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The Geologic Development of the Pasco Basin, South-Central Washington

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Field Trip Guide to the Geologic Development of the Pasco Basin, South-Central Washington

For the October 16 and 17 NWGS Field Trip

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Introduction

Flood basalt volcanism occurred in the Pacific Northwest, USA, between 17.5 and 6 Ma when over 300 basaltic lavas of the Columbia River Basalt Group (CRBG) were erupted from fissures in eastern Washington, eastern Oregon, and western Idaho (Fig. 1) (Swanson et al., 1979a). These flood basalts cover over 200,000 km2 of the Pacific Northwest and have an estimated volume of more than 234,000 km3 (Camp et al., 2003). Concurrent with these massive basalt eruptions was the folding and faulting of the basalt in the western part of the Columbia Basin and development of generally east-west trending anticlinal ridges and synclinal valleys collectively known as the Yakima Fold Belt.

Setting

The Columbia River Basalt Group covers much of eastern Washington, northern and eastern Oregon, and western Idaho. Recent studies (e.g., Cummings et al., 2000; Hooper et al., 2002; Camp et al., 2003) have shown the oldest flows occur in southern Oregon and that volcanism progressed northward to the Columbia Basin. The Columbia Basin is the northern part the Columbia River flood-basalt province (Reidel and Hooper, 1989) and forms an intermontane basin between the Cascade Range and the Rocky Mountains.

The Columbia Basin includes two structural subdivisions or subprovinces: the Yakima Fold Belt and the Palouse Slope. The Yakima Fold Belt includes the western and central parts of the Columbia Basin and consists of a series of anticlinal ridges and synclinal valleys with northwest to southeast structural trends. The Palouse Slope is the eastern part of the basin and is the least deformed subprovince with only a few faults and low amplitude, long wavelength folds on an otherwise gently westward dipping paleo-slope (Swanson et al.. 1980).

The Blue Mountains subprovince of the Columbia River flood-basalt province forms the southeastern boundary of the Columbia Basin. The Blue Mountains is a northeast-trending anticlinorium that extends 250 km from the Oregon Cascades along the southeastern edge of the Columbia Basin. It overlies accreted terrane rock assemblages and Eocene and Oligocene volcaniclastic rocks.

In the Yakima Fold Belt portion of the Columbia Basin, 4 to 5 km of the CRBG overlies over 6 km of Tertiary continental sedimentary rocks that, in turn, overlie accreted terranes of Mesozoic age (Fig. 2). These rocks are overlain by late Tertiary and Quaternary fluvial and glaciofluvial deposits (Campbell, 1989; Reidel et al., 1989a; Smith et al., 1988; DOE, 1988). In the Palouse subprovince of the Columbia Basin, a thin (<100 m) sedimentary unit separates about 2 km or less of basalt from the crystalline basement which consists of continental crustal rock typical of that underlying much of western North America (Reidel et al., 1989a). The western edge of the late Precambrian/early Paleozoic continental margin and Precambrian North American craton occurs near the juncture of the Palouse and Yakima Fold Belt subprovinces.

STRATIGRAPHY OF THE PASCO BASIN

The generalized stratigraphy of the Yakima Fold Belt and western margin of the Columbia Plateau is shown in Figure 3. The dominant rocks of the area are the Columbia River Basalt Group and intercalated sedimentary rocks of the Ellensburg Formation (Fig. 4). These are overlain by younger sedimentary rocks of the Ringold Formation, the Pleistocene catastrophic flood deposits of the Hanford formation, and other localized strata.

STRATIGRAPHY OF THE COLUMBIA RIVER BASALT GROUP

The CRBG consists of a thick sequence of about 300 continental tholeiitic flood-basalt flows that were erupted from about 17 to 5.5 Ma (Swanson et al., 1979a). Although the eruption of CRBG flows spans nearly a 12-mi II ion-year period, the majority of the CRBG (>96 volume percent) was erupted over a period of about 2.5 million years, between 17 to 14.5 Ma (Swanson et al., 1979a). Individual CRBG flows typically extend over many tens of thousands of square kilometers. The source for these flows was a series of north-northwest-trending linear fissure systems located in eastern Washington, eastern Oregon, and western Idaho (generally within the Palouse subprovince of Fig. 1).

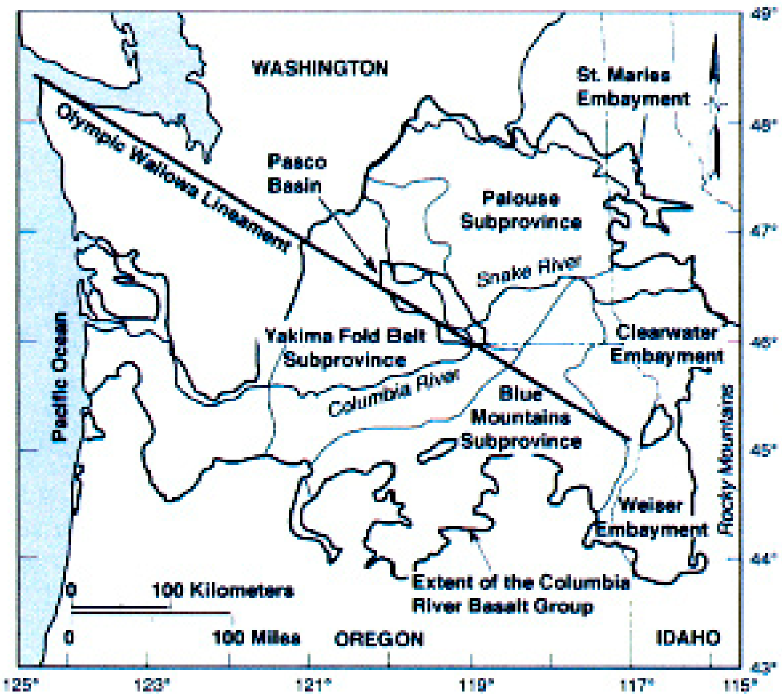


Figure 1: (Left) Generalized geology of the Columbia Basin

Detailed study and mapping of the Columbia River flood basalts have demonstrated that there are significant variations in lithological, geochemical, and paleomagnetic polarity properties between flows (and packets of flows) which has allowed for the establishment of stratigraphic units that can be reliably identified and correlated on a regional basis (e.g., Swanson et al., 1979a; Beeson et al., 1985; Reidel et al., 1989b). Based on the ability to recognize the flows, the CRBG has been divided into five formations (Swanson et al., 1979a): Imnaha, Grande Ronde, Picture Gorge, Wanapum, and Saddle Mountains Basalt (Figs. 3 and 4). Flows of the Saddle Mountains Basalt are exposed at the surface, with underlying flows of the Wanapum and Grande Ronde Basalts mainly in the subsurface. Intercalated with, and in some places overlying, the CRBG are epiclastic and volcaniclastic sedimentary rocks of the Ellensburg Formation (Waters, 1961; Swanson et al., 1979b; Smith et al., 1988). Most volcaniclastic material occurs in the western basin; in the central and eastern basin, epiclastic sediments of the ancestral Clearwater and Columbia rivers form the dominant lithologies (Fecht et al., 1982, 1987).

Lava Features and Nomenclature

The immense size of Columbia River flood-basalt lavas makes it difficult to determine what constitutes a single eruption and what does not. Historically, Columbia River flood-basalt descriptions have used the term cooling unit to describe a lobe. A single cooling unit is defined as having a flow top and a base that show evidence of more rapid cooling or chilling compared to the interiors (Fig. 5). Although many of the surface features observed on recent eruptions of pahoehoe lavas have excellent counterparts on flood basalts (e.g. pahoehoe lobes, tumulus, vesicle sheets), some of the nomenclature that has been applied to those eruptions has proven difficult to adapt to flood basalts (Self et al., 1997). For example, in the terminology of Walker (1972), large single lobes as much as 30 m thick are called simple flows and many similar sized lobes totaling 100 m thick are called compound flows. Self et al. (1998) have attempted to resolve these differences by refining existing terms and introducing new ones. For example, they define a lobe as the smallest coherent package of lava, &flo\v as the product of a single outpouring of lava, and & flow field as lava covering a large area that has many separate outpourings. The term lobe is easy to apply but problems still remain recognizing what constitutes a flow or flow field.

The concept of inflated lava flows has also become important to models describing emplacement of flood-basalt lavas. Hon

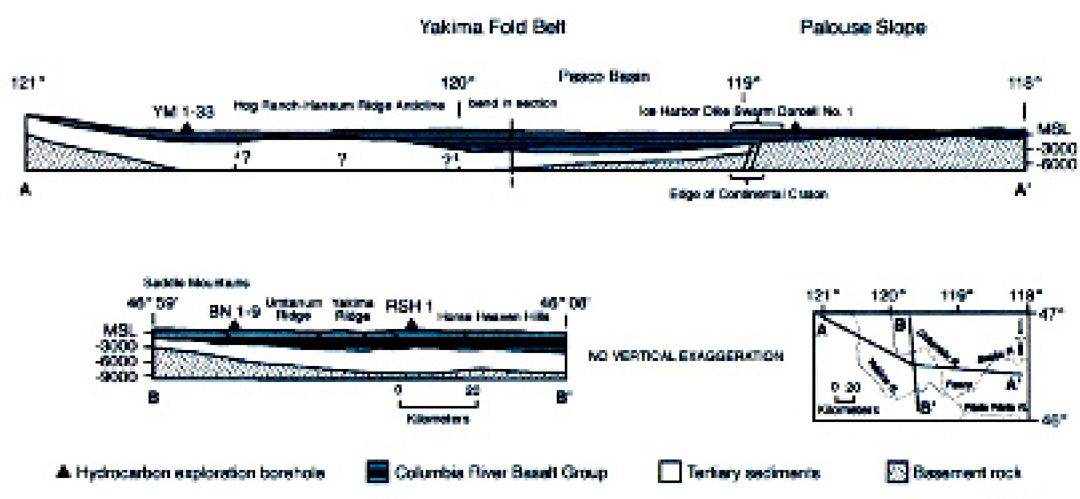
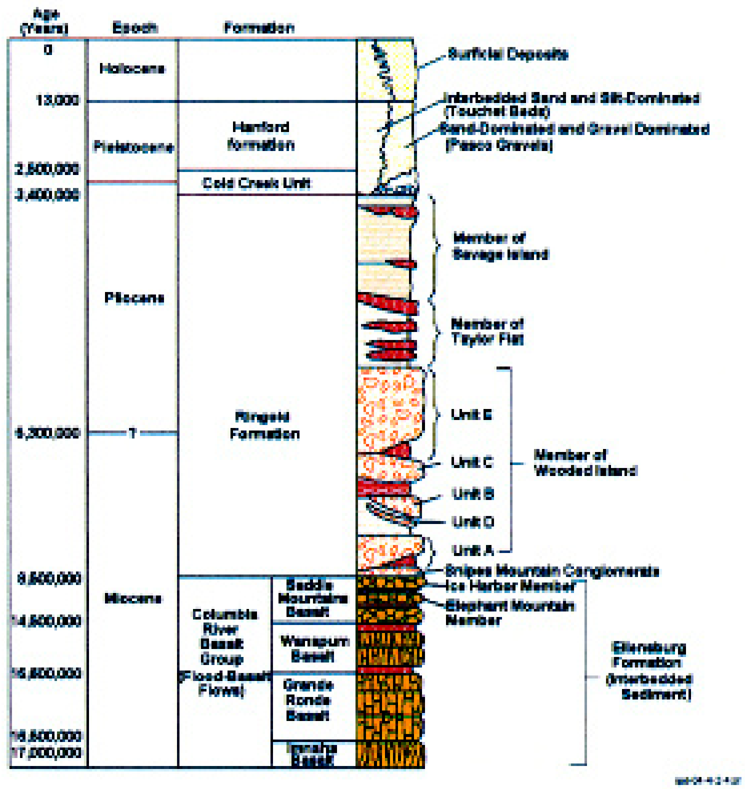


