wanapum-Saddle Mountains Basalt contact and is erosional. The contact is marked by a sedimentary unit, the Mabton interbed, which has eroded back into the hillside.

The main fault runs along the base of the mountain but is covered by sediments; no displacement of the sediments has been observed. The fault dies out to the southeast before reaching the Yakima River. Basalt flows along the north side of Rattlesnake Mountain dip between 50° to 70° to the north. The second bench below the upper one marks an upper thrust fault placing gently south-dipping basalt flows above the steeply north-dipping ones. The anticlinal axis has been thrust over and eroded from the present exposures. The upper thrust dies out to the southeast and northwest and is responsible for the greater structural relief along this part of Rattlesnake Mountain. From this locality, the eastward plunge of the Yakima folds is very apparent. To the north in the distance, only Gable Butte and Gable Mountain of the Umtanum Ridge anticline protrude above the sediment-filled basin (Fig. 16). A buried ridge east of Gable Mountain, called the Southeast anticline, marks the eastward termination of the Umtanum Ridge structural trend. Gable Mountain and Gable Butte are second-order en echelon anticlines developed on the Umtanum anticline (Fecht 1978). The Yakima Ridge anticline also plunges southeast and is buried by sediments of the Ringold Formation and Hanford formation. On the north side of Rattlesnake Mountain is the old Rattlesnake Hills gas field.

34.2 Leave gravel; follow dirt road. The old Rattlesnake gas field is to left at 9 o'clock. Note the green area indicating Observatory Spring at 10 o'clock.

The Rattlesnake gas field has played an important role in the history of oil and gas exploration in the Columbia Basin. The small hill 1 mi north of Rattlesnake Mountain is the location of the Rattlesnake gas field that produced natural gas sold to local towns in the 1920's and 1930's. The small hill is an anticline, like Rattlesnake Mountain only much smaller, and natural gas was found between the lava flows. Probably most of the methane is at the top of the Priest Rapids Member. Natural gas was trapped under the anticline because of the arched shape. The first deep hydrocarbon exploration well, RSH-1 (near Point A, Fig. 16), was drilled to a depth of 3,249 m in the 1950's on the Rattlesnake Hills south of this point and was still in the Columbia River Basalt Group (Reidel et al. 1982). There was no significant quantity of gas discovered in that borehole. Geophysical data indicate that there is at least another 305 m or more of basalt making a total thickness of at least 3,657 m. Analysis of the chemistry of the basalt from the borehole indicates that there is no significant repeat in stratigraphy; this constrains the dip of the frontal fault zone to at least 45° south or greater.

35.2 Old gas well site at 9 o'clock.

38.5 East end of the Snively Basin at 9 o'clock. This area marks the intersection of the northwest-trending Rattlesnake Mountain and the east-west-trending Rattlesnake Hills (Fig. 3). The intersection of the two trends is marked by a decrease in amplitude of the Rattlesnake Mountain structure to the northwest. The Snively Basin complex extends farther to the north than does Rattlesnake Mountain, although it does not have anywhere near the amount of vertical structural relief that Rattlesnake Mountain has. This is probably because the Snively Basin complex is made up of a series of thrust sheets that extend northward rather than

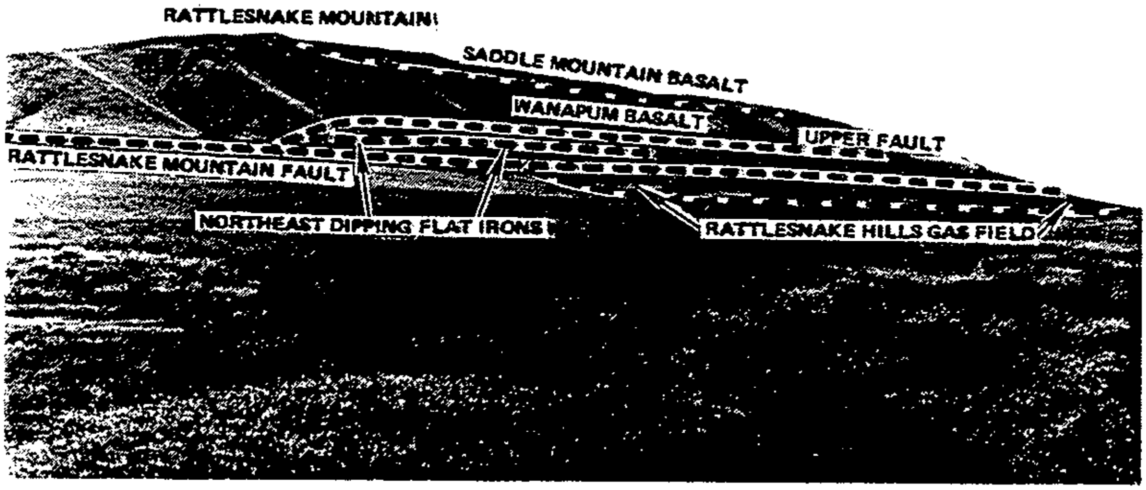


Figure 22. View of the north side of Rattlesnake Mountain, Stop 4.

stacking up on top of each other as on Rattlesnake Mountain.

40.0 Road intersection.

Go straight off main road onto side road that goes up east side of alluvial fan.

40.4 STOP 5. STRUCTURE OF SNIVELY BASIN AREA (FIGURE 18).

Stop at bend in road and walk to knoll that overlooks valley and alluvial fan.

This portion of the Snively Basin is a complex geologic area that marks the intersection of the northwest-trending Rattlesnake Mountain trend and the east-trending Rattlesnake Hills trend (Fig. 3). There are several thrust faults exposed in this area. The general geology of the area is shown in Figure 23. The exposures of basalt above the alluvial fan are Saddle Mountains Basalt flows that strike to the NW and dip about 50° to the northeast. Lying above these N-E dipping basalt flows are nearly horizontal Saddle Mountains Basalt flows that have been thrust up onto the lower flows.

This area shows the relationship between the N-W striking structure of Rattlesnake Mountain and the E-W striking structure of the Rattlesnake Hills. The structurally lower N-W striking basalt flows are some of the northwest-most exposures of the Rattlesnake Mountain anticline. The anticline has lost most of its structural relief by this point and appears not to extend beyond this exposure. The flows above the thrust fault are part of the E-W striking Rattlesnake Hills structure. The E-W trend does not appear to extend any farther east than this area. This locality is interpreted to be where the E-W striking Rattlesnake Mountain has been thrust up onto the N-W-trending Rattlesnake Mountain structure. The debris that lies north of Snively Basin is interpreted to be tectonic landslide debris from the landsliding of basalt flows that have been oversteepened as they were thrust overtop of the N-W-trending Rattlesnake Mountain structure.

There are several springs, including Benson Spring, that emanate from this area. These springs are coming from the top of the Priest Rapids Member basalt flows, such as Observatory Spring. The recharge area here is not confined to a small section, but the springs appear to be fed from the entire area. The several thrusted blocks in this area have repeated the exposures of the Priest Rapids Member basalt and have thus created several springs, but all from the same horizon. Up the creek to the east, there is a tear fault that also has a small spring.

Return to the road intersection.

40.8 Turn left at the intersection and continue west on the road along the north side of the Snively Basin complex.

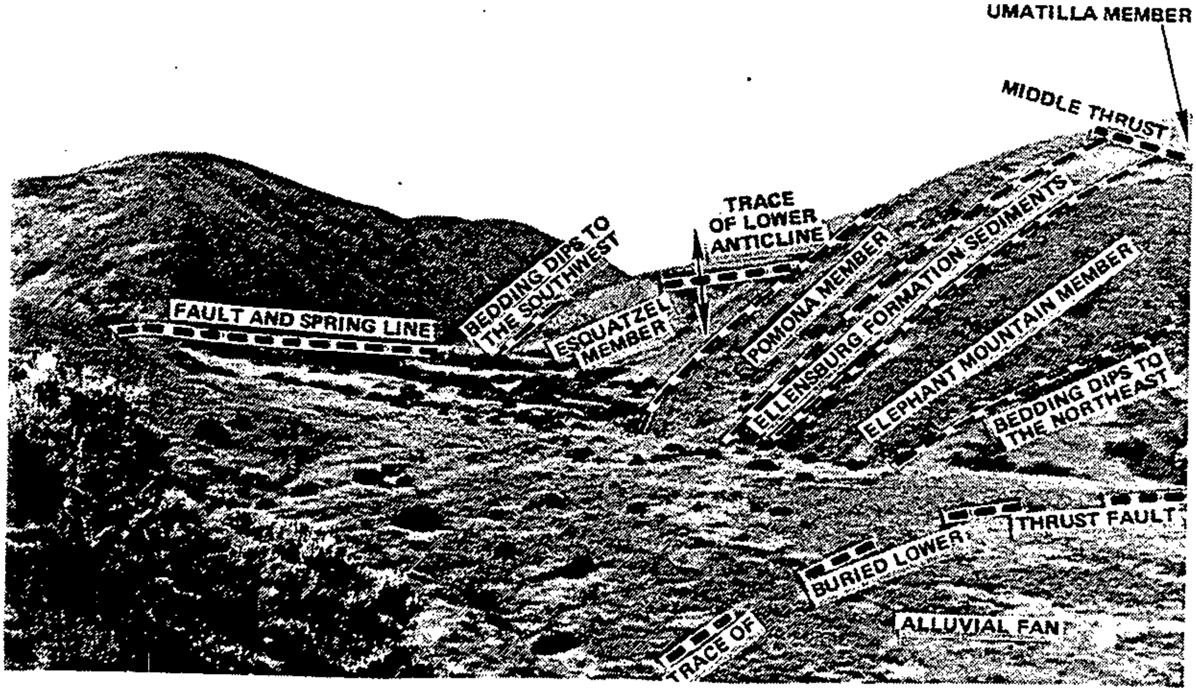


Figure 23. Geologic relations at Stop 5. In the photo the N-W continuation of the Rattlesnake Mountain structure (lower exposures) where Saddle Mountain Basalt is overlain by a repeated section of Saddle Mountains Basalt that has been thrust faulted over it.

41.6 Road intersection. Turn left at the road intersection. Continue following the road along the base of the ridge; this road follows approximate position of the frontal fault.

44.5 On knoll at 10 o'clock is one of the Hanford Array seismic stations operated by Westinghouse Hanford Company.

45.7 STOP 6. SNIVELY BASIN FRONTAL FAULT ZONE (FIGURE 18).

Park at wide spot where the road crosses gully bottom. At this locality walk up the gully to south of road and examine faulted basalts and Ringold (?) units, and Plio-Pleistocene deposits. This locality (Fig. 24) is a good place to observe repeating of beds along the frontal fault zone; similar structures are found along many of the Yakima folds. Walking up the creek from the road, one first passes through caliche-covered colluvium and alluvial fan deposits of probable Ringold age. Thrust up onto these deposits is the basalt of the Elephant Mountain Member. Farther up the creek and resting on the Elephant Mountain Member basalt is a packet of Ringold paleosols and other sediments that overlie the basalt. Thrust up on this sediment package is a repeat of the Elephant Mountain Member basalt. The sediments in contact with the repeated Elephant Mountain Member basalt at the upper end of the creek contain some ash, suggesting that the Rattlesnake Ridge interbed comprises some of these sediments. Farther up the creek and lying under the Elephant Mountain Member is the Pomona Member.

In spite of the faulting, the basalt is surprisingly intact and unbrecciated. This is very typical of many fault zones, although many other frontal fault zones are brecciated, and internal structure in the basalt flows is unrecognizable. The basalt flows that remain intact are usually those that are in the Saddle Mountains Basalt and are interbedded with sediments. The Grande Ronde Basalt, which lacks interbedded sediments, is usually so brecciated that the internal features of the basalt cannot be recognized.

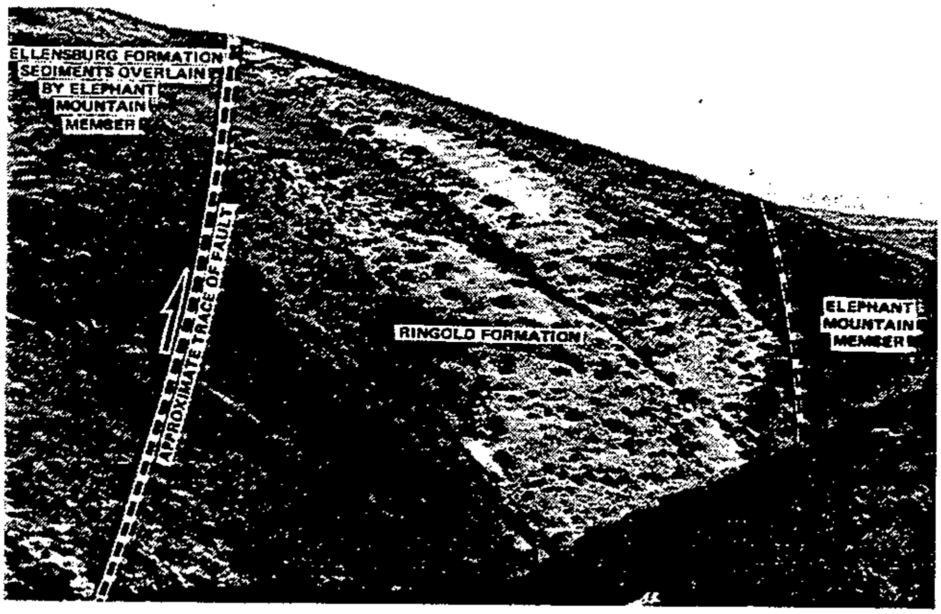


Figure 24. Snively Basin frontal fault zone, Stop 6. South-dipping Elephant Mountain Member that is overlain by Ringold Formation equivalent sediments has been thrust over by a repeated section of the Elephant Mountain Member and Ellensburg Formation.

46.6 STOP 7. SUPRABASALT PEDOGENIC CARBONATES (FIGURE 18).

Exposed in the gullies on either side of the road is a series of pedogenic calcium carbonate horizons (caliches) (Fig. 25) that are dipping into the basin. The horizons on the south (left) side of the road generally overlie basalts, while those on the north side of the road overlie sediments of the Ringold Formation (?). In some of the ravines along the north side of Rattlesnake Mountain, multiple caliche horizons interbedded with locally derived basaltic colluvium are found. Basalt gravels derived from nearby Rattlesnake Mountain and the Rattlesnake Hills are abundant in these caliches.

These caliches and similar ones throughout the region probably began to form following the end of Ringold deposition approximately 3.4 Ma.

As they formed and ridges continued to be uplifted, the caliches were uplifted and tilted. The pedogenic carbonates exposed in this area and on the ridges around the Pasco Basin probably correlate at least in part to caliche zones encountered in the subsurface in the western Cold Creek syncline.

47.1 STOP 8. RINGOLD FORMATION AND PLIO-PLEISTOCENE(?) (FIGURE 18).

Small exposures of lacustrine strata typical of the upper unit of the Ringold Formation (Fig. 26) are present in this area. One such exposure is found in the ravine just to the north of the road. The Ringold lacustrine deposits seen in the ravine are dominated by plane laminated silt and clay. Ripple cross-laminated silty fine-grained sands such as those commonly encountered in these lake deposits in the eastern Pasco Basin (along the White Bluffs) are not found in the outcrop at this stop. The absence of sandy strata in the outcrop at this stop suggests that fluvial distributaries were not active in the southwestern part of the basin. The thin pedogenic carbonate horizon at the top of the outcrop is generally correlative to the caliches seen at the previous stop.

47.7 Intersection; go straight. The route now is over an alluvial fan complex. Springs emanating from

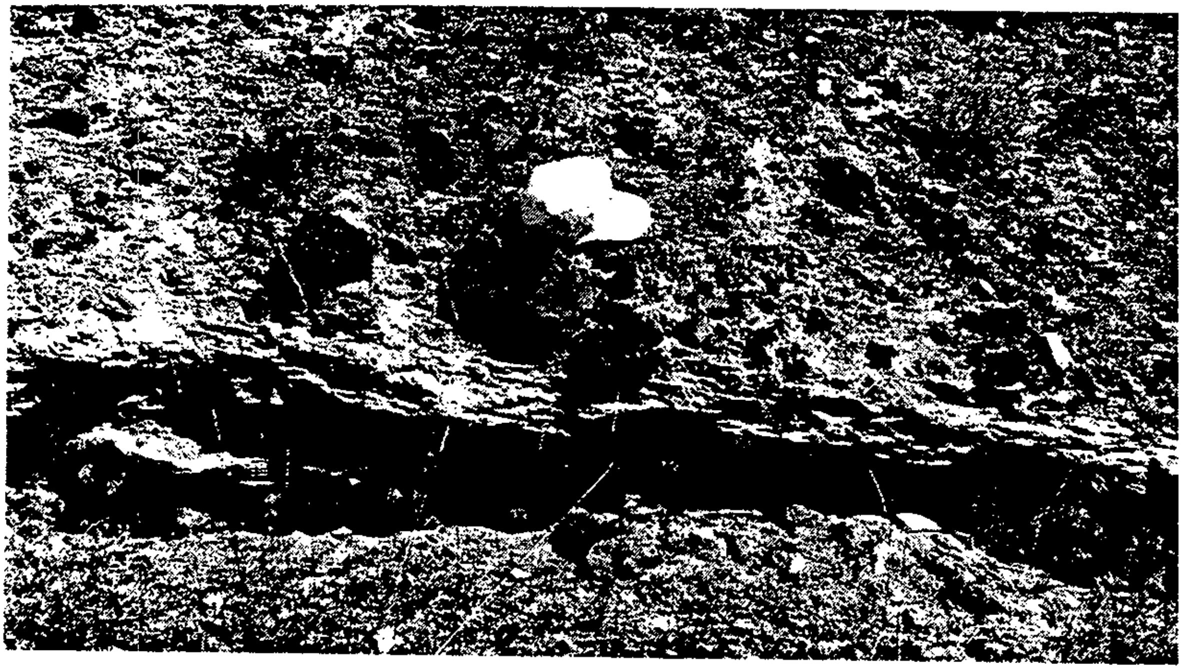


Figure 25. Basaltic gravels and pedogenic calcium carbonate exposed in the ravine north of road at Stop 7.

Figure 26. Laminated muds of the upper part of the Ringold Formation found in the gully north of the road, Stop 8. Muds are overlain by pedogenic calcium carbonate (caliche).

confined aquifers in Snively Basin flow into the fan and below ground.

We believe that these springs make a significant contribution to the unconfined aquifer system at the Hanford Site. Light-colored slope at 9 o'clock is an exposure of Ringold muds similar to those at previous stop. These muds are overthrusted by the Columbia River Basalt Group in the Snively Basin complex.

48.1 Gully on right. Colluvial debris flow deposits of the Snively fan are exposed on right. Ravine road is following cuts through core of anticline; basalts are dipping to north.

48.6 Cross creek.

48.4 Crossing the core of an anticline; basalts are of the Priest Rapids Member. At this locality the basalts are tightly folded and the road crosses the axis of a northwest-trending anticline associated with the Snively Basin complex.

48.5 Cross creek. The water for this creek emanates from a series of springs farther up the creek. The first spring comes out of the flow top of the Priest Rapids Member exposed in the core of this anticline.

48.7 STOP 9. UMATILLA MEMBER AND SMALL THRUST FAULT (FIGURE 18).

The Umatilla Member is a very fine-grained to glassy basalt flow. Throughout much of the area, a glassy entablature with many small cooling joints forms most of the flow. This can be observed on the east wall of the valley about 15 m above the road. At road level the flow is fine-to-medium grained and has columnar joints that are more widely spaced.

A small thrust fault cuts through the basalt of the Umatilla Member and is exposed on right side of road at road level (Fig. 27). Faults dip approximately 15° to south. Here the thrust fault is marked by a small, several centimeters wide zone of basalt that has been fractured and brecciated. Many small clasts can be seen in the small fault zone. The relative sense of movement is for the upper block to have moved north with respect to the lower block.

48.8 Basalt of the Esquatzel Member is exposed where the road enters the wide valley. The Esquatzel Member here is mainly a fine- to medium-grained basalt flow with columnar jointing.

49.1 Site of old Snively Ranch. Bear right at intersection; basalt of the Pomona Member is exposed along the left side of the road. The road will now be crossing the axis of Snively Basin syncline.

49.8 Intersection with road on left, go straight. The road on the left goes uphill to a small spring emanating from the top of the Priest Rapids Member.

49.8 Cross Dry Creek and trace of fault. To right is a spring in the top of the Priest Rapids Member. As elsewhere on the Hanford Site, dry creeks such as this one have water flowing below the surface that is fed by springs coming from the confined aquifers.

51.1 STOP 10. STRUCTURE OF THE WESTERN END OF THE SNIVELY BASIN (FIGURE 18).

First switch-back on road out of Snively Basin. Stop and turn around. View of Snively Basin.

The view here provides a unique opportunity to observe the main features of the Snively Basin structural complex (Fig. 28). Overall, the structure is that of a broad, low amplitude, fault-bounded syncline. The fault crossed at mile 49.8 at the base of the slope is one of the bounding faults.

This fault has thrust the entire Saddle Mountains Basalt section onto the Elephant Mountain Member. There is about 300 m of offset of the Elephant Mountain Member on this fault. This fault has exposed the Priest Rapids Member in gullies along the entire length of the hill slope. In every gully where the Priest Rapids Member is exposed, a spring emerges from the top of the basalt flow. These springs are a steady source of water for the basin; eventually the water from the springs drains down Snively Creek (which parallels the route that we followed into the basin) and into the unconfined aquifer.

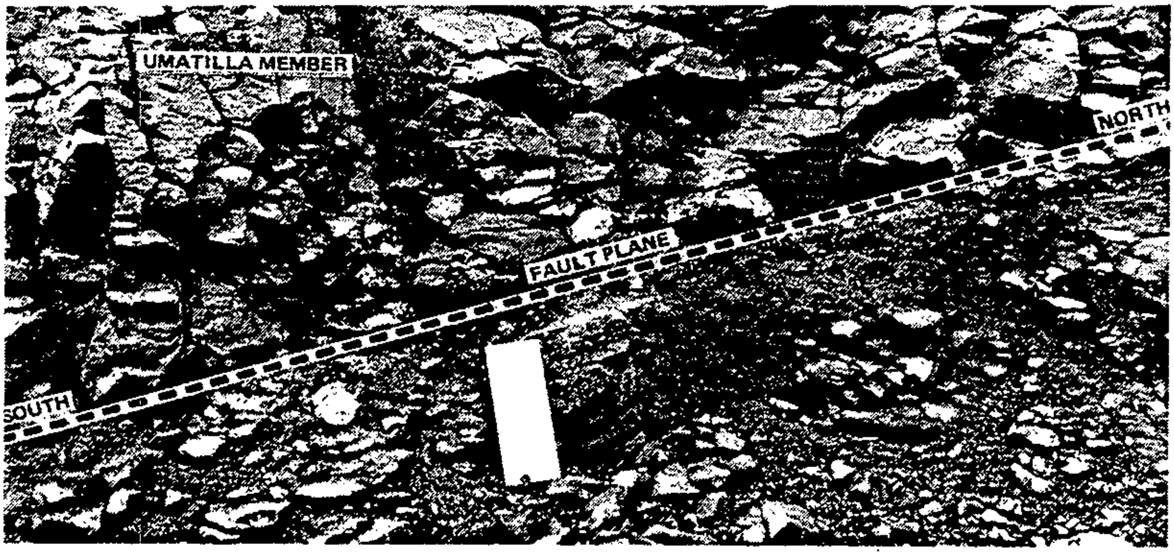


Figure 27. Small thrust fault in the Umatilla Member, Stop 9. Upper plate moved to the right (north).