Figure 2 Cross-Section through the Columbia Basin

Figure 3: Generalized stratigraphy of the Pasco Basin



et al. (1994) described inflated flows from Hawaii where they documented the growth and inflation of lobes of lava by the internal injection of more lava. With each pulse of new lava, the flow grows thicker. Flows advance by breakouts at the front of the flow. As more lava erupts it causes inflation of flows and break outs of new lava at the flow front. This mechanism can insulate hot lava great distances from the vent (Self et al., 1997, 1998).

Inflated Columbia River flood-basalt lavas can be recognized by two criteria. The first is the recognition of lobes and breakouts as described by Self et al. (1998). These are equivalent to multiple lobes described above that may or may not be traced back to the main lobe. The second criterion is the recognition of vertical compositional zonation in the lavas. Reidel and Fecht (1987) and (Reidel, 1998) described lavas of the Saddle Mountains Basalt that were inflated lavas over 200 km from the vent areas. They recognized distinct compositions in an inflated lava flow at the Pasco Basin that matched several individual lava flows that occurred at the vent area. The oldest compositions were at the top and bottom of the lava and progressively younger lava compositions occurred toward the center of the flow.

Internal Basalt Flow Features

Intraflow structures are primary internal features or stratified portions of basalt flows exhibiting grossly uniform macroscopic characteristics. These features originate during the emplacement and solidification of each flow and result from variations in cooling rates, degassing, thermal contraction, and interaction with surface water. They are distinct from features formed by tectonic processes.

Columbia River Basalt Group flows typically consist of a flow top, a dense, flow interior, and a flow bottom of variable thickness. Figure 5 shows the types of intraflow structures that are typically observed in a basalt flow; most flows do not show a complete set of these structures.

The flow top is the chilled, glassy upper crust of the flow. It may consist of vesicular to scoriaceous basalt, displaying either pahoehoe or a'a characteristics, or it may be rubbly to brecciated (Waters, 1961; Diery, 1967; Swanson and Wright, 1981). Typically, the flow top comprises approximately 10% of the thickness of a flow; however, it can be as thin as a few centimeters or occupy almost the entire flow thickness. Almost all CRBG flows display pahoehoe features; some have rubbly to brecciated flow tops but none are considered to represent a'a flows.

Flow top breccia occurs as a zone of angular to subrounded, broken volcanic rock fragments that may or may not be supported by a matrix and is located adjacent to the upper contact of the lava flow. A mixture of vesicular and nonvesicular clasts bound by basaltic glass often characterizes the breccia zone. The percentage of the breccia to rubbly surface is typically less that 30% but locally can be as much as 50% of the flow. This type of flow top usually forms from a cooled top that is broken up and carried along with the lava flow before it ceases movement.

The basal part of a Columbia River basalt lava flow is predominantly a glassy, chilled zone a few centimeters thick that may be vesicular. Where basalt flows encounter bodies of water or saturated sediments, the following features may occur:

- Pillow-palagonite complexes. Discontinuous pillow-shaped structures of basalt formed as basalt flows into water. The space between the pillows is usually composed of hydrated basaltic glass (palagonite) and hyaloclastite.
- Hyaloclastite complexes. Deposits resembling tuff that form when basalt shatters as it flows into water.
- Foreset bedded breccias. These form as basalt flows into water and build out their own delta. Hyaloclastite and pillow-palagonite complexes usually compose the foreset beds.
- Peperites. Breccia-like mixture of basalt (or hyaloclastite or palagonite) and sediment that form as basalt burrows into sediments, especially wet sediments.
- Spiracles. A fumarolic vent-like feature that forms due to a gaseous explosion in fluid lava flowing over water-saturated soils or ground.

Internal fractures or joints in Columbia River Basalt Group lavas set them apart from smaller more recent lavas. CRBG

Series		Group		Formation	Series	Isotopic Age (m.y)	Magnetic Polarity
Miocene	Upper	Columbia River Basalt Group	Yakima Basalt Subgroup	Saddle Mountains Basalt	Lower Monumental Member	6	N
					Ice-Harbor Member	8.5	
					Basalt of Goose Island		N
					Basalt of Martindale		R
					Basalt of Basin City		N
					Buford Member		R
					Elephant Mountain Member	10.5	N, T
	Middle				Pomona Member	12	R
					Esquatzel Member	N	
					Weissenfels Ridge Member		
					Basalt of Slippery Creek		N
					Basalt of Tenmile Creek		N
					Basalt of Lewiston Orchards		N
					Basalt of Cloverland		N
					Asotin Member	13	
					Basalt of Huntzinger		N
					Wilbur Creek Member		
					Basalt of Lapwai		N
					Basalt of Wahluke		N
					Umatilla Member		
					Basalt of Sillusi		N
					Basalt of Umatilla		N
				Wanapum Basalt	Priest Rapids Member	14.5	
					Basalt of Lolo		R
					Basalt of Rosalia		R
					Roza Member		T, R
					Shumaker Creek Member		N
					Frenchman Springs Member		
					Basalt of Lyons Ferry		N
					Basalt of Sentinel Gap		N
					Basalt of Sand Hollow	15.3	N
					Basalt of Silver Falls		N, E
					Basalt of Ginkgo	15.6	E
					Basalt of Palouse Falls		E
					Eckler Mountain Member		
					Basalt of Dodge		N
					Basalt of Robinette Mountain		N
					Vantage Horizon		
				Grande Ronde Basalt	Member of Sentinel Bluffs	15.6	N_2
					Member of Slack Canyon		
					Member of Fields Spring		
					Member of Winter Water		
					Member of Umtanum		
					Member of Ortley		
					Member of Armstrong Canyon		
	Lower			Prineville Basalt	Member of Meyer Ridge		R_2
					Member of Grouse Creek		
					Member of Wapshilla Ridge		
					Member of Mt. Horrible		
					Member of China Creek		N_1
					Member of Downey Gulch		
				Picture Gorge Basalt	Member of Center Creek		R_1
					Member of Rogersburg		
					Teepee Butte Member		
					Member of Buckhorn Springs	16.5	
				Imnaha Basalt			R_1
							T
							N_0
						17.5	R_0

Figure 4: Nomenclature of the Columbia River Basalt Group

lavas have internal jointing that is classed as either entablature or colonnade. Entablature jointing consists of small columns of fine¬grained basalt most commonly in the upper parts of the lavas that overlie larger columns of coarser basalt that form the colonnade. Entablature columns are defined by fractures with typical spacings of ~10 cm; fractures that define the colonnades typically have spacings of about 0.5 to 1 m. Long and Wood (1986) have shown that the entablatures have a quenched texture and represent rapid cooling compared to the colonnade, which developed under comparatively slow cooling. A typical entablature represents top down cooling and the colonnade represents comparatively slower bottom up cooling.

The colonnade consists of relatively well-formed polygonal columns of basalt, usually vertically oriented and typically 1 m in diameter or larger (some as large as 3 m have been observed). Colonnade, as defined by Tomkeieff (1940), occurs in the basal portion of flows. In CRBG flows, the colonnade can make up the entire flow thickness, or there may be one or more colonnades present that are tiered with entablatures.

Zones or layers of vesicles occur in the interior portions of the lavas and are physically distinct from a vesicular flow top. These vesicle zones or sheets are nearly ubiquitous in the Columbia River basalt lavas. The vesicle zones can range from a few cm to as much as several meters in thickness. Typically they are transitional between massive basalt above and below, and are not physical boundaries of cooling units or lobes. The vesicle zones have been interpreted as gas trapped by an advancing solidification front (McMillan et al., 1989) and as distinct pulses of a continuing eruption (Walker et al., 1999).

Vesicle pipes and cylinders are cylindrical zones of gas bubbles that form as gas evolves from that lava and rises toward the top of the flow. Pipes and cylinders are distinguished by their size; cylinders are larger, but there is a continuum of sizes between the two. Vesicle cylinders, pipes, and sheets usually occur in relatively thin flows (5-30 m) composed mainly of colonnades and flow tops.

Vesicle sheets are horizontal to subhorizontal layers of vesicles. They typically are fed by vesicle cylinders and form below the solidification front. Vesicle zones within the interior of thicker flows can be thin (centimeters to meters thick) and can be laterally continuous, sometimes for kilometers.

Vesicle zones are usually thicker than vesicle sheets but probably form in much the same way. Vesicle zones can be up to several meters thick and are typically located in the dense interior of a lava flow.

Lava tubes have not been observed in CRBG flows. This is because the flows were emplaced as sheets and were not tube fed as Hawaiian flows are. However, locally tube-like features have been observed but typically do not extend great distances.

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 and others, 1979a). Most volcaniclastic material in the Ellensburg Formation was produced by volcanic events in the Cascade Mountains. Along the western margin deposition was primarily by volcanic debris flows (lahars) and related stream and sheet floods. Some air fall and pyroclastic-flow deposits are also present. The age of the formation along the western margin in the Naches drainage is between 16.5 and 7.4 Ma. (Smith and others, 1988). The bulk of the material in the Naches River drainage was derived from a single source near Bumping Lake (Fig. 4). Farther east in the central Plateau, Ellensburg Formation is mixed with sediments deposited by the ancestral Clearwater and Columbia rivers (Fecht and others, 1982, 1987).