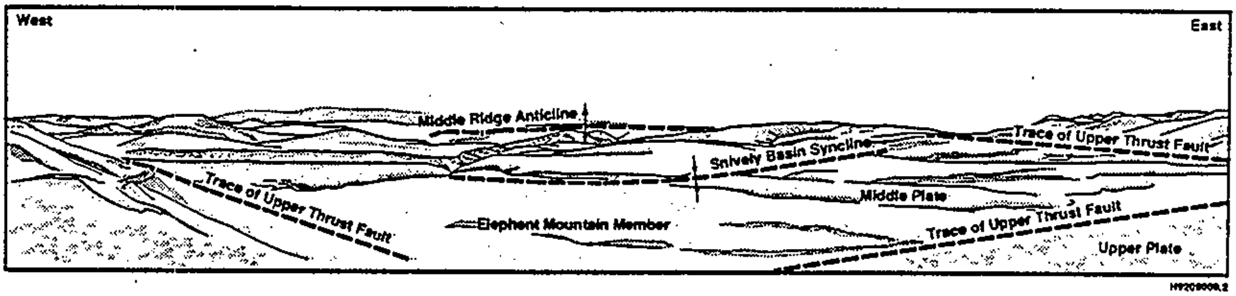


Figure 28. Panoramic view of the Snively Basin syncline area, Stop 10.

The north end of the basin is marked by a hill that rises above the broad synclinal basin. This is an anticlinal ridge that rims the basin. We crossed this anticline (mile 48.4) as we entered the narrow valley, and it was this anticline that exposed the first spring that we saw. Note that to both the east and west, the anticlinal ridge merges with the ridge from which we are viewing the area. Snively Basin is a closed basin.

Turn around and retrace the route.

54.6 Intersection; turn left.

55.5 To the south is an excellent view of the alluvial fan along the north side of Snively Basin.

55.6 At 11 o'clock see tear fault cutting through Yakima Ridge. This is described at Stop 12.

56.8 Intersection; continue straight ahead.

57.3 Intersection; road to left goes to the ALE Field Station.

57.5 Road to right goes to the Benson Ranch site; follow road to left.

57.6 Cross Dry Creek. Turn left at intersection immediately after crossing creek. Just past intersection is a fork in the road; take left fork.

Dry Creek is filled with water year round. A U.S. Geological Survey stream gauging station is located where we cross the creek (upstream side). This station has shown that the water flow is relatively constant. The flow emanates about 2 km up the valley and disappears underground 3 km downstream to the east.

58.6 **STOP 11. DRY CREEK AND HEAD OF RATTLESNAKE SPRINGS (FIGURE 18).**

Gully to left is the source of water for Dry Creek. This is Rattlesnake Springs. The springs begins in the deep valley (8 m below the surface) that exposes a thick sequence of sediments. The age of the sediments is between 12,000 years and 6,300 years b.p. based on Mount Mazama ash, which occurs near the top, and Glacier Peak ash, which occurs downsection. In the many years of observing this spring, it has always started at this locality.

58.8 **STOP 12. SOUTHERN BLOCK OF YAKIMA RIDGE (FIGURE 18).**

Yakima Ridge is an anticlinal ridge that forms the southern boundary of the Cold Creek syncline. It is one of the more complex anticlinal ridges in that it has a southern block that is separated from the main ridge trend. This southern block is a narrow (1 km), 5-km-long asymmetrical, eroded anticline with a south vergence and a buried thrust fault on the south side.

This stop provides an opportunity to examine a small N-S trending tear fault that cuts the southern block of Yakima Ridge (Fig. 29). The tear fault has approximately 200 m of sinistral movement. On the west side of the fault are simple north-dipping beds of the Saddle Mountains Basalt; here the fold has been eroded away, exposing only the north flank. On the east side of the tear fault, an upper thrust fault is exposed in the Umatilla Member; north of the thrust fault are gently north-dipping units, but south of the thrust are steeply south-dipping units. The change in dip is controlled by the thrust fault and not an anticlinal axis. The west side is thrust 500 m farther south than the east side; the beds exposed on the east side have been eroded away from the west side, giving an apparently different geometry when, in fact, they are the same.

This ridge is similar to other anticlinal ridges such as in the Snively Basin area. The buried thrust fault along the southern block of Yakima Ridge probably places Umatilla or Priest Rapids basalt flows over basalt of the Elephant Mountain Member. Rattlesnake Springs occurs about 0.3 km east and downstream of the tear fault. One probable steady source of water for Rattlesnake Springs is the confined aquifer of the Priest Rapids Member where the thrust fault along the southern block of Yakima Ridge. brought it near the surface. We suggest that where the tear fault and the thrust fault meet, a more permeable groundwater flow path was formed, accounting for the location of Rattlesnake Springs.

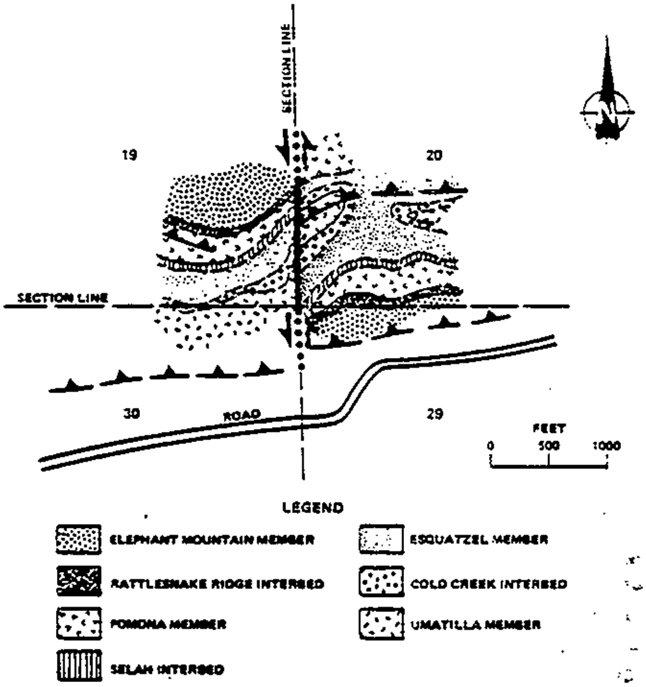


Figure 29. Geologic map of the north portion of Yakima Ridge, Stop 12.

58.0 At this intersection an optional side trip can be taken to see well exposed Touchet Beds, clastic dikes, and bergmounds.

OPTIONAL SIDE TRIP TO TOUCHET BEDS, CLASTIC DIKES, AND BERGMOUNDS (STOPS 13, 14, and 15)

0.0 Turn to left and follow road to north.

0.1 End of Yakima Ridge plunging into Pasco Basin plainly seen on the left.

1.6 Site of BWIP borehole DH-33 on right.

2.4 Road narrows and becomes sand.

3.5 Intersection with powerline road; turn left.

4.3 Turn right and park by powerline pole.

STOP 13. BERGMOUNDS - ICE RAFTED DEBRIS, SLACKWATER DEPOSITS, AND CLASTIC DIKES (FIGURE 18).

Walk to the north to the first main gully.

The hummocky topography between the powerline and the valley ahead is covered by a large number of angular, exotic gravels. These exotic gravels consist of a variety of granitics, gneisses, quartzites, and schists that are most commonly encountered on the tops of the small hummocky mounds. The exotic gravels are interpreted to have been deposited from melting icebergs that were stranded in slackwater areas in Lake Lewis around the periphery of the basin. Slackwater deposits of the Hanford formation are exposed in the steep banks on the north side of the creek valley. The slackwater deposits consist of graded beds or rhythmites of plane to ripple cross-laminated sand and silt 3 to 30 cm thick (Baker et al. 1991). Paleocurrent directions in these deposits show both west-directed (upgradient) and east-directed (downgradient) transport. Pedogenically altered horizons also are found in this outcrop. These horizons generally consist of mottled, red-brown intervals where bedding is disrupted or destroyed.

These deposits are interpreted to have been deposited by cataclysmic flood waters in slackwater areas around the periphery of Lake Lewis. The lower part of each rhythmite with its upgradient paleocurrents is interpreted to have been deposited during initial flood surges as flood waters first entered the basin and flowed up tributary valleys. As the flood surge dissipated and the basin began to drain, the upper part of each rhythmite was deposited. Where paleosols are encountered in these slackwater deposits, complete draining of the lake and subsequent subaerial exposure occurred. Where several rhythmites are superimposed without intervening paleosols, flood events are inferred to have contained several pulses or surges.

Clastic dikes (Fig. 30) are found truncating the slackwater deposits in many of the banks along this creek. The dikes are vertical, subvertical, and subhorizontal features that contain clay, silt, fine- to coarse-grained sand, granules, and occasionally small pebbles. Individual dikes commonly contain numerous vertical to subvertical layers or zones dominated by sands and minor small gravels. These coarse layers often are separated by thin (< 1 cm) clay layers. Clastic dikes in the Pasco Basin most likely formed as a result of dewatering of fine-grained beds following the release of confining pressure as Lake Lewis drained. The presence of multiple layers in each dike suggests repeated dewatering along individual dikes.

Return to main road log route or continue uphill to west to view Ringold-like gravels and structure in western Pasco Basin.

5.1 STOP 14. UPLIFTED SNIPES MOUNTAIN, RINGOLD-LIKE GRAVELS ON YAKIMA RIDGE (FIGURE 18).

Quartzitic gravels containing quartzo-feldspathic matrix sands are exposed along the road and down the ravine to the north. These gravels directly overlie basalt of the Elephant Mountain Member and are similar to cores from the Ringold Formation taken from the Cold Creek syncline just a few kilometers to the east and the Snipes Mountain conglomerates. However, because of the absence of absolute ages, it is not clear if the gravels in this area correlate to the lowest Ringold gravels of unit A or the slightly older Snipes Mountain Conglomerate.

Immediately prior to and during the earliest stages of Ringold deposition, the Columbia River is interpreted to have followed a course across the easternmost end of Yakima Ridge (Fecht et al. 1987). During this period, the Columbia River exited the Pasco Basin in the area of Sunnyside Gap. The Snipes Mountain gravels exposed in the area of this stop are inferred to have been deposited by the Columbia River immediately before it shifted position into the central part of the Pasco Basin.

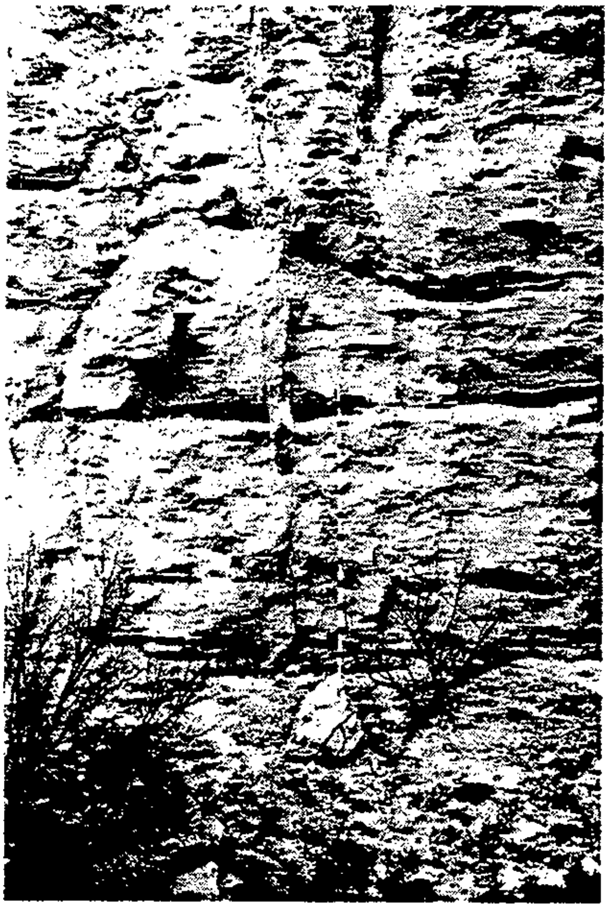


Figure 30. Clastic dikes cutting silt-dominated deposits of the Hanford formation, Stop 13.

7.1 **STOP 15. STRUCTURE OF THE WESTERN PASCO BASIN (FIGURE 18).**

From this vantage point, the structure of the western portion of the Pasco Basin can be seen (use Fig. 20 for reference). To the north is the south flank of Umtanum Ridge. The plunge of the ridge is very apparent from this view; the plunging basalt can be traced to the east where it is buried by flood gravels that form the 200 Area Plateau. In the distance to the east, Gable Mountain and Gable Butte can be seen. Both are doubly plunging, en echelon anticlines that stand as isolated structural highs along the Umtanum Ridge trend. To the far north marking the horizon is the Saddle Mountains, a 110-km-long anticlinal ridge that marks the northern boundary of the Pasco Basin.

RETURN TO MAIN ROAD LOG ROUTE.

The mileage resumes at start of optional side trips.

59.2 Intersection at Dry Creek crossing. Continue straight ahead.

60.7 Crossing the buried trace of the Yakima Ridge anticline. At this point most of the structure has decreased, but an ancestral course of the Columbia River about 13 Ma probably eroded away much of the crest of the anticline (Fecht et al. 1987).

61.5 Gate 118 on SR 240; turn left. At 12 o'clock is Umtanum Ridge; at 9 o'clock to 11 o'clock is Yakima Ridge; and at 1 o'clock to 2 o'clock is Cold Creek Bar (200 Area Plateau).

65.6 Mile marker 1; Cold Creek valley parallel to road. Climb up onto Cold Creek Bar. Note prominent hills, which are bergmounds.

Turn right to Yakima Barricade from SR 240 (left turn leads to Yakima and Moxie).

66.7 Yakima Barricade, Traveling east on Hanford Rt. 11 across the top of the Cold Creek Bar.

68.5 14 mile marker.

69.8 Army Loop Road to right. Rt. 11 is now four lanes. Gable Butte at 9 - 10 o'clock, Gable Mountain at 11 o'clock.

71.1 Road to 200 West Area (north gate) on right, cross railroad tracks.

71.3 **OPTIONAL SIDE TRIP TO SEE GABLE BUTTE ANTICLINE AND SADDLE MOUNTAINS BASALT (STOPS 16, 17, and 18) (FIGURE 18).**

0.0 Turn left toward Gable Butte after crossing railroad tracks.

1.0 Borehole 699-55-76 on left.

1.1 Road bends to right.

1.2 Cross railroad tracks and bear right.

1.5 Cross railroad tracks and bear to the north (left). Road parallels railroad tracks.

1.75 **STOP 16. ELEPHANT MOUNTAIN MEMBER, COLUMBIA RIVER BASALT GROUP.**

The Elephant Mountain Member is a fine- to coarse-grained basalt flow. It is plagioclase microphyric and occasionally diktytaxitic. The flow usually has a well-developed colonnade with columns as much as 1 m in diameter.

1.8 **STOP 17. POMONA MEMBER, COLUMBIA RIVER BASALT GROUP.**

The Pomona Member of the Columbia River Basalt Group is a fine-grained, sparsely plagioclase-phyric basalt flow. One of the most distinctive features is the wedge-shaped plagioclase phenocrysts that are as much as 0.1 cm long. The flow forms distinctive columns that are exposed at this locality. At the base of the flow are large, well-formed pillows that can be recognized by the black, glassy rims.

2.0 Cross railroad tracks.

STOP 18. UMATILLA MEMBER, COLUMBIA RIVER BASALT GROUP.

The Umatilla Member is a very fine-grained to glassy basalt flow. Throughout much of the area, a glassy entablature with many small cooling joints forms most of the flow. The base of the flow is fine- to medium-grained and has columnar joints that are more widely spaced.

The valley between basalt exposures is the axis for a secondary anticline in the Gable Butte structure. Pomona Member and Elephant Mountain Member dip to the south; Umatilla dips to the north.

2.1 Pomona Member dips to the north.

2.3 Begin outcrops of Elephant Mountain Member on west.

2.5 Pomona Member.

2.7 Junction with 100 C Cut-off Road. B and C reactors in the distance. Turn right toward Gable Mountain.

3.0 Intersection of 100 C Cut-off Road and Rt. 4 north. Turn right (south).

5.6 Junction of Rt. 11 and Rt. 4. Go to mile 74.9 on log and continue straight ahead.

CONTINUE WITH MAIN ROAD LOG AT INTERSECTION OF RTS. 4 AND 11.

72.6 Road to 200 West Area (east gate) on right.

74.9 Turn right onto Hanford Rt. 4 south; climb back up onto Cold Creek Bar.

75.7 Cross railroad tracks.

76.8 Turn right (west) onto Hanford Rt. 3.

77.3 Turn right into batch mix plant; cross pipeline; bear to left before mix plant.

77.5 In back of batch plant bear right.

77.9 **STOP 19. COARSE FLOOD DEPOSITS IN THE COLD CREEK BAR (FIGURE 18).**

Drive to end of road stopping in gravel pit. Gravels exposed in this pit (Fig. 31) display many of the stratigraphic and textural characteristics typical of the coarse-grained flood deposits. Exposures in the middle part of the lower half of the pit wall show the large-scale cross-bedding (foreset bedding) common to coarse-grained flood sediments deposited in and near main flood channelways. Tracing these cross-bedded gravels laterally across the pit face shows that they grade up-current into a massive cobble-to-small boulder gravel and down-current into flat to low-angle bedded pebble-to-cobble gravel. Strata overlying the cross-bedded gravels contain more sandy deposits although they are still very coarse.

Grain size typically ranges from medium-grained to granular. Stratification in these finer strata, consisting of planar and trough cross-bedding and low-angle bedding, is smaller scale than that seen in the underlying deposits.

Figure 31. Gravel-dominated facies of the Hanford formation exposed in the northern part of the Batch Plant gravel pit, Stop 20.

The deposits preserved in the pit characteristically consist of clast-supported, granule-to-cobble gravel that lacks significant matrix. Because of the absence of matrix, these gravels typically display an open-framework texture. In addition, even where mud content in these flood gravels is as high as 10% to 20% (as is commonly seen in this outcrop), an open-framework texture is still present. The sandy deposits associated with these open-framework gravels generally contain little or no cement and because of the abundance of coarse sand and granules also are typically open-framework.

Turn around.

78.0 STOP 20. INTERBEDDED SANDS AND GRAVELS IN THE FLOOD DEPOSITS (FIGURE 18).

Turn right into second gravel pit at the batch plant. Deposits from two separate floods are exposed in this pit (Fig. 32). The lower flood deposit consists of planar cross-bedded pebble gravel that grades laterally into cross-bedded pebble medium-grained to granular sand. This lateral transition is inferred to represent a gradual decrease in flow strength and is common in many occurrences of the laminated or transitional flood sand facies. The lower interval is overlain by a plane to low-angle bedded gravel and sand sequence more suggestive of the gravelly or main channelway facies. While this upper interval is part of the gravelly facies, the abundance of sand in the matrix (compared to STOP 19) suggests these gravels may be grading laterally into the transitional sand-dominated facies. Differentiation of the two floods is based on greater cementation of sands in the lower sequence relative to the upper. The entire sequence is overlain by cobble-rich gravel showing Stage I pedogenic carbonate development on the undersides of the clasts and a red-brown soil zone.

The strata exposed in the pit faces at STOPS 19 and 20 are laterally equivalent yet very different. The variation seen between the two pits as well as the variation seen in each pit is indicative of the lateral stratigraphic variability commonly encountered in the flood deposits at the Hanford Site. This variability commonly makes detailed correlations difficult. However, the various facies found in the Hanford formation generally form larger scale packages and sequences, and these usually can be traced over large areas.

Return to Hanford Rt. 3.

78.5 Route 3, Turn left.

79.0 Turn right onto Hanford Rt. 4.

Figure 32. Interstratified gravel-dominated and sand-dominated facies at the Batch Plant gravel pit, Stop 21.

79.9 **OPTIONAL SIDE TRIP. STOP 21. U.S. ECOLOGY PIT (FIGURE 18)**

Turn Right onto U.S. Ecology access road. Drive to left around the outside of the perimeter fence. At the west end of the pit a small rise allows a view of the pit face. The U.S. Ecology pit has been excavated in Touchet Beds. Thin rhythmic beds of sand and silt with graded bedding can be seen in the wall of the pit (see Fig. 13). Also interbedded with the Touchet Beds is the Mount St. Helen's S set ash. This ash bed is approximately 13,000 years old, indicating that these sediments were deposited during the last major flooding event to affect this part of the Hanford Site.

RETURN TO MAIN ROAD LOG ROUTE

80.4 Entrance to 200 East Area on the left, Baltimore Avenue.

81.6 Turn left onto Grout Pit Site access road. Follow paved perimeter road around outside of 200 East fence.

82.0 Turn right.

82.6 Go through gate and turn left at first intersection.

82.9 At fork veer left; do not go down pit access road. Continue into parking lot.

83.0 **STOP 22. SAND-DOMINATED DEPOSITS OF THE HANFORD FORMATION (FIGURE 18).**

Park at top of pit and examine exposures of the sand-dominated facies of the Hanford formation exposed in the southeast corner of the excavation. These deposits consist dominantly of coarse-grained sands and granules interbedded with finer sands and silty sands. Silty beds also are found and pebbles are encountered mixed with the sands and forming thin (<5 clast thick) interbeds. Sedimentary structures are dominated by plane lamination, although some small-scale cross-bedding and scours are found. Clastic dikes also are found in this outcrop.

The sand-dominated facies is interpreted to have been deposited away from major flood channelways where gravel-dominated deposits accumulated (Baker et al. 1991). The exposures at this stop were deposited adjacent to a channelway located just to the north. Boreholes and excavations less than 1 km to the north encounter largely gravel-dominated facies.

Return to Hanford Rt. 4.

83.4 Turn right onto Hanford Rt. 4 or turn left for optional side trip.

OPTIONAL SIDE TRIP (STOP 23).

0.8 Drop down off Cold Creek Bar.

2.7 Mile marker 7.

3.5 Turn right onto Army Loop Road.

4.7 Central landfill located on the right. Road is crossing stabilized sand dunes. Rattlesnake Mountain is at 12 o'clock.

10.0 Goose Egg Hill at 9 o'clock.

10.3 STOP 23. THE TOUCHET BEDS AND CLASTIC DIKES (FIGURE 18).

Silty sediments composing the slackwater facies of the Hanford formation, or Touchet Beds, are exposed in the outcrop on the north side of the road. The Touchet Beds typically consist of graded rhythmites (fining upwards layers of silt and fine-grained sand) that formed in slackwater areas of Lake Lewis as fine suspended sediments settled onto the lake bottom. The grading in these deposits indicates that turbulence in the lake decreased over time as the flood surge into the Pasco Basin lost energy. Individual rhythmites have been interpreted to record such things as individual floods and/or oscillations in the lake as different parts of a single flood entered the basin from different directions.