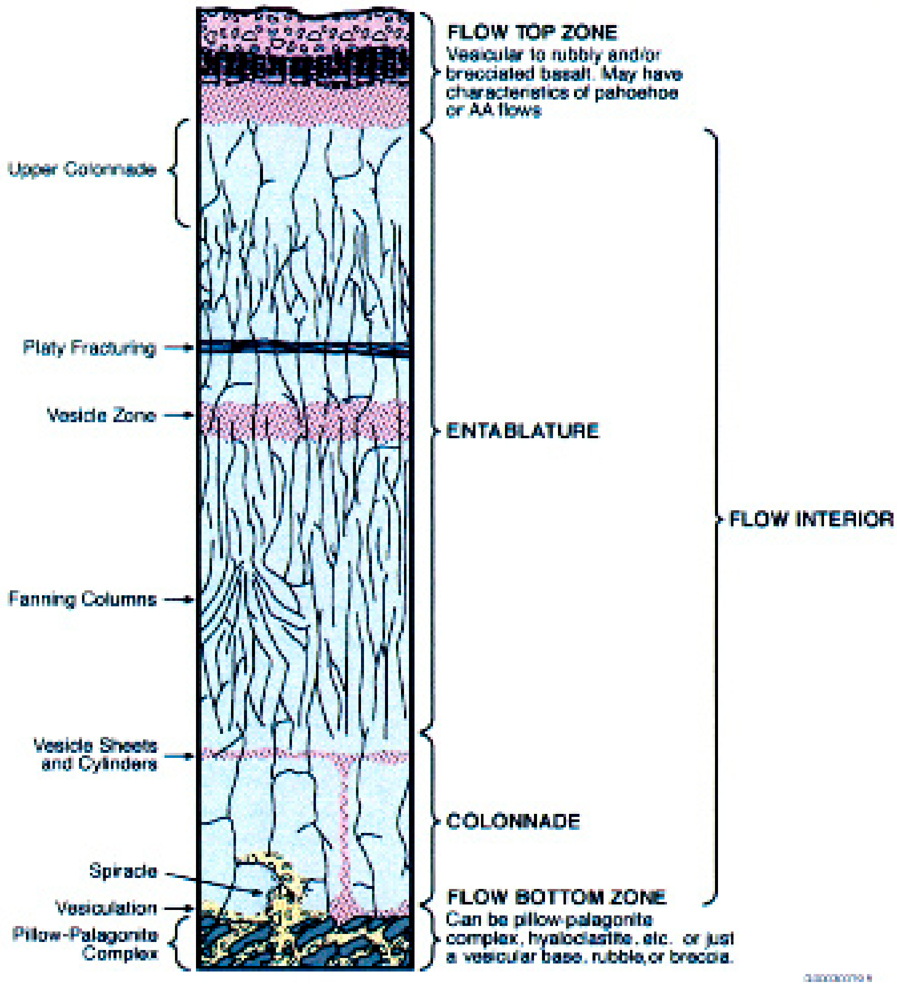


Figure 5: Intraflow structures of the Columbia River Basalt Group lava flows

SUPRABASALT SEDIMENTS

Sediments continued to be deposited in most synclinal valleys long after the eruptions of the Columbia River basalt. During the late Miocene to middle Pliocene the Ringold Formation was deposited on the central Columbia Plateau. The Pleistocene-aged Hanford formation was deposited in the basin as the result of periodic pro-glacial cataclysmic flooding. Thin alluvial deposits situated stratigraphically between the Ringold Formation and Hanford formation are found throughout the Pasco Basin. These deposits are referred to informally as the Cold Creek unit, and the pre-Missoula gravels (Fig. 3).

Ringold Formation

Exposures of the Ringold Formation (Fig. 3) are limited to the White Bluffs within the Pasco Basin, and the Smyrna and Taunton Benches within the Othello Basin. However, extensive data on the Ringold Formation are available from boreholes. The Ringold Formation (and correlative strata) overlies Columbia River basalt is structural basins throughout the region.

The Ringold Formation in the Pasco Basin is up to 185 m thick in the deepest part of the Cold Creek syncline and 170 m thick in the western Wahluke syncline. The Ringold Formation pinches out against the Gable Mountain, Yakima Ridge, Saddle Mountains, and Rattlesnake Mountain anticlines.

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 and others, 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 it contains significant, previously undocumented stratigraphic variation (Lindsey and Gaylord, 1989; Lindsey, 1991) that is best described on the basis of sediment facies associations.

Sediment facies associations in the Ringold Formation, defined on the basis of lithology, stratification, and pedogenic alteration, include fluvial gravel, fluvial sand, overbank deposits, lacustrine deposits, and basaltic alluvium. Ringold sediments were deposited in fluvial-lacustrine environments by the ancestral Columbia River and its tributaries in generally east-west trending valleys in response to development of the Yakima Fold Belt. Within the Pasco Basin the Ringold Formation is interpreted to be late Miocene to late Pliocene (8.5 to 3.4 Ma) in age on the basis of vertebrate fossils, magnetostratigraphy, and stratigraphic position (Packer and Johnson, 1979; Tallman et al., 1979;Fechtetal., 1987;Gustafson, 1985).

Cold Creek Unit (formally the Plio-Pleistocene unit)

Ringold sediments in the Pasco Basin are overlain by a paleosol system consisting of as much as 25 m of basaltic detritus and pedogenic calcrete (Stage III and Stage IV) designated the Cold Creek unit. 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 Cold Creek 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. A second Plio-Pleistocene-aged paleosol system found in the region is rarely exposed and only in ridge terrain. This system consists of 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.

Pre-Missoula Gravels

Fluvial deposits from major rivers (Yakima, Snake, Columbia) lying stratigraphically between the Ringold Formation and the Hanford formation also are found in the Pasco Basin. In the central Pasco Basin a thick sheet of well-rounded and well sorted gravel, informally called the “Pre-Missoula gravels” (PSPL, 1982), disconformably overlies the Ringold Formation. These strata generally consist of quartzose to gneissic clast-supported pebble to cobble gravel with a quartzo-feldspathic sand matrix. The pre-Missoula gravel is up to 25 m thick, contains less basalt than underlying Ringold gravels and overlying Hanford deposits, have a distinctive white or bleached color, and sharply truncate underlying strata. Based on magnetic polarity and stratigraphic position, this unit is interpreted to be early Pleistocene. The upper part of this unit has reversed polarity overprinted on normal polarity. Thus, deposition probably occurred during a normal polarity event, either Jaramillo (900 to 970 Ka) or Olduvai (1.67 to 1.87 Ma) subchrons within the Matuyama reversed chron. 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 Cold Creek unit.

Hanford Formation

The Hanford formation (informal) consists of pebble to boulder gravel, fine- to coarse-grained sand, and silt that generally are divided into gravel-dominated facies and fine-grained deposits. The fine-grained deposits, which make up the most extensive and voluminous part of the Hanford formation, are divided into two facies: (1) plane-laminated sand and (2) normally graded rhythmites, also referred to as “Touchet Beds”. The Hanford formation is commonly divided into two informal members: the Pasco gravels and the Touchet Beds (Myers and others, 1979; Tallman et al., 1981; Fecht et al., 1987; DOE, 1988). The Pasco gravels generally correspond to the gravelly facies, and the Touchet Beds to the sandy to silty facies. The Hanford formation is thickest in the Cold Creek bar in the vicinity of 200 West and 200 East Areas where it is up to 65 m thick. Hanford deposits are absent on ridges above approximately 360 m above sea level.

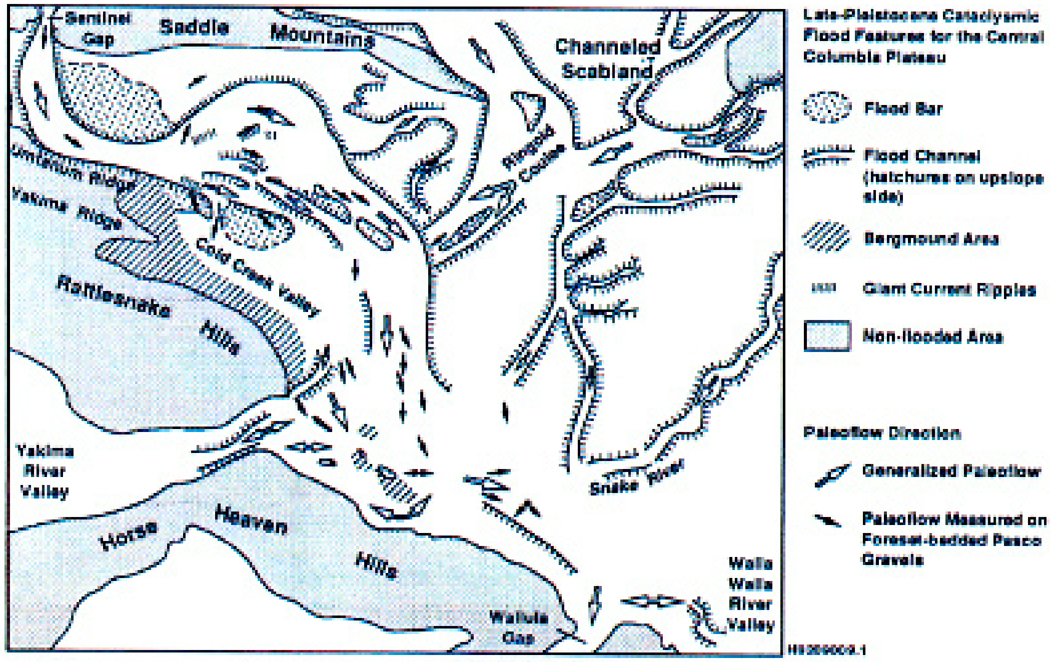
Gravel-dominated facies consist of coarse-grained sand and granule to boulder gravel that display massive bedding, plane to low-angle bedding, and large-scale cross-bedding in outcrop. Matrix commonly is lacking in these gravels, giving them an open-framework texture. Gravels dominate the Hanford formation in a linear tract stretching from Sentinal Gap down the central Pasco Basin to Wallula Gap. The gravel-dominated facies were deposited by high-energy flood waters in or immediately adjacent to the main cataclysmic flood channelways.

The laminated sand facies consists of fine- to coarse-grained sand displaying plane lamination and bedding and less commonly plane and trough cross-bedding in outcrop. These sands may contain small pebbles or pebble-gravel interbeds less than 20 cm thick. The silt content of these sands is variable, but where it is low an open framework texture is common. The laminated sand facies is most common in the central Cold Creek Syncline and it is transitional between the gravel-dominated facies to the north and the rhythmite facies to the south. The laminated sand facies was deposited adjacent to main flood channelways as water spilled out of the channelways, loosing competence (Fig. 6).

The rhythmite facies consists of silt and fine- to coarse-grained sand that commonly display normally graded rhythmites a few centimeters to several tens of centimeters thick in outcrop (Myers and others, 1979; DOE, 1988). Plane lamination and ripple cross-lamination is present in this facies. This facies is found all around the edge of the Pasco Basin. These sediments were deposited under slackwater conditions and in backflooded areas (DOE, 1988).

Three episodes of cataclysmic flooding are recognized in the Pasco Basin. Based on reversed magnetic polarity, the oldest flood deposits antedate the Matuyama-Brunhes magnetic reversal, 770+20 Ka. Reversed-polarity flood gravels are exposed at several

Figure 6: Main channel ways of the Missoula Floods



locations within 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 111 and Stage IV pedogenic carbonate development. A minimum age for this calcrete determined by Th/U dating is about 200 Ka. Fine-grained deposits inferred to be of this age contain paleosols with weekly developed B horizons. These flood deposits occur along the top of a prominant 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 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. Most rhythmite sequences in southern Washington are of late Wisconsin age, but in at least two locations, older sequences are preserved at Cummings Bridge and at Yakima Bluffs.

Mainstream alluvium was deposited during relatively long time intervals separating major cataclysmic flood episodes. However, with the exception of the Pre-Missoula Gravel, these deposits rarely are preserved within the Pasco Basin, probably because of scouring by cataclysmic floods, which removed most of the mainstream channel alluvium deposited between floods.

Holocene Surficial Deposits

Holocene surficial deposits consist of silt, sand, and gravel that form a thin (<16 ft) veneer across much of the Hanford Site. These sediments were deposited by a mix of eolian and alluvial processes. Eolian sand, derived form the reworking of flood deposits since about 13 Ka, blankets much of the east-central Pasco Basin. Both active and stabilized crescentric dunes have been formed by prevailing winds out of the southwest.

THE YAKIMA FOLDS AND THE YAKIMA FOLD BELT

The Yakima Fold Belt covers about 14,000 km2 of the western Columbia Basin (Fig. 7) and formed as basalt flows and intercalated sediments were folded and faulted under north-south directed compression. Most of the present structural relief in the Columbia Basin has developed since about 10.5 Ma when the last massive outpouring of lava, the Elephant Mountain Member, buried much of the central Columbia Basin. The main deformation is concentrated in the Yakima Fold Belt; there is only minor deformation on the Palouse Slope. Almost all the present structural relief exposed at the surface is post-CRBG.
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The Yakima Fold Belt consists of narrow anticlinal ridges separated by broad, synclinal valleys. The anticlines and synclines are typically segmented. Most have a north vergence; however, some anticlines such as the Columbia Hills, and a few segments of some other ridges, have a south vergence. Fold length ranges from 1 km to over 100 km; fold wavelengths range from several kilometers to as much as 20 km. The folds

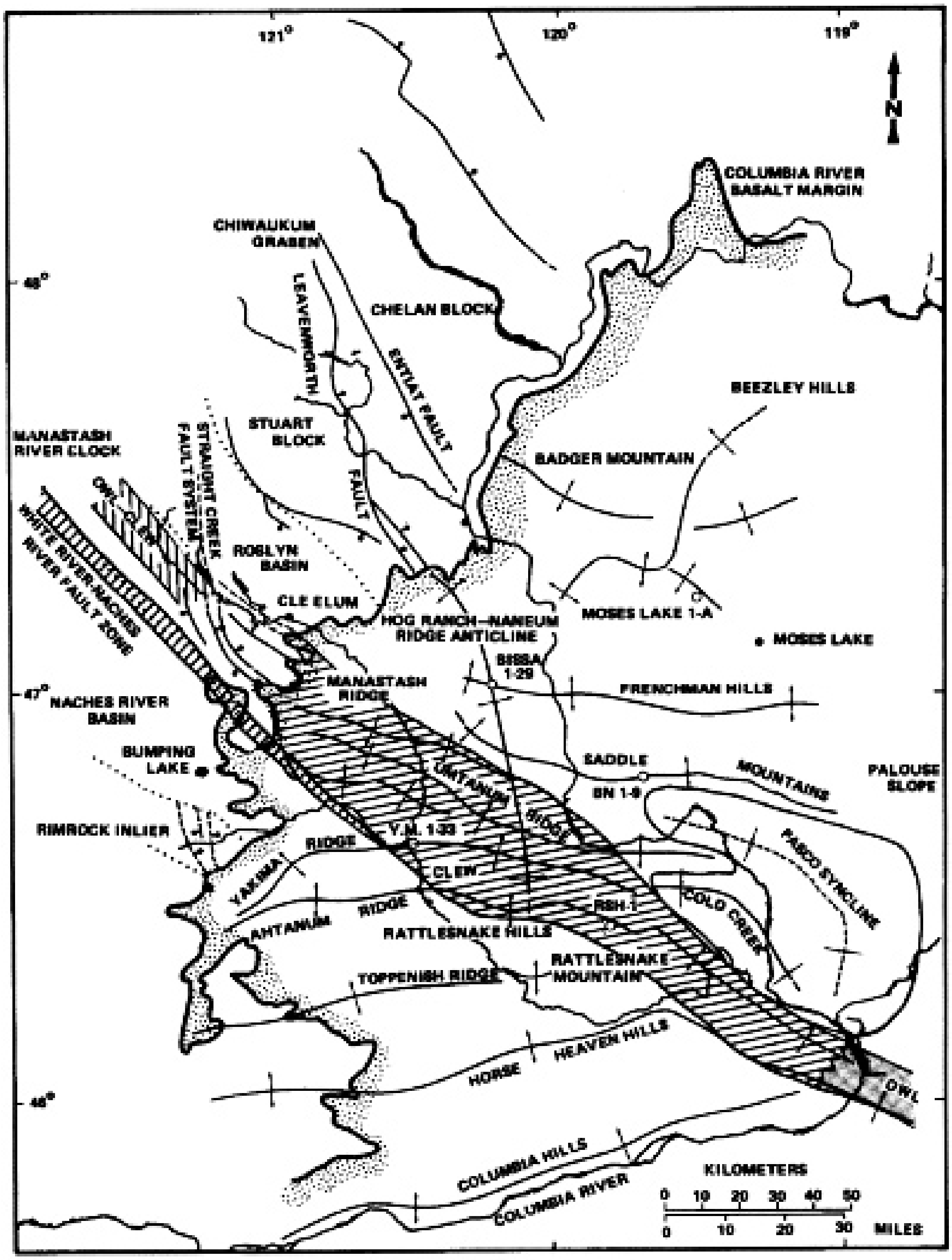


Figure 7. Generalized map of the Yakima Fold Belt.

are segmented by crosscutting faults and folds (Reidel, 1984; Reidel et al. 1989b). Structural relief is typically less than 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-trending Hog Ranch-Naneum Ridge anticline.

Anticlines in the southwest part of the Yakima Fold Belt, southwest of the Cle-Elum-Wallula deformed zoned (CLEW) (Fig. 7), generally have N50°E trends (Swanson et al., 1979b; Reidel et al. 1989b). Anticlines in the central part have east trends except along the CLEW where a N50°W trend predominates. The Rattlesnake Hills, Saddle Mountains, and Frenchman Hills have overall east trends, but Yakima Ridge and Umtanum Ridge change eastward from east to N50°W in the CLEW. The Horse Heaven Hills, the N50°W trending Rattlesnake Hills, and the Columbia Hills abruptly terminate against the CLEW.

Although rarely exposed, nearly all the steep forelimbs of the asymmetrical anticlines are faults. These frontal fault zones typically consist of imbricated thrusts (Bentley, 1977; Goff, 1981; Bentley in Swanson et al., 1979; Hagood, 1986; Reidel, 1984, 1988; Anderson, 1987) that are emergent at ground surface. Near the ground surface, the thrust faults merge into the shallow dipping surface of the basalt (Reidel, 1984). Where erosion provides deeper exposures, these frontal faults are steep reverse faults [e.g., 45°S in the Frenchman Hills at the Columbia River water gap, (Grolier and Bingham, 1971) and 50-70° north in the Columbia Hills at Rock Creek, Washington (Swanson et al. 1979b)].

Hydrocarbon exploration boreholes provide direct evidence for the dips of these frontal faults. Reidel et al. (1989b) have shown that the Saddle Mountains fault must dip more than 60° where the Shell-ARCO 1-9 BN borehole was drilled. Drilling of the Umtanum fault near Priest Rapids Dam (PSPL, 1982) suggests that this fault dips southward under the ridge with a dip of at least 30° to 40° (PSPL, 1982) but perhaps as high as 60° (Price, 1982; Price and Watkinson, 1989).

Although it is difficult to assess, total shortening increases from east to west across the Yakima Fold Belt. At about 120° longitude, it is estimated to be between 15 km and 25 km (Reidel et al., 1989b), or about 5%. Typically, shortening on an individual anticline as a result of folding is approximately 1 to 1.5 km. The amount of shortening on faults expressed at the surface is generally unknown. Estimates range from several hundreds of meters to as much as 3 km.

Synclines in the Yakima Fold Belt are structurally low areas formed between the gently dipping limb of one anticline and the steeply dipping limb of another where that limb was thrust up onto the gently dipping limb of the neighboring anticline. Few synclines within the Yakima Fold Belt were formed by synclinal folding of the basalt.

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. Exceptions, however, include the doubly plunging anticlines within the Rattlesnake-Waliula alinement (RAW) of the CLEW (Fig. 7) 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 and others, 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.

The steep limb of the asymmetrical anticlines in the east-central fold belt is almost always faulted (Fig. 2). 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 and others, 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 and others, 1979b), the Horse Heaven Hills 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. 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, WA, 50-70 degrees north (Swanson and others, 1979b)).

Subsurface Structure

The dip of the frontal fault plane and the structure of the anticlines at depth remains controversial. A multitude of possible models (such as Suppe's (1983, 1985) fault-bend fold or fault-propagation fold, Jamison's (1987) detachment fold, and Mitchell and Woodward's (1988) kink-detachment fold) can all produce similar surface geometries and thus have provided abundant food for thought influencing many of the models that have been proposed for the fold belt. No clear answers have come forth because of the lack of direct observations, however. We will present some information during the field trip from some of the recent hydrocarbon exploration on the Columbia Plateau that helps constrain subsurface interpretations.

Regional thickness variations of units and tectonic implications

The greatest thickness of both pre-Columbia River Basalt Group Tertiary rocks (Campbell, 1989) and Columbia River basalt (Reidel and others, 1982; Reidel, 1984; Reidel and others, 1989b) occurs in the central Columbia Plateau. Magnetotelluric data (Berkman and others, 1987) and seismic- reflection data (Catchings and Moody, 1988) suggest that both the Columbia River Basalt Group and subbasalt sediments thicken from the Palouse slope into the area covered by Yakima Fold Belt. The Columbia River Basalt Group ranges from 500 to 1500 m thick on the Palouse slope but abruptly thickens to more than 4000 m in the Pasco Basin area (Reidel and others, 1982; 1989b). Although the total thickness of the subbasalt sediments is not known, these sediments appear to thicken dramatically beneath the Yakima Fold Belt (Campbell, 1989; Reidel and others, 1989b).