The clastic dikes commonly found associated with Touchet Beds (and other deposits) probably formed as the lake drained and pore waters contained within flood sediments escaped as confining pressure was released. The patterned ground that occurs across much of the basin is the surface expression of the larger clastic dikes.

RETURN TO MAIN ROAD LOG ROUTE AT MILE 84.4

84.4 Continue west along Route 4 past south entrance to 200 East.

86.5 Rt. 3 on left.

88.2 Intersection of Rt. 4 and Rt. 11. Continue north (straight) on Rt. 4. Gable Gap flood channel straight ahead.

88.6 Borehole DC-18 located on left.
Borehole DC-18 was drilled in Gable Gap as part of the BWIP. The borehole reached a depth of 1,561 ft. A series of faults was penetrated in the Frenchman Springs Member (depths 1,238 to 1,561 ft) that is interpreted to be related to the frontal fault associated with Gable Mountain and Gable Butte.

89.7 Road to former Near Surface Test Facility of the former BWIP Project on right.

91.2 Wahatus Peak at 12 o'clock. This is composed of intracanyon basalt of the Asotin Member (Reidel 1987).

91.6 Junction between Rts. 1 and 4. Continue straight ahead. White Bluffs visible ahead and to right.

92.7 Flood cut channel and 100-N at 10 o'clock.

93.0 Powerlines.

93.4 100-N entrance.

93.5 Flood-cut channel (mile post 6).

94.1 RR crossing, leaving channel and entering chaotic megaripple field.

94.7 STOP 24. GIANT RIPPLE MARKS NEAR 100-N AREA (FIGURE 18).

The conical mounds just south of this stop (Fig. 33) are giant ripples produced by the cataclysmic floods. In the past they were thought to be bergmounds which form as grounded, sediment-laden icebergs melt, depositing their sediment load. The giant ripples seen here are depositional features similar to, but larger than, the small ripple marks commonly observed along rivers, creeks, and at the ocean. Small ripples generally have a height of only a few millimeters, while the giant ripples are as much as 7 m high.

Sets of giant ripples form "ripple trains." Two ripple trains are found in the immediate area.

Figure 33. Giant Ripples near 100-N Area, Stop 24.

The large prominent conical mounds form a 1-km-wide ripple train that extends about 2.5 km east and west of the stop. The ripples were created during waning flow (~15 m/s) in about 75 m of water as floodwaters swept across the site. The water velocity and erosive power of the floodwaters resulted in eroding the face of the White Bluffs eastward to near its present location.

A second set of giant ripples forms a subtle ripple train about 1 km long in a small erosional channel south of the stop. Giant ripples as much as 1 m high were formed when floodwaters receded to a level near the top of the large conical mounds. The floodwaters that formed the second train were about 12 m deep and flowing at a rate of about 6 m/s.

The basaltic clasts dominate the gravel composition in the Hanford formation in the northern part of the Hanford Site. Much of basaltic gravel was eroded from the Saddle Mountains and Umtanum Ridge.

95.0 Turn right onto Rt. 2.

95.6 **STOP 25. POST-MISSOULA GLACIOFLUVIAL AND EOLIAN DEPOSITS (FIGURE 18).**

Turn left onto Pit 21 access road and proceed down road into pit. Exposed in the base of the pit and most of the pit walls are gravels of the Hanford formation. The gravels were deposited during the last Missoula flood. Overlying the gravels in the northeast wall of the pit is a 3-m-thick sequence of interbedded sand and silt (Figure 34). The silts are eolian deposits. The sands are interpreted as a Post-Missoula glaciofluvial deposit based on its position above (15 m) the Columbia River floodplain and plain-laminated silty medium sands. The sand was likely deposited out of main channel areas from floodwaters that were the result of outbursts from ice-margin lakes as the Cordilleran Ice Sheet retreated north. The upper unit is a 1-m-thick eolian deposit that is similar in texture to the lower eolian unit. The upper unit contains an interbedded ash from the 6,800 b.p. eruption of Mount Mazama (the present Crater Lake National Park).

96.1 Return to Rt. 2 and turn left.

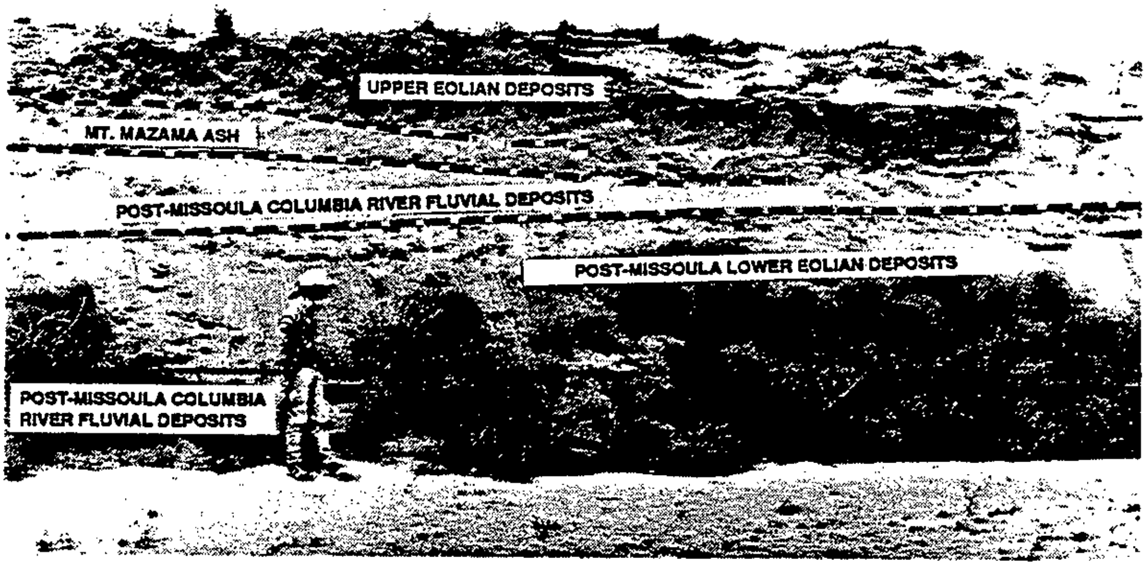


Figure 34. Post-cataclysmic flood sands and muds exposed at the 100-D pit, Stop 25.

99.5 Mile marker 7.

100.4 100-F Area.

104.5 Straight ahead into old Hanford Town Site, main road goes to right.

105.3 Original Hanford High school on right, continue straight.

105.6 STOP 26. THE RINGOLD FORMATION (FIGURE 18).

Turn left onto gravel road, drive to pump house. The Ringold Formation is exposed on the bluffs across the Columbia River.

The Ringold Formation is the thickest of the suprabasalt sedimentary units at the Hanford Site. Ringold strata at the Hanford Site are almost completely restricted to the subsurface. However, extensive outcrops of Ringold strata analogous to deposits in the subsurface are found in the White Bluffs along the eastern and northern shore of the Columbia River (Fig. 35).

Three main facies types or associations dominate the Ringold Formation in the subsurface. They are (1) fluvial gravels, (2) paleosol and overbank systems, and (3) lacustrine muds. Study of outcrop analogues of these deposits and intact core reveals textural and stratigraphic trends unlike those seen in the Hanford formation.

Fluvial gravels in the Ringold Formation consist dominantly of clast-supported pebble-to-cobble gravel with a fine- to coarse-grained sand matrix. These gravels usually are imbricated and low-angle bedding, massive bedding, shallow channel scours, and large-scale planar cross-bedding are present. Thin (<2 m), lenticular interbeds of sand and silty overbank deposits are present in these gravels. Ringold gravel compositions reflect a variety of igneous, metamorphic, and sedimentary source terrains, while matrix sands usually are quartzo-feldspathic. The most notable difference between gravels found in the Ringold Formation and those in the Hanford formation is their textural characteristics. Ringold gravels are matrix-rich and at least partially cemented and compacted. Hanford gravels, on the other hand, are characteristically open-framework and commonly contain little or no matrix sand. The Ringold Formation is dominated by gravels in the western Cold Creek syncline (200 Areas) and eastern Cold Creek syncline (300 and 1100 Areas) (Fig. 36). Little or no gravel is found in the Ringold Formation on the Wahluke slope (near the 100-D, 100-H, and 100-F Areas), while gravel is fairly abundant in the central Cold

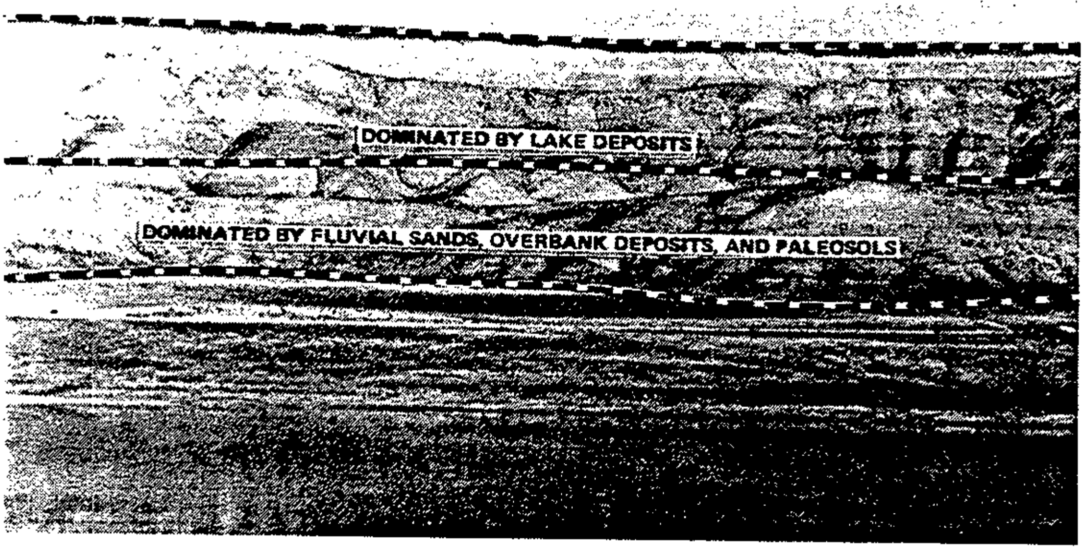


Figure 35. View of the Ringold Formation in the White Bluffs across the Columbia River from the Hanford Site, Stop 26.

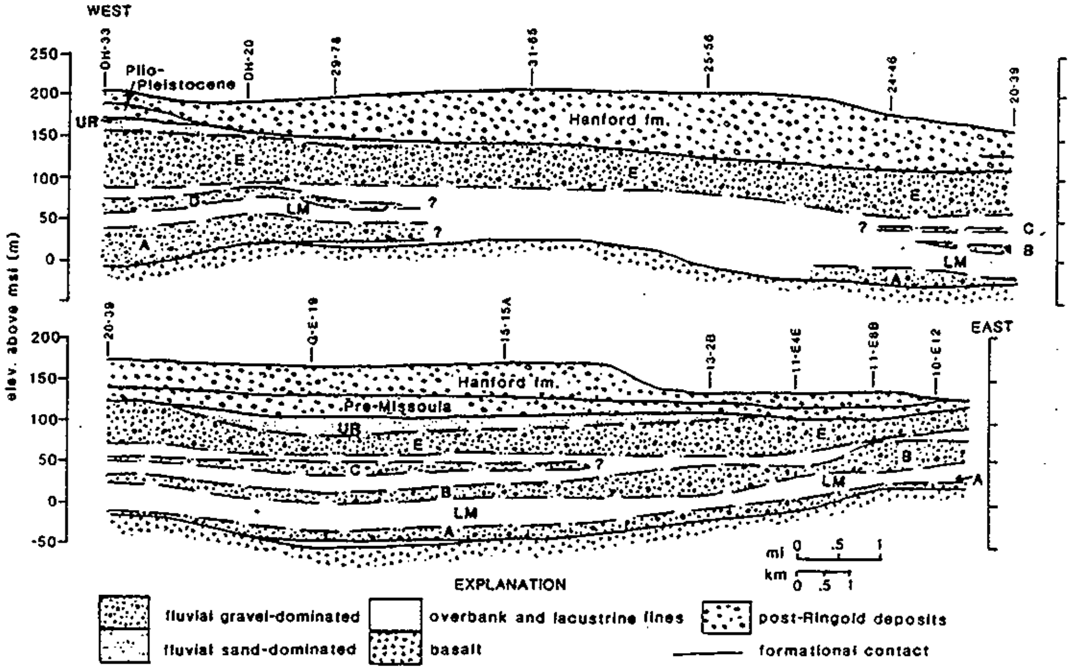


Figure 36. Geologic cross section of the Hanford Site illustrating the distribution of major facies tracts in the Ringold Formation.