The regional thickness pattern of both the Columbia River Basalt Group and underlying Tertiary sediments indicate that prior to the eruption of the Columbia River Basalt Group, the area encompassing the present day Yakima Fold Belt had subsided relative to the Blue Mountains and Palouse Slope and filled with sediments. There is no evidence of encroachment by the sea into the central Columbia Plateau during the Tertiary. The continental nature of the sediments (Campbell, 1989) suggests that aggradation kept pace with subsidence, and the subaerial nature of the Columbia River Basalt Group (Reidel and others, 1982, 1989a) indicates that subsidence continued through the eruption of the basalts and basalt accumulation kept pace with subsidence. Furthermore, the suprabasalt sediments from the Pasco Basin indicate that subsidence continued beyond the Miocene and into the Pliocene. Evidence for the thinning and pinchouts of basalt flows onto the Blue Mountains (e.g. Ross, 1978; Hooper and Camp, 1981; Fox and Reidel, 1987) indicates that the Blue Mountains were growing during the eruption of the Columbia River Basalt Group and while the central Plateau was subsiding. The regional tectonic setting of the central Columbia Plateau throughout much of the Cenozoic, therefore, appears to be one of a subsiding intermontane basin (graben or rift?) that is bounded on the west by the rising Cascade Range, on the south by the slowly growing Blue Mountains, and on the east by a relatively stable westward dipping paleoslope.

The Olympic-Wallowa lineament - The Olympic-Wallowa lineament has been recognized as a major through-going topographic feature in Washington (Raisz, 1945; Figs. 1 and 7). This feature aligns with pre-basalt structural trends northwest of the Columbia Plateau and in the Columbia Plateau. Within the Yakima Fold Belt, deformation along Manastash Ridge and abrupt bending of the eastern ends of Umtanum Ridge, Yakima Ridge, and Rattlesnake Ridge are considered to be evidence for Miocene or younger deformation along the OWL. This portion of the OWL is called the Cle Elum-Wallula deformed zone (CLEW).

Just northwest of the Columbia River basalt margin, on Manastash Ridge, numerous northwest trending faults and shear zones of the Straight Creek fault system occur subparallel to the OWL (Tabor and others, 1984). It is not known whether the OWL affects Tertiary rocks here or if deformation is solely related to the Straight Creek fault system.

White River-Naches River Fault Zone - The Naches River and Little Naches River flow in a rather straight, southeasterly direction from near the crest of the Cascade Range toward Yakima, Washington (Fig. 7). The White River-Naches River fault zone (WR-NR) is a major fault zone and is aligned with this 50 km-long valley system (Naches-Little Naches rivers) that separates two terranes of dissimilar structure, stratigraphy, and topography (Campbell, 1988). Northeast of the White River-Naches River fault zone, faults and folds in pre-Tertiary through Pliocene rocks parallel (N 60° W) splays of the Straight Creek fault zone. Southwest of the White River-Naches River fault zone, faults in pre-Tertiary rocks trend N 5° E to N 20° W. Middle and late Tertiary rocks in this area reflect Miocene folding and are commonly aligned east-west.

Within the basalts the White River-Naches River fault zone appears to influence fold development in the Yakima Fold Belt as far southeast as Yakima. The fault zone separates a domain of east-northeast trending folds on the southwest from dominantly northwest trending folds on the northeast, and defines structural low points along the Yakima Ridge and Rattlesnake Hills anticlines. The fault zone can be shown to offset flows of the Columbia River Basalt Group for several kilometers southeast of the margin (Campbell, 1988).

The White River-Naches River fault zone derives its name from an alignment northwest of this area between this fault zone in the Naches River and the White River fault (Hammond, 1963; Frizzell and others, 1984), a major fault that continues at least 50 km west-northwest of the area. The total length of the entire fault zone, from Enumclaw to Naches, exceeds 90 km.

Tectonic Brecciation and Shearing

Tectonic breccia and shear zones are common in geologic structures in the CRBG (Goff, 1981; Reidel, 1984; Barsotti, 1986). Three types of breccias are recognized: shatter breccias, anastomosing breccias, and shear zone and fault breccias (Price. 1982).

- **Shatter breccias** are simply shattered basalt in which the original primary features of the basalt are still preserved.

- **Anastomosing breccias** are composed of lenticular basalt fragments with a submicroscopic, pulverized basalt matrix, and are nontabular basalt breccias of no apparent measurable orientation.

- **Shear zones and fault breccias** are tabular breccia zones that have three stages of development. The first stage is the development of a set of parallel, sigmoidal extension fractures superimposed on primary structures. The second stage involvesrigid rotation of millimeter-scale basalt blocks, causing the initial granulation of basalt.
The third stage involves development of discrete slip sur-

faces either within, or bounding, a tabular breccia.

Flow top breccias are distinguished from tectonic breccias by several characteristics. Tectonic breccia typically contains more angular clasts of smaller size, usually a few centimeters or less, than flow top breccia. Clasts in flow top breccia often are bound by original glass and are an admixture of vesicular and nonvesicular basalt, whereas clasts in tectonic breccia have a homogeneous texture. The presence of subparallel fracturing within a tectonic breccia zone results in clasts being arranged parallel to subparallel to each other, which also contrasts with the random, chaotic nature of clasts in flow top breccias. Slickensides are present on some surfaces in tectonic breccias and absent in flow top breccias without tectonic fracturing. Tectonic breccias typically display a crushed basalt matrix, while flow top breccias may be partially to fully filled with secondary minerals or palagonite between fragments, or the fragments may be welded together.

Major high-angle, reverse to thrust faults along anticlinal ridges are associated with very thick breccia zones. In the Saddle Mountains, these zones are very distinct and in Sentinel Gap consist of a several-hundred-meter-thick zone of shatter breccias (Reidel. 1984). Similar breccia zones have been found in Umtanum Ridge (Price, 1982; Barsotti, 1986) and at Wallula Gap.

FIELD TRIP

The field trip begins at Vantage, Washington (Fig. 8). Exit at Huntzinger Road and turn north to the town of Vantage. The trip will begin in the parking lot for the restaurant on the west side of the road as you come into town. This restaurant can be recognized by its orange roof and nearly octagonal shape.

Stop 1. Introduction to Pasco Basin. Looking south from Vantage is Sentinel Gap and the Saddle Mountains (Fig. 9). The Saddle Mountains are a typical Yakima Fold and form the northern boundary of the Pasco Basin, one of the largest structural basins in the Yakima Fold Belt.

Stop 2. Saddle Mountains Fault Zone. Drive south from Vantage on Huntzinger Road as far as the Yakima Training Center.

The Saddle Mountains is a broad anticlinal uplift that trends generally east-west for 110 km (68 mi) and forms the northern boundary of the Pasco Basin (Fig 8). This area has been mapped in detail by Reidel (1988) and described by Reidel (1984). Two dominant structural features associated with the Saddle Mountains are the Saddle Mountains anticline and the Saddle Mountains fault, although the complex geometry of the anticline has resulted in other secondary anticlines, synclines, and monoclines that parallel the main trend of the structure

The Saddle Mountains can be divided into six segments on the basis of differences in geometry of the fold. The McDonald Springs and Smyrna Bench segments are the most complex structurally. The Saddle Mountains fault is a high angle reverse or thrust fault that has a dip angle greater than 45 degrees (Reidel and others, 1989). Although it generally parallels the Saddle Mountains anticline, it does not appear to have the same length and may not extend east of Smyrna Bench. At least 3.0 km (1.9 mi)of crustal shortening due to horizontal compression has been measured on the Saddle Mountains fault on the west side of Sentinel Gap (Reidel, 1984, p. 972), but this decreases to no detectable shortening at the east end in the Eagle Lakes area.

The Sentinel Gap area marks the boundary between two segments, the Sentinel Gap segment to the east and the McDonald Springs segment to the west. The segment boundaries at Sentinel Gap is a tear fault and the Columbia River took advantage of this zone of weakness. The Columbia River has flowed through here since at least Grande Ronde time and perhaps longer.

Stop 3. Saddle Mountains, Sentinel Gap Segment. Return to Vantage, cross the Columbia River and head south toward Richland . Exit 1-90 at SR 26 and then turn right on SR 243. At the town of Beverly, turn east on Lower Crab Creek Road. The next stop is several miles down the gravel road where a good view of the Saddle Mountains north face can be seen (Fig 10). Here one of the small basins that contain Ringold sediments has been uplifted as the structure grew. Also note the abrupt cross folding in the basalt.

Stop 4. Sentinel Gap and Columbia River basalt. Proceed back to SR 243 and turn south toward Richland. The next stop is in Sentinel Gap to examine typical Columbia River basalt.

The main flows at this section are those of the upper portion of the Grande Ronde Basalt - the Sentinel Bluffs Member (Fig. 11). A recent study by Reidel (in press Journal of Geology) shows that the stratigraphy here is very complex. The eruption of Sentinel Bluffs Member lava flows marked the end of Grande Ronde Basalt volcanism, the most voluminous period of the Columbia River Basalt Group. Over 10,000 km3 of lava erupted from northerly trending feeder dikes in eastern Washington and northern Oregon, and flowed westward down an ancestral paleoslope covering over 169,700 km2 of the flood-basalt province. The Sentinel Bluffs Member consists of six phases or types defined by their compositions. Lava flows having the first compositional type were the most voluminous and reached the Pacific Ocean. The volume of later lava flows having the other compositional types declined with time until the final eruption produced the second largest volume of basalt.
At the source area, compositional variation in Sentinel Bluffs lava flows is relatively small. This homogeneity allows the individual compositional types and, thus, phases of the eruption to be easily recognized. Farther west, however, compositional heterogeneity increases with several compositional types occurring in individual lava flows. The Cohassett flow has more compositional heterogeneity than any Sentinel Bluffs Member lava flow. It is interpreted to

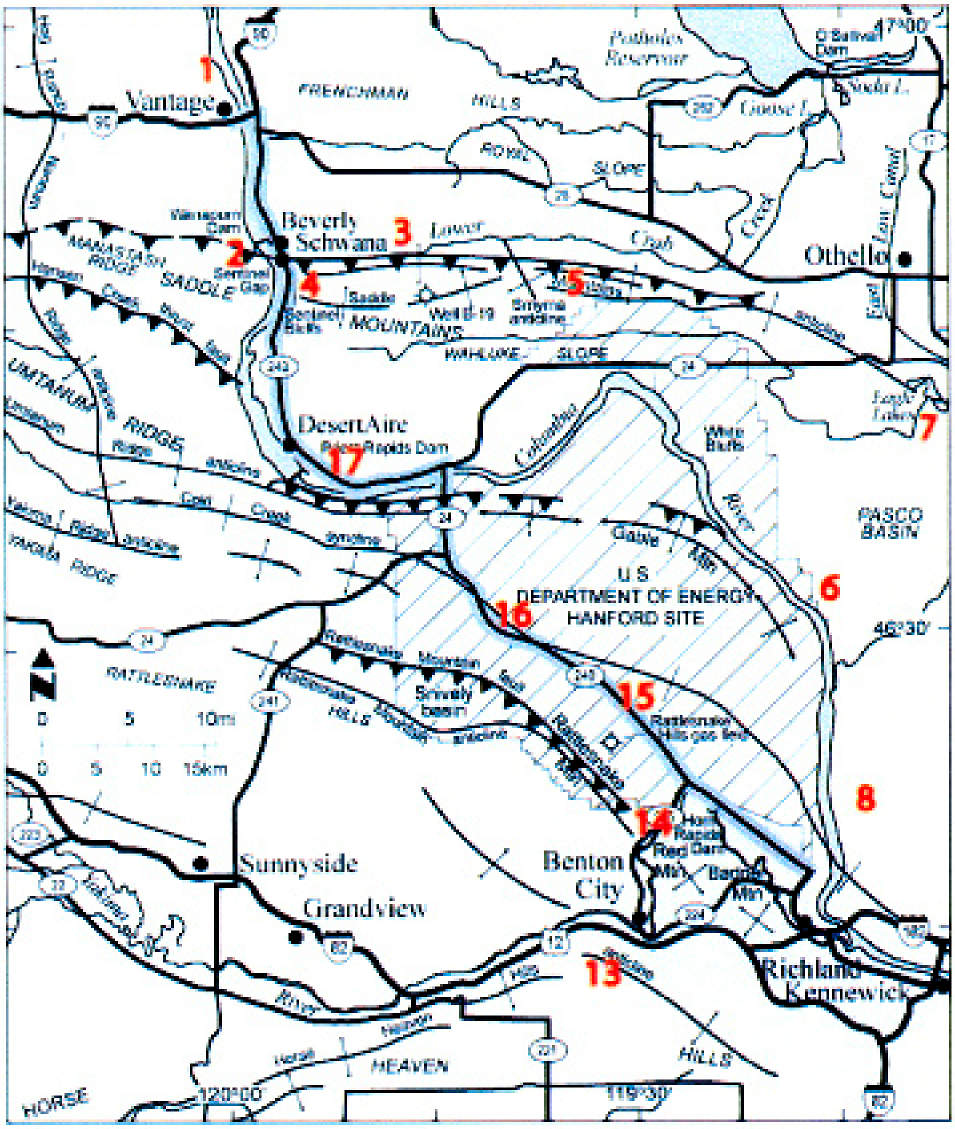


Figure 8. (Above) Geologic map of the western portion of the Pasco Basin showing field trip stops from the first day and several from the second day.

be a local lava flow that formed as one compositional type after another was injected into the first and inflated it to form a lava flow with compositional zoning reflecting the sequence of eruptions. The compositions of the layers remain intact except for mixing along their contacts. Thin vesicular horizons separate compositional layers in the upper part of the lava flow but not in the lower part. A thick vesicular horizon called the interior vesicular zone marks the boundary between the last two compositional types to be injected. Other Sentinel Bluffs flows appear to have formed in a similar way. The compositional types and the field relations are best explained by rapid changes in magma composition feeding and inflating the flows and, suggest rapid eruption and emplacement of the lava flows.

Stop 5. Smyrna Bench segment of the Saddle Mountains. From Stop 4 continue south to the turnoff for the town of Mattawa (County Road 24 SW). Follow 24 SW until it joins SR 24. Follow SR 24 for 7.5 miles and then look for the turn off on the north side of the road for the Saddle Mountains Wahluke Slope road. This is a paved road that goes to the top of the Saddle Mountains. Follow this road to the crest of the Saddle Mountains and then turn left at the intersection. Follow the crest road west to Wahatis peak.

Stop 6. White Bluffs and Ringold

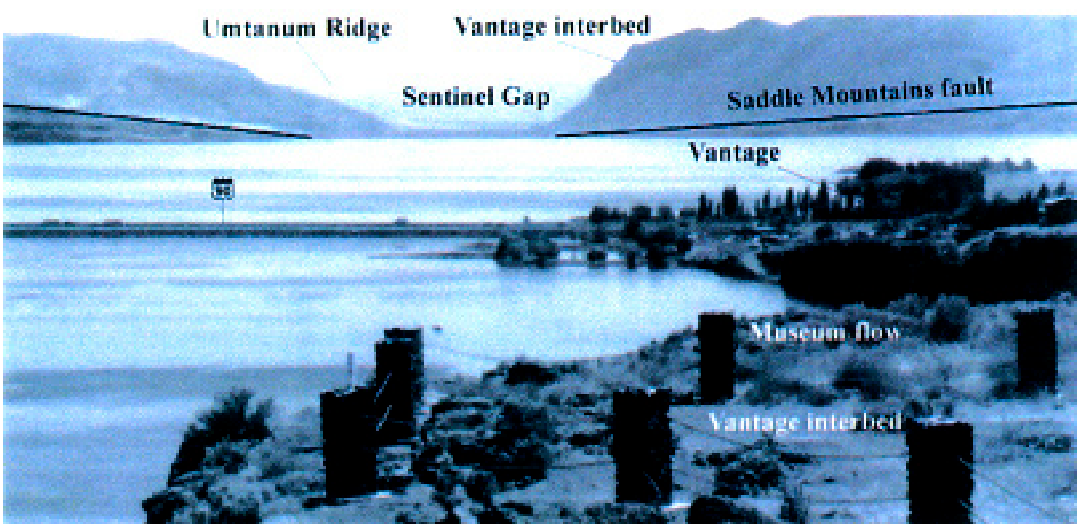


Figure 9 (Left) Sentinal Gap from the Ginkgo Petrified Forest State Park in Vantage

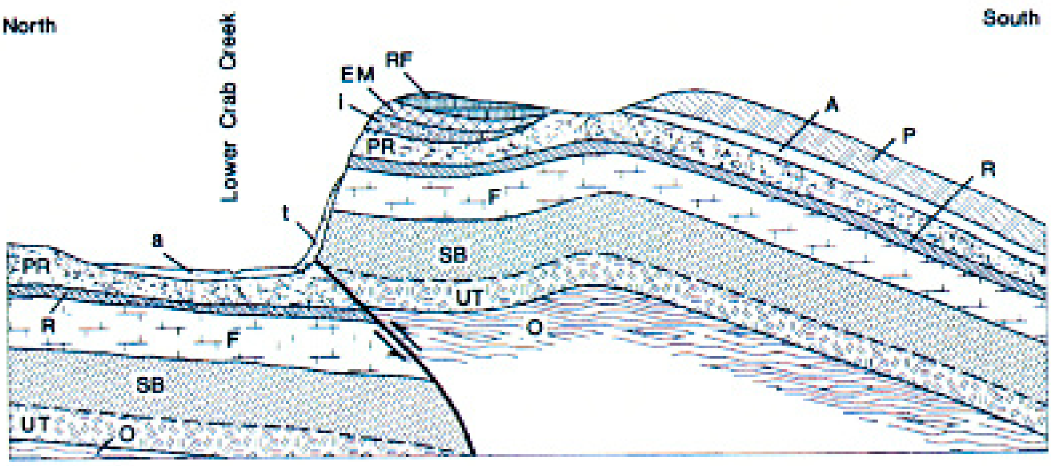


Figure 10 Diagrammatic cross-section through the Saddle Mountains east ol Sentinel Gap View to the east, not to scale UT, Umtanum, and O. Ortley units of the Grande Ronde Basalt; SB, Sentinel Bluffs unit of Grande Ronde Basalt; F, Frenchman Spring* Member flows; R, Roza Mombor, PR, Priest Rapids Member; A, Asotin Member; P, Pomona Member; i. sedimentary interbcd; liM, Ulephant Mountain Member; RF, Ringold Formation; a, alluvium; t, talus Uppercase symbols indicate units whose age is Miocene or Pliocene; lower-case letters indicate units of Pleistocene or Recent age Note that the Elephant Mountain. Ringold fanqlomerate. and Interbed on the north face pinch out to the south The Pomona, intcrbed. and Asotin pinch out to the north. (Modified from Rcidel. 1988 J

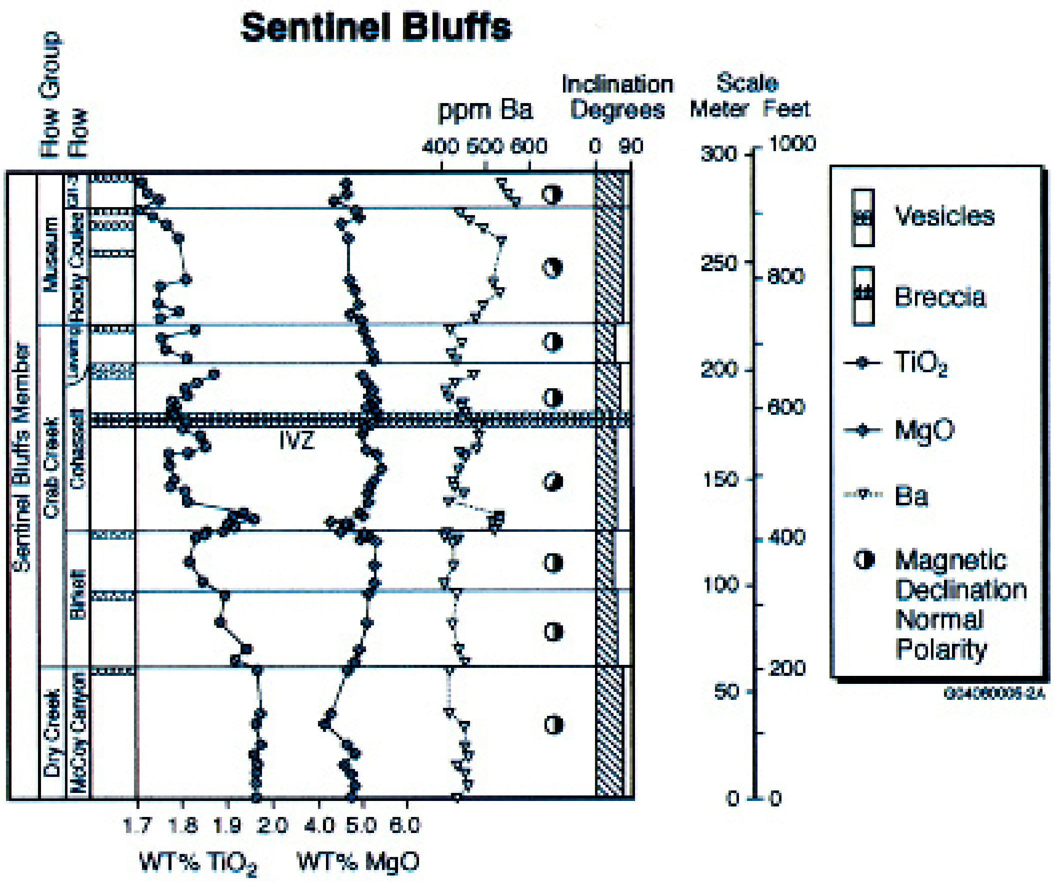


Figure 11. The Sentinel Bluffs Member exposed at Sentinel Gap (from Reidel, in press). Flow designations are from Landon and Long (1989 GSA SP 239). These have been revised in Reidel (in press) and are shown in Figure 12.