Creek syncline and western Wahluke syncline (100-N, 100-K, and 100-B/C Areas).

The overbank and paleosol deposits in the Ringold Formation generally consist of silty sand and sandy silt displaying evidence of pedogenic alteration. The most common evidence of pedogenesis includes secondary $CaCO_3$ cement, root castes and burrows, hackly weathering and soil slickensides, and disrupted bedding. These deposits are relatively rare in the Ringold Formation in the western Cold Creek syncline (200 West Area), while they are common in the east-central Cold Creek syncline (200 East and 300 Areas) and throughout the Wahluke syncline (100-B/C, 100-K, and 100-N Areas). Paleosols and overbank deposits probably dominate the Ringold Formation on the Wahluke slope (100-D, 100-H, and 100-F Areas).

One basin-wide sequence of lake deposits is found in the Ringold Formation beneath the Hanford Site (Fig. 36). These deposits consist of massive to thinly laminated clay and silty clay and occur near the bottom of the Ringold Formation. This sequence of lake deposits is found everywhere except in the 300 Area and near structural highs.

OPTIONAL SIDE TRIP TO RINGOLD FORMATION OUTCROPS (FIGURE 18)

In order to examine outcrops of the Ringold sediment types found in the subsurface at the Hanford Site, it is necessary to go to the White Bluffs located east of the Hanford Site. To get to the Bluffs, drive east on I-182 and U.S. 12 towards Pasco. Exit the highway at Road 68 (approximately 2 miles east of the Columbia River Bridge) and then go north. Follow Road 68 north to where it forks, at which point take the right fork (Taylor Flats Road). Continue north on Taylor Flats Road until reaching the intersection of W. Fir Road with Taylor Flats Road (1 mile north of Edwin Markham Elementary School) and turn left. Follow W. Fir Rd. west toward the Columbia River. At the top of the bluff overlooking the river, the road will make a sharp left, then a right turn around a house and into some vineyards. The road will then descend onto a bench covered in vineyards. Once across the bench, the road will finally descend to the river in two switchbacks. At the bottom of the hill, turn sharply to the right onto an unmarked road that goes north along the river. Visible immediately ahead is a bluff composed of Ringold gravels overlain by fluvial sands and overbank deposits. These deposits can be examined at a number of localities for the next several miles along the river.

To see good examples of Ringold lake deposits, return to Taylor Flats Road and continue north until Taylor Flats Road ends at a T intersection. At this intersection turn left onto Ringold Road. Ringold Road will drop down two hills north of the intersection. At the bottom of the second hill, Ringold Road turns sharply to the left while another road continues straight ahead. Turn left at this intersection. Follow the road down the hill to a four-way intersection with the River road. Turn right and cross the bridge across the irrigation water waste way. This road heads north past the Ringold Fish Hatchery and onto the Wahluke Wildlife Refuge. The bluffs along the road are in lacustrine, overbank, and fluvial sands of the Ringold Formation. The best exposures of these deposits in the bluffs are found at turnouts 5, 6, and 7.

END OF OPTIONAL SIDE TRIP

Return to paved road and turn right (106.6); Return to Rt. 2.

106.6 Turn left onto Hanford Rt. 2.

107.9 Intersection of Hanford Rts. 2 and 11. Turn left to finish main trip or turn right to go to two optional stops on the south side of Gable Mountain.

OPTIONAL SIDE TRIP (STOP 27).

0.0 Turn right onto Hanford Rt. 11; climb up onto flood bar.

1.7 Abandoned burrow pit in the Hanford formation on the right.

3.2 Turn right onto paved road.

3.9 Turn left and proceed on the perimeter road along the outside the fence.

4.1 Turn left toward main powerlines and follow Powerline Road.

5.1 STOP 27. GABLE MOUNTAIN (FIGURE 18).

Turn right (north) toward trenches and park.

As part of power plant siting and other projects on the Hanford Site, several faults on Gable Mountain were investigated by trenching studies. The studies of these faults lead to the determination that these faults should be classified as being capable faults as per the U.S. Nuclear Regulatory Commission classification.

This guide describes two of the faults: the Central fault and the South fault. The Central fault is a tear fault that trends northeast 2 miles across Gable Mountain (Fecht 1978). The South fault is a 1,700-ft-long fault with an east-west trend and a south-dipping fault plane. A series of boreholes and trenches was used by Golder and Associates (PSPL 1982) to determine the nature of this fault and related faults. The work was done for the siting of the Skagit Hanford Nuclear Project.

The first field site is at the bottom of the hill along the South fault (Fig. 37). The South fault was originally thought to be part of the Central fault, but the Golder work showed it to be a separate, unconnected fault. Golder estimated less than approximately 50 ft of fault displacement as measured in the Rattlesnake Ridge interbed. Overlying glaciofluvial sediments were not displaced by the fault. A series of trenches was dug through the fault exposing repeated sections of the Elephant Mountain Member and the Rattlesnake Ridge Interbed. In addition to the brecciation of the basalt and interbed from faulting, invasive relationships between the basalt and sediment can also be seen here. The invasive flows are identified by the blocky basalt with red-black rinds and tan-buff sediments between blocks.

The second field site is the Central fault. To reach this site, follow the jeep trail just to the east of the trenches across the South fault up the south flank of Gable Mountain for about a mile. The trail crosses the Central fault and parallels it on the west side. A series of trenches will be visible at the base of a 30-ft-high basalt cliff (Fig. 38). The cliff is the scarp marking the uplifted block of the fault. The scarp is Elephant Mountain Member and displays a well-developed pillowed structure.

The Central fault is a NE-SW striking fault with a reverse sense of movement; the fault plane dips to the SE. The north end of the fault dies out in

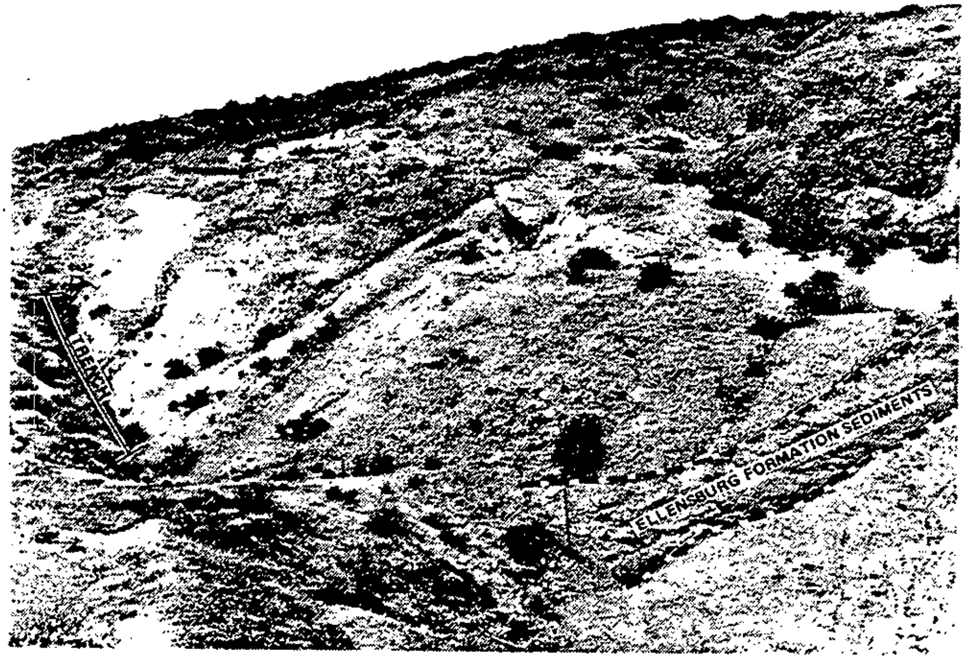


Figure 37. Photograph of the South fault trench on the south side of Gable Mountain, Stop 27A.

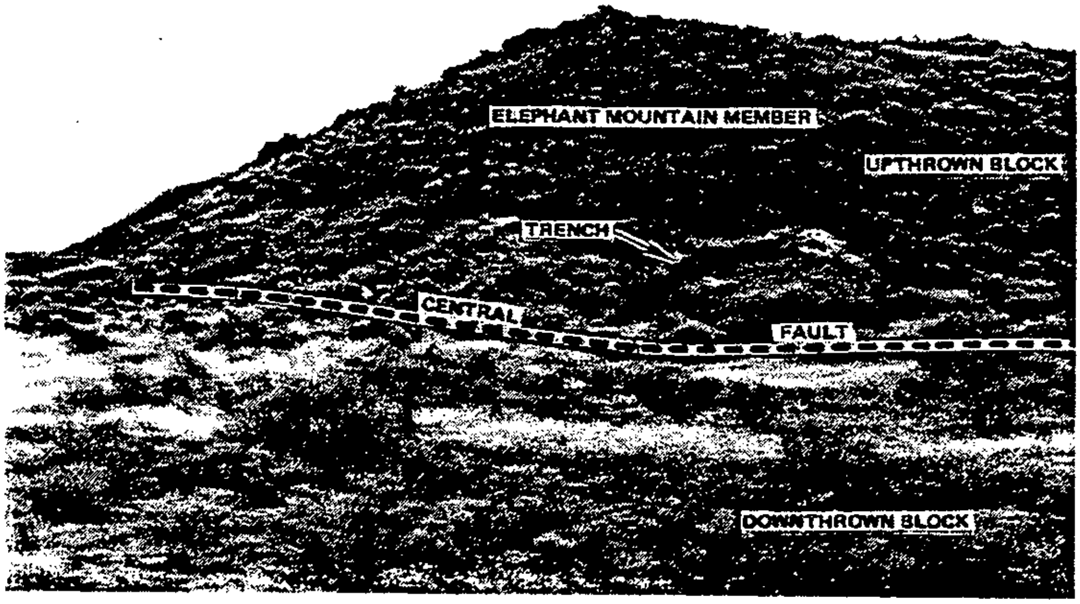


Figure 38. Photograph of the trench at the base of the cliffs on Gable Mountain, Stop 27B. The cliff is the trace of the Central fault.

the hinge zone of the anticline. The Central fault displaces basalt and the overlying glaciofluvial sediments. A trench log (Fig. 39) for Trench GT-2 shows the complexity of this fault zone. There is about 0.2 ft of displacement in the glaciofluvial sediments and about 182 ft of movement on the Rattlesnake Ridge interbed. Long-term displacement rates are approximated to be between 3.3×10^{-3} and 4.6×10^{-3} mm/year.

Retrace route back to Rt. 11, then turn left.

RETURN TO MAIN ROAD LOG ROUTE

Resume mileage at 107.9 at the intersection of Rt. 11 and Rt. 2.