Formation. Return to SR 24 and turn left toward Othello, Washington. Go about 2 miles and then turn right into the Wahluke Slope Wildlife area. Follow the paved road until you reach the locked gate and overlook of the Columbia River. At this stop we will view the Hanford Site and be able to examine the upper part of the Ringold Formation, the lake beds.

Wahatis Peak is on the Smyrna bench segment of the Saddle Mountains. This segment is a box fold (Figs. 14 and 15). Here we will discuss the evolution of this part of the Saddle Mountains structure.

Stop 7. Eagle Lakes Segment of the Saddle Mountains. Return to SR 24 and turn east toward Othello, Washington. Follow Sr 24 for about 13.5 mile and turn south on Sage Hill Road. This is at the base of the Saddle Mountains on the north side. Sagehill Raod takes you back up over the Saddle Mountains. Follow Sagehill Road for approximately 2 miles then turn left on Eagle Road. This will take you to an overlook of the Eagle Lakes segment of the Saddle Mountains. At this stop we will view and discuss the eastern most and least deformed segment of the Saddle Mountains.

Stop 8. Ringold Formation Gravels. Return to Sagehill Road and turn south. Follow Sagehill Road to Basin City. At Basin City turn west and follow Road 170. Road 170 is the main road but will become Rickert Road in about 3 miles. This road takes you through Ringold Coulee (see Fig. 6), which is the only flood channel that is not floored by basalt. Continue on the road as it takes you up the south wall of the coulee. Continue until you reach Taylor Flats Road which is about 8 miles from Basin City. Turn south on Taylor Flats Road (at this point, you are on the Eltopia-Ringold Road [yes, it changed its name again] and are headed east. Follow Taylor Flats Road south for 3 mile then turn west on Fir Road. Follow Fir Road to the point (about 2 miles) when it appears to end but really doesn't. It makes a left, then right jog at the farm then drops down into the Columbia Valley. Follow it to the river. When you reach the river, park and walk north on the gravel road. This is the old Pasco-White Bluffs Road that has been removed in many spots by landslides. Follow the gravel road to the cliffs of conglomerate. Visible immediately in front 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.

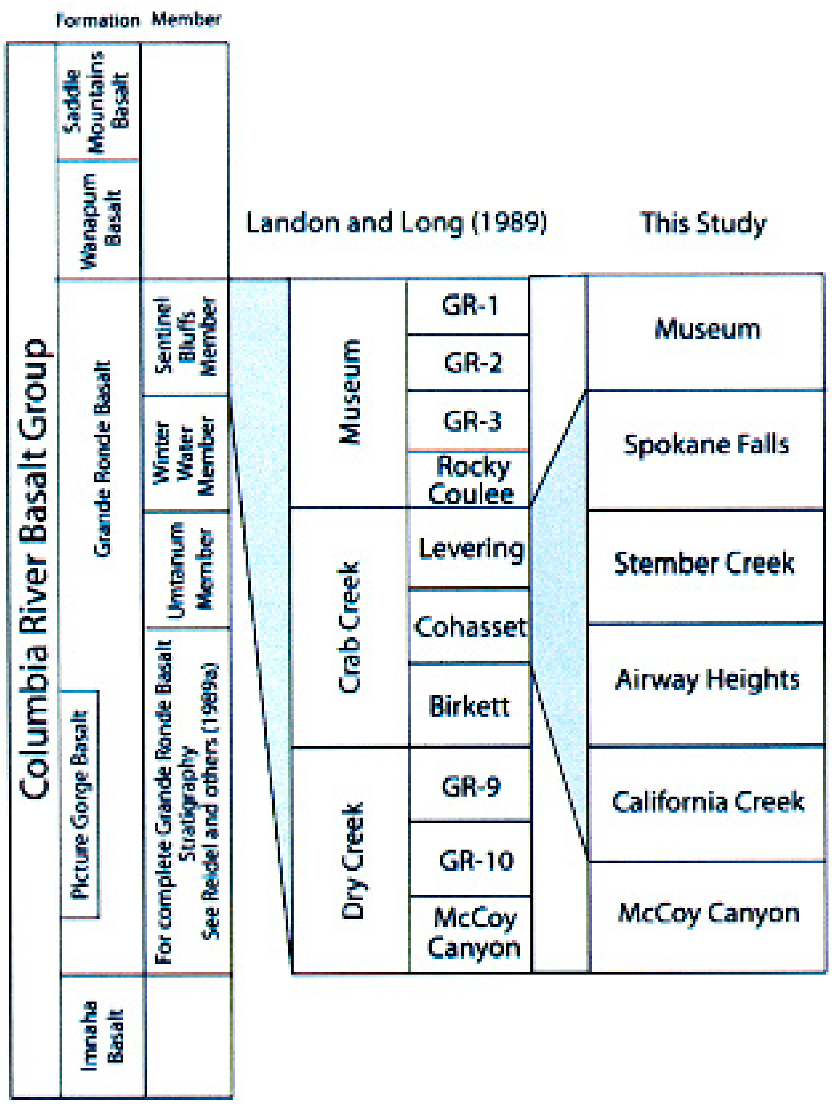


Figure 12. Revised stratigraphic nomenclature suggested by reidel (in press) for the Sentinel Gap Member based on a regional evaluation of the source region, flows and composition.

END OF DAY ONE.

Return to Taylor Flats Road and follow it to 1-182. Turn west on 1-182 to Richland. Exit on George Washington Way and follow it for several miles to the Clarion Hotel.

Day Two.

Meet at the Clarion Hotel. Figure 15 shows the route for the first part of Day 2. Figure 8 has the remainder of Day 2.

Stop 9. The 8.5 Ma Ice Harbor vent system. From the Clarion Hotel in Richland, follow George Washington Way back to I-182. Use the Pasco entry ramp. Follow 1-182 through Pasco and continue on to the Snake River bridge. Immediately beyond the Snake River, turn east on to SR 124. Follow SR 124 for about 6 miles then turn north on Monument Road which is the road to Ice Harbor Dam. Follow the road and when the road bends right to the fish viewing room, turn left and follow the gravel raod as far as you can. This will take you to a spatter vent for the 8.5 Ma Ice Harbor Member, basalt of Martindale.

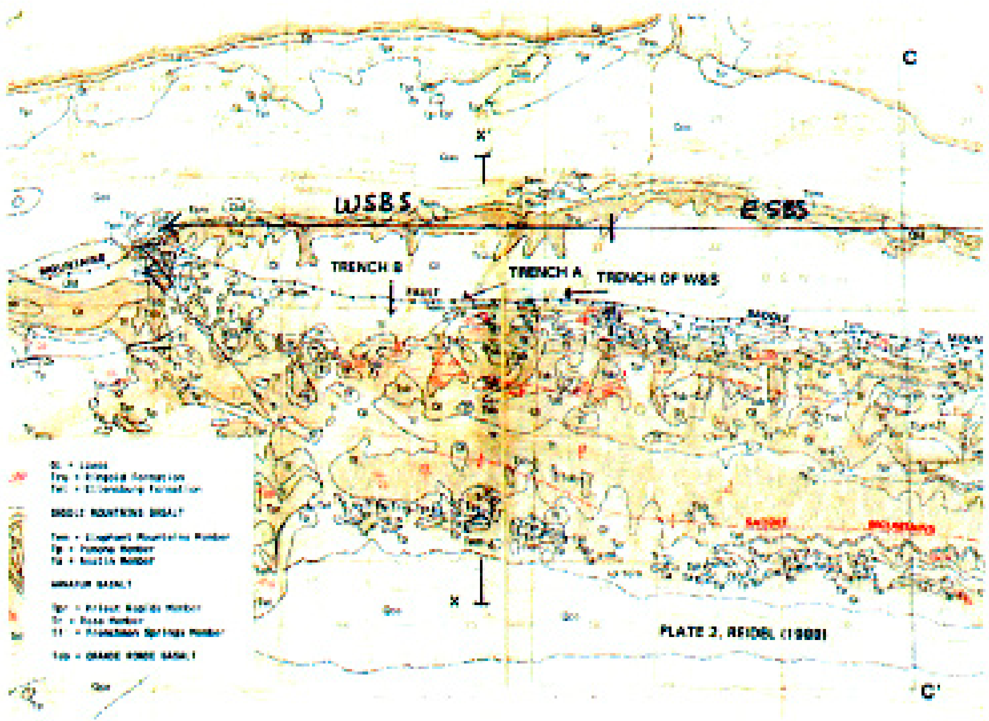


Figure 13. geologic map of the Wahatis Peak area (Reidel 1988).

This outcrop is a well preserved spatter vent on the southeast side of the Snake River on the downstream end (west) of Ice Harbor Dam Here the craggy bluff (Fig. 16) is a remnant of an 8.5 million-year old volcano. Erosion has removed part of the volcano, exposing the inside. This volcano is relatively small, only about 650 feet wide and 150 feet high and is only one of many volcanoes that fed the nearby lava flow. The volcano is composed of tephra (from the Greek for ash, it refers to volcanic material thrown into the air during a volcanic eruption), and lava (all molten rock flowing from the volcano).

Near the base of the vent is tan colored tephra that is made up of very fine volcanic ash particles and larger bombs. Some of the bombs are pieces from older buried lava flows that were ripped loose and brought up to the surface by the erupting lava. On top of the tan tephra is dark basalt called spatter. These are large pieces of lava that were thrown into the air during the eruption, fell to the ground, and cooled near the fis-sure. This process built up the sides of the volcano and was the second part of the fireworks show. This part of the show would have looked like large masses of red-glowing lava being thrown 10s of feet into the air before landing and splashing like cow pies. Overlying the tephra is lava that flowed from the volcano.

If you walk down the path for a half a mile west to the next craggy bluff (a small quarry), you will see a fracture through a lava flow filled with basalt. This is a dike cutting the lava flow. A dike is a fracture used by lava to go from the magma chamber deep in the Earth to the surface where it erupts. The dike stands out as a rubbly 10 ft wide zone cutting up through a lava flow

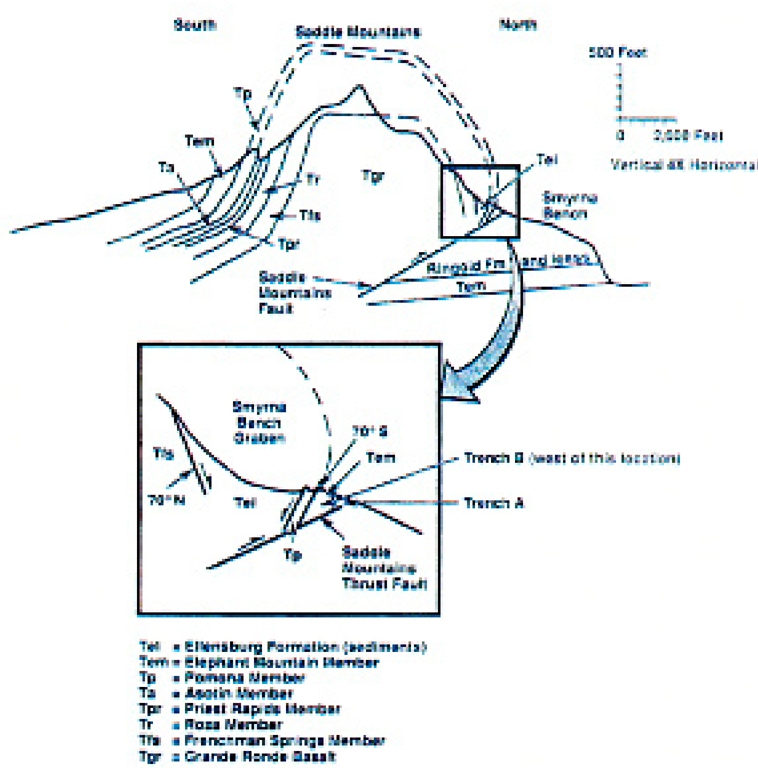


Figure 14. Cross section through the Smyrna Bench Segment of the Saddle Mountains. Shown are the location of two trenches cut to determine the age and amount of movement on the Saddle Mountains fault.

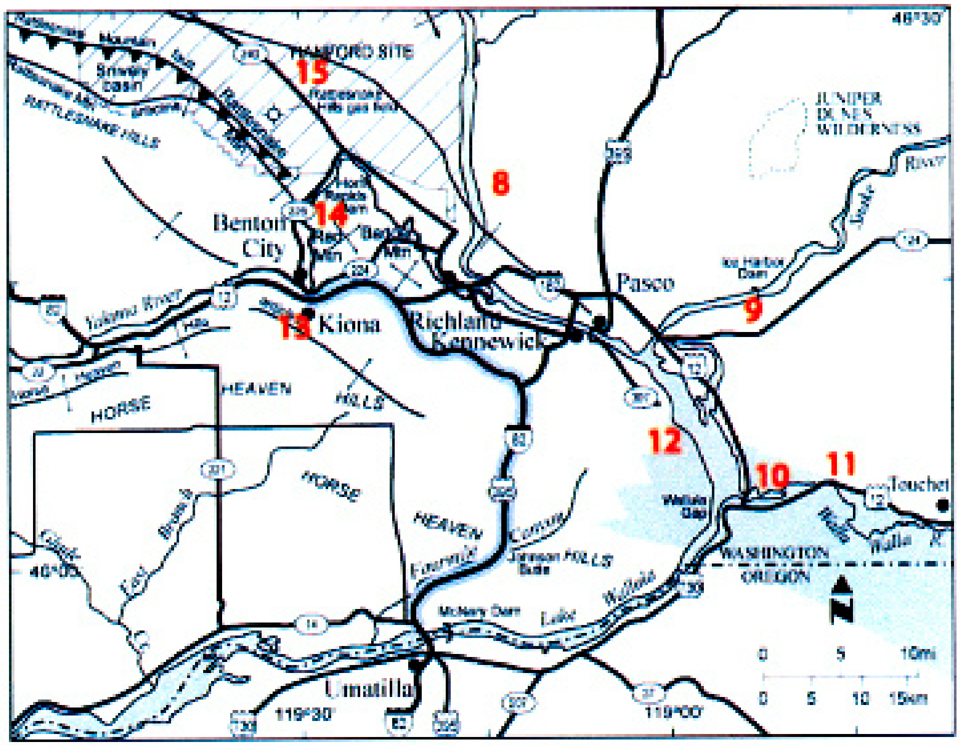


Figure 15. The Eastern Portion of the Pasco Basin showing stops 9 through 15. Stops 16 and 17 are on Figure 8.

from the volcano you just saw. The lava flow has very distinct vertical fractures.

Stop 10. Wallula Gap. From Stop 9, return to 1-182. Turn left which is now US 12 and follow the road to Wallula Gap. When you cross the Walla Walla River (Wallula Junction), turn right on to US 730. Turn right into the Port area just beyond the junction.

US 730 lies on top of the Wallula Fault Zone, part of the Olympic Wallowa lineament. To the south of the road is the uplifted portion. The Port area is on the down-dropped block. North of the road is the Saddle Mountains Basalt section tilted steeply to the north (Umatilla Member, Pomona Member, Elephant Mountain Member and Ice Harbor Member, with intervening sedimentary layers of the Ellensburg Formation). US 12 lies on what should be

Figure 16. Ice Harbor Member spatter cone at Stop 9.

considered the upper fault and in the Walla Wall River is the main fault zone which is not exposed.

At this stop we will also discuss the Missoula floods and the role Wallula Gap played in their history.

Stop 11. Clastic Dikes and Touchet Beds. Return to US 730 and proceed east for about 5 miles and stop at one of the pull offs on the north side of the road.
At this stop you can see good examples of the slackwater sediments (Fig. 17) from glacial lake Lewis and excellent examples of clastic dikes. Our current ideas on the origin of clastic dikes is that they are analogous to sand boils that form in wet, unconsolidated sediment during earthquakes. At this stop we can discuss how they relate to the Wallual Fault Zone.

Stop 12. The Butte and Finley Quarry. From Stop 11, retrace your route to the Snake River bridge. Continue north on 1-182 until you see exit signs for "A Street" (about 1-1.5 miles) and Finley. Follow A Street through Pasco to the turn off for "The Cable Bridge" that goes to Kennewick. Go straight on the main route beyond the bridge and follow it as it bends left (east). This is Chemical Drive. Stay on Chemical drive until you reach the turn to the town of Findley. Go through Findley and continue up the hill (called The Butte) until you see a pull off on the left for the quarry entrance. Here we will walk up into the quarry and view the fault zone exposed in the quarry.

The quarry is in the Umatilla Member of the Saddle Mountains Basalt. Along the north side of the quarry is a well exposed fault. This quarry was studied extensively as part of the licensing of Energy Northwest's #2 power plant. The fault here is covered by alluvial fan deposits that are older than 250,000 years. Also, note the fracturing in the basalt that is related to the fault. If the county hasn't hauled it away, there is a small stream channel high on the quarry wall. This channel was cut into the 13 Ma Umatilla Member and filled with 12 Ma Pomona member basalt. There is a thin ash layer at the base of the channel that was fused when the baslt flowed over it. Current thinking is that this ask was derived from massive rhyolitic eruptions on the Snake River Plain.

Stop 13. Horse Heaven Hills view point. From Stop 12, retrace your path to the Cable Bridge. Just before the Cable Bridge, turn left on to Columbia Drive and follow it to US 395. head south on US 395 and get on 1-82 headed toward Yakima. Follow 1-82 to the Benton City exit. At the ext turn left to Kiona. Follow the road until you see McBee Grade Road on the left (about 1.5 miles). Follow the grade to the top of the Horse Heaven Hills. Here we have an excellent view of the Olympic Wallowa lineament and the structures that comprise it. At this locality we will talk about the nature of the Yakima folds at depth and the evidence for faulting along the OWL.

Stop 14. Yakima Water Gap. From McBee Grade, return to 1-82. However, now continue on the road, which becomes SR 224, through Benton City and along the Yakima River. We will stop about 5 miles up the road where Rattlesnake Mountain crosses the river. As you drive this section, look for evidence of faulting of the basalts on the east side of the river. Mapping has shown that the oldest lava flow, the 12 Ma Pomona, through the youngest, the 8.5 Ma Ice Harbor are not faulted. This is evidence for the absence of strike-slip faulting along this portion of the OWL (Fig. 7).

Stop 15. Rattlesnake Mountain View. Continue along SR 224 to where it intersects SR 240. Turn left on SR 240 and continue about 10 miles to a turn off on the west side of the road. Here we will discuss the structure of Rattlesnake Moun-

Figure 17. Touchet Beds and Clastic Dikes at Wallula Gap.

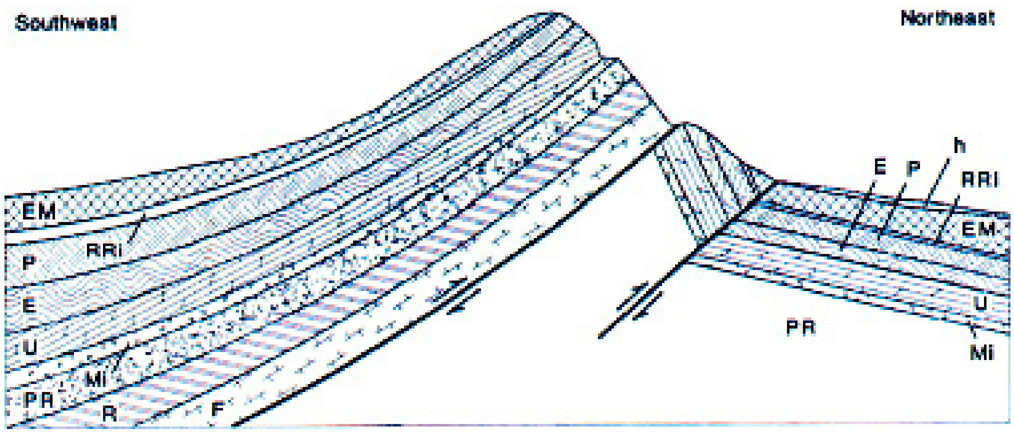


Figure 18. Cross section through the Rattlesnake Mountain structure. Letters denote units: h - Hanford formation; EM - Elephant Mountain; RRI - Rattlesnake Ridge Interbed, Ellensburg Formation; P - Pomona; R - Esquatzel; U - Umatilla; Mi - Mabton sedimentary interbed; PR- Priest Rapids; R - Roza; F - Frenchman Springs

tain and why the ridge changes elevation along the trace. Figure 18 shows a diagrammatic cross section through the highest portion