107.9 Reacquire main road log at intersection of Rts. 2 and 11.

108.9 Mile marker 1.

110.0 Extension of buried Southeast anticline.

110.6 **OPTIONAL SIDE TRIP TO SAND DUNES (STOP 28)**

0.0 Turn left onto dirt road that follows powerlines.

1.8 Take right fork.

2.3 **STOP 28. ACTIVE HOLOCENE SAND DUNES ON THE HANFORD SITE (FIGURE 18).**

Holocene and Recent sand dunes (Fig. 40) are concentrated in the south-central and eastern portions of the Hanford Site. Dominant dune types include vegetated parabolic and blowout dunes as well as unvegetated barchan, barchanoid, transverse, and complex forms (Gaylord et al. 1991). Petrographic analyses indicate the dunes sands were derived from reworking of Pleistocene flood deposits and are migrating along east- and northeast-directed paths (Gaylord et al. 1991). The dunes are migrating at rates of 2.5 to 4.5 m/year.

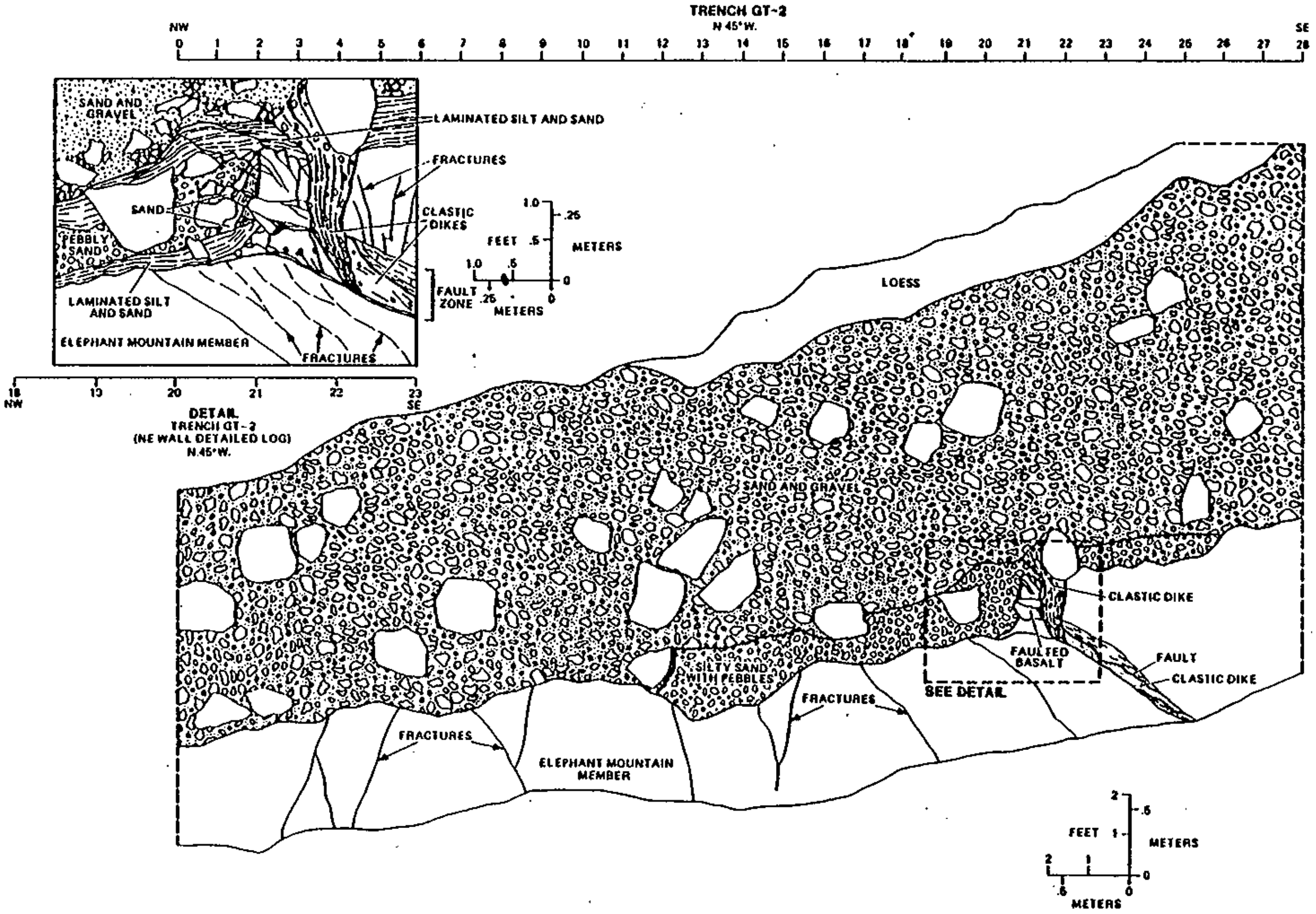


Figure 39. Trench log from trench GT-2 across the Central fault on Gable Mountain (from PSPL 1982).

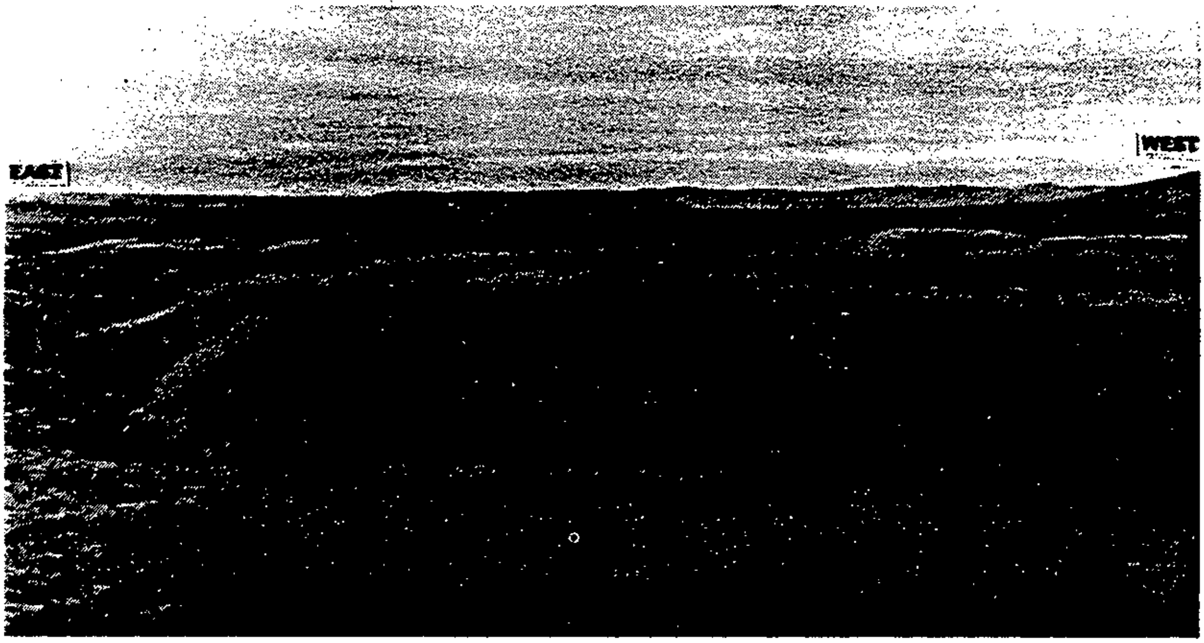


Figure 40. Sand dunes from the south east part of the Hanford Site, Stop 28.

The majority of the active dunes on Site were deposited after the 6,800 year b.p. Mazama eruption (Gaylord et al. 1991).

Retrace route to main road. Resume mileage at 110.6.

111.0 Pacific Northwest Laboratory's Microbial investigations borehole.

113.8 Burrow pit in gravel-dominated deposits of the Hanford formation.

115.2 Wye barricade.

END ROAD LOG

REFERENCES

Baker, V. R., B. N. Bjornstad, A. J. Busacca, K. R. Fecht, E. P. Kiver, U. L. Moody, J. G. Rigby, D. F. Stradling, and A. M. Tallman, 1991, "Quaternary Geology of the Columbia Plateau," *The Geology of North America*, Vol. K-2, Quaternary Nonglacial Geology, Conterminous U.S.

Barrash, W., J. G. Bond, and R. Vankatakrishnan, 1983, "Structural Evolution of the Columbia Plateau in Washington and Oregon," *American Journal of Science*, Vol. 283, No. 9.

Beeson, M. H., T. L. Tolan, and J. L. Anderson, 1989, "The Columbia River Basalt Group in Western Oregon: Geologic Structures and Other Factors that Controlled Flow Emplacement Patterns," in *Volcanism and Tectonism in the Columbia River Flood-Basalt Province*, S. P. Reidel and P. R. Hooper (eds.), Geological Society of America Special Paper 239.

Bentley, R. D., 1977, "Stratigraphy of the Yakima Basalts and Structural Evolution of the Yakima Ridges in the Western Columbia Plateau," in *Geology Excursions in the Pacific Northwest*, E. H. Brown and R. C. Ellis (eds.), Western Washington University Press.

Bentley, R. D., 1980, *Wrench Tectonic Model for the Late Cenozoic Evolution of Oregon and Washington* [abstract]: Geological Society of America Abstracts with Programs, Vol. 12, No. 7.

Bjornstad, B. N., 1984, *Suprabasalt Stratigraphy Within and Adjacent to the Reference Repository Location*, SD-BWI-DP-039, Rockwell Hanford Operations,, Richland, Washington.

Bjornstad, B. N., K. R. Fecht, and A. M. Tallman, 1987, *Quaternary Stratigraphy of the Pasco Basin Area, South-Central Washington*, RHO-BW-SA-563A, Rockwell Hanford Operations, Richland, Washington.

Campbell, N. P., 1989, "Structural and Stratigraphic Interpretation of the Rocks under the Yakima Fold Belt Based on Recent Surface Mapping and Well Data," in *Volcanism and Tectonism in the Columbia River Flood-Basalt Province*, S. P. Reidel and P. R. Hooper (eds.), Geological Society of America Special Paper 239.

Davis, G. A., 1977, "Tectonic Evaluation of the Pacific Northwest Pre-Cambrian to Recent: Preliminary Safety Analysis Report," in *Washington Public Power Supply System, 1977, Washington Public Power Supply System Nuclear Project Number 2, Preliminary Safety Analysis Report*, Washington Public Power Supply System, Appendix 23, Subappendix 2R C.

Davis, G. A., 1981, "Late Cenozoic Tectonics of the Pacific Northwest with Special Reference to the Columbia Plateau," in *Washington Public Power Supply System, 1977, Washington Public Power Supply System Nuclear Project Number 2, Preliminary Safety Analysis Report*, Washington Public Power Supply System, Appendix 23, Subappendix 2.5 N.

Delaney, C. D., K. A. Lindsey, and S. P. Reidel, 1991, *Geology and Hydrology of the Hanford Site: A Standardized Text for Use in Westinghouse Hanford Company Documents and Reports*, WHC-SD-ER-TI-0003, Westinghouse Hanford Company, Richland, Washington.

DOE, 1988, *Site Characterization Plan, Consultation Draft*, DOE/RW-0164, Vols. 1-9, U.S. Department of Energy, Washington, D.C.

Fecht, K. R., 1978, *Geology of Gable Mountain-Gable Butte Area*, RHO-BWI-LD-5, Rockwell Hanford Operations, Richland, Washington.

Fecht, K. R., A. M. Tallman, M. J. Marratt, and G. V. Last, 1979, *Geology of Separations Areas, Hanford Site, South-Central Washington*, RHO-ST-23, Rockwell Hanford Operations, Richland, Washington.

Fecht, K. R., S. P. Reidel, and A. M. Tallman, 1982, *Evolution of the Columbia River System in the Central Columbia Plateau of Washington from Miocene to Present* [abstract]: Geological Society of America Abstracts with Program, Vol. 14, No. 4.

Fecht, K. R., S. P. Reidel, and A. M. Tallman, 1987, "Paleodrainage of the Columbia River System on the Columbia Plateau of Washington State--A Summary," J. E. Schuster (ed.), *Selected Papers on the Geology of Washington, Division of Geology and Earth Resources*, Bulletin 77.

Freeman, O. W., J. D. Forrester, and R. L. Luper, 1945, *Structure of the Western Portion of the Physiographic Divisions of the Columbia Intermontane Province: Association of American Geographers Annals*, Vol. 35.

Gaylord, D. R., L. D. Stetler, and G. D. Smith, 1991, *Holocene and Recent Eolian Activity at the Hanford Site, Washington* (abstract), American Geophysical Union Fall Meeting, Abstracts with Programs.

Goff, F. E., 1981, *Preliminary Geology of Eastern Umtanum Ridge, South-Central Washington*, RHO-BWI-C-21, Rockwell Hanford Operations, Richland, Washington.

Graham, M. J., 1984, *Hydrology of the Separations Area*, RHO-ST-42, Rockwell Hanford Operations, Richland, Washington.

Grolier, M. J., and J. W. Bingham, 1971, *Geologic Map and Sections of Parts of Grant, Adams and Franklin Counties, Washington*, U.S. Geological Survey Miscellaneous Geologic Investigations Series Map I-589, scale 1:62,500.

Gustafson, E. P., 1985, "Soricids (Mammalia, Insectivora) from Blufftop Local Fauna, Blancan Ringold Formation of Central Washington, and the Correlation of Ringold Formation Faunas," *Journal of Vertebrate Paleontology*, Vol. 5.

Hagood, M. C., 1986, *Structure and Evolution of the Horse Heaven Hills, South-Central Washington*, RHO-BW-SA-344, Rockwell Hanford Operations, Richland, Washington, 176 p., 1 plate, scale 1:24,000.

Keinle, C. F., R. D. Bentley, and J. L. Anderson, 1977, "Geologic Reconnaissance in the Cle Elum-Wallula Lineament and Related Structures," in *Washington Public Power Supply System, 1977, Washington Public Power Supply System Nuclear Project Number 2, Preliminary Safety Analysis Report*, Washington Public Power Supply System Vol. 2A, Amendment 23, Subappendix 2R D.

Jamison, W. R., 1987, "Geometric Analysis of Fold Development in Overthrust Terrains," *Journal of Structural Geology*, Vol. 9, No. 2.

Laval, W. N., 1956, *Stratigraphy and Structural Geology of Portions of South-Central Washington*, Doctor of Philosophy Thesis, University of Washington.

Lindsey, K. A., 1991, *Revised Stratigraphy for the Ringold Formation, Hanford Site, South-Central Washington*, WHC-SD-EN-EE-004, Westinghouse Hanford Company, Richland, Washington.

Lindsey, K. A., and D. R. Gaylord, 1989, *Sedimentology and Stratigraphy of the Miocene-Pliocene Ringold Formation, Hanford Site, South-Central Washington*, WHC-SA-0740-FP, Westinghouse Hanford Company, Richland, Washington.

Machette, M. N., 1985, "Calcic Soils of the Southwestern United States," in *Soils and Quaternary Geology of the Southwestern United States*, D. L. Weide (ed.), Geological Society of America Special Paper 203.

Mangan, M. T., T. L. Wright, D. A. Swanson, and G. R. Byerly, 1986, "Regional Correlation of Grande Ronde Basalt Flows, Columbia River Basalt Group, Washington, Oregon, and Idaho," *Geological Society of America Bulletin*, Vol. 97, No. 11.

Mitchell, M. M., and N. B. Woodward, 1988, "Kink Detachment Fold in the Southwest Montana Fold and Thrust Belt," *Geology*, Vol. 16, No. 2.

Myers, C. W., S. M. Price, J. A. Caggiano, M. P. Cochran, W. J. Czimer, N. J. Davidson, R. C. Edwards, K. R. Fecht, G. E. Holmes, M. G. Jones, J. R. Kunk, R. D. Landon, R. K. Ledgerwood, J. T. Lillie, P. E. Long, T. H. Mitchell, E. H. Price, S. P. Reidel, and A. M. Tallman, 1979, *Geologic Studies of the Columbia Plateau--A status report: Richland, Washington*, RHO-BWI-ST-4, Rockwell Hanford Operations, Richland, Washington.

Newcomb, R. C., 1958, "Ringold Formation of the Pleistocene Age in the Type Locality, The White Bluffs, Washington," *American Journal of Science*, Vol. 256.

Newcomb, R. C., J. R. Strand, and F. J. Frank, 1972, *Geology and Groundwater Characteristics of the Hanford Reservation of the Atomic Energy Commission*, Washington, Professional Paper 717, U.S. Geological Survey, Washington, D.C.

NRC, 1982, *Safety Evaluation Report* (Related to the operation of WPPSS Nuclear Project) No. 2, NUREG-0892 Supplement No. 1, U.S. Nuclear Regulatory Commission, Washington, D.C.

Packer, D. R., and J. M. Johnston, 1979, *A Preliminary Investigation of the Magnetostratigraphy of the Ringold Formation*, RHO-BWI-C-42, Rockwell Hanford Operations, Richland, Washington.

Price, E. H., and A. J. Watkinson, 1989, "Structural Geometry and Strain Distribution within East Umtanum Ridge, South-Central Columbia Plateau," in *Volcanism and Tectonism in the Columbia River Flood-Basalt Province*, S. P. Reidel and P. R. Hooper (eds.), Geological Society of America Special Paper 239.

PSPL, 1982, *Skagit/Hanford Nuclear Project, Preliminary Safety Analysis Report*, Vol. 4, App. 20, Amendment 23, Puget Sound Power and Light Co., Bellevue, Washington.

Reidel, S. P., 1983, "Stratigraphy and Petrogenesis of the Grande Ronde Basalt from the Deep Canyon Country of Washington, Oregon and Idaho," *Geological Society of America Bulletin*, Vol. 94, No. 4.

Reidel, S. P., 1984, "The Saddle Mountains--the Evolution of an Anticline in the Yakima Fold Belt," *American Journal of Science*, Vol. 284, No. 8.

Reidel, S. P., 1987, *Geologic Map of Saddle Mountains, Central Washington*, RHO-CW-SA-463, (5 plates), Rockwell Hanford Operations, Richland, Washington.

Reidel, S. P., and K. R. Fecht, 1981, "Wanapum and Saddle Mountains Basalts of the Cold Creek Syncline Area," *Subsurface Geology of the Cold Creek Syncline*, RHO-BWI-ST-14, C. W. Meyers and S. M. Price (eds.), Rockwell Hanford Operations, Richland, Washington.

Reidel, S. P., K. R. Fecht, M. C. Hagood, and T. L. Tolan, 1989a, "Geologic Evolution of the Central Columbia Plateau," in *Volcanism and Tectonism in the Columbia River Flood-Basalt Province*, S. P. Reidel and P. R. Hooper (eds.), Geological Society of America Special Paper 239.

Reidel, S. P., T. L. Tolan, P. R. Hooper, M. H. Beeson, K. R. Fecht, J. L. Anderson, and R. D. Bentley, 1989b, "The Grande Ronde Basalt, Columbia River Basalt Group--Stratigraphic Descriptions and Correlations in Washington, Oregon, and Idaho," in *Volcanism and Tectonism in the Columbia River Flood-Basalt Province*, S. P. Reidel and P. R. Hooper (eds.), Geological Society of America Special Paper 239.

Routson, R. C., R. E. Wildung, and T. R. Garland, 1977, "Mineral Weathering in an Arid Watershed Containing Soil Developed from Mixed Basaltic-Felsic Parent Material," *Soil Science*, Vol. 124.

Smith, G. A., N. P. Campbell, and M. W. Deacon, Muhammad Shafiqullah, 1988, "Eruptive Style and Location of Volcanic Centers in the Miocene Washington Cascade Range: Reconstruction from the Sedimentary Record," *Geology*, Vol. 16, No. 4.

Suppe, J., 1983, "Geometry and Kinematics of Fault-Bend Folding," *American Journal of Science*, Vol. 283, No. 7.

Suppe, J., 1985, *Principles of Structural Geology*, Prentice-Hall, Inc, New Jersey.

Swanson, D. A., and T. L. Wright, 1976, "Field Guide to Field Trip Between Pasco and Pullman, Washington, Emphasizing Stratigraphy, Vent Areas, and Intracanyon Flows of the Yakima Basalt," in *Proceedings, Geological Society of America Cordilleran Section Meeting*, Pullman, Washington, Field Guide 1.

Swanson, D. A., T. L. Wright, P. R. Hooper, and R. D. Bentley, 1979a, "Revisions in Stratigraphic Nomenclature of the Columbia River Basalt Group," *U.S. Geological Survey Bulletin* 1457-G.

Swanson, D. A., J. L. Anderson, R. D. Bentley, V. E. Camp, J. N. Gardner, and T. L. Wright, 1979b, *Reconnaissance Geologic Map of the Columbia River Basalt Group in Washington and Adjacent Idaho*, U.S. Geological Survey Open-file Report 79-1363.

Swanson, D. A., T. L. Wright, V. E. Camp, J. N. Gardner, R. T. Helz, S. M. Price, S. P. Reidel, and M. E. Ross, 1980, *Reconnaissance Geologic Map of the Columbia River Basalt Group, Pullman and Walla Walla Quadrangles, Southeast Washington and Adjacent Idaho*, U.S. Geological Survey Miscellaneous Investigations Map I-1139.

Tabor, R. W., V. A. Frizzell, J. A. Vance, and C. W. Naeser, 1984, "Ages and Stratigraphy of Lower and Middle Tertiary Sedimentary and Volcanic Rocks of the Central Cascade, Washington--Application to the Tectonic History of the Straight Creek Fault," *Geological Society of America Bulletin*, Vol. 95, No. 1.

Tallman, A. M., K. R. Fecht, M. J. Marratt, and G. V. Last, 1979, *Geology of the Separations Areas, Hanford Site, South-Central Washington*, RHO-ST-23, Rockwell Hanford Operations, Richland, Washington.

Tallman, A. M., J. T. Lillie, and K. R. Fecht, 1981, "Suprabasalt Sediments of the Cold Creek Syncline Area," in *Subsurface Geology of the Cold Creek Syncline*, C. W. Myers and S. M. Price (eds.), RHO-BWI-ST-14, Rockwell Hanford Operations, Richland, Washington.

Thornbury, W. D., 1965, *Regional Geomorphology of the United States*, John Wiley and Sons, Inc., New York, New York.

Tolan, T. L., and S. P. Reidel, 1989, "Structure Map of a Portion of the Columbia River Flood-Basalt Province," in *Volcanism and Tectonism in the Columbia River Flood-Basalt Province*, S. P. Reidel and P. R. Hooper (eds.), Geological Society of America, Special Paper 239, Plate 1, Boulder, Colorado.

Tolan, T. L., S. P. Reidel, M. H. Beeson, J. L. Anderson, K. R. Fecht, and D. A. Swanson, 1989, "Revisions to the Extent and Volume of the Columbia River Basalt Group," in *Volcanism and Tectonism in the Columbia River Flood-Basalt Province*, S. P. Reidel and P. R. Hooper, (eds.), Geological Society of America Special Paper 239.

Vance, J. A., G. A. Clayton, J. M. Mattinson, and C. W. Naeser, 1987, "Early and Middle Cenozoic Stratigraphy of the Mount Rainier-Tieton River Area, Southern Washington Cascades," in *Selected Papers on the Geology of Washington*, J. E. Schuster (ed.), Washington Division of Geology and Earth Resources, Bulletin 77.

Waters, A. C., 1961, "Stratigraphy and Lithologic Variations in the Columbia River Basalt," *American Journal of Science*, Vol. 259.

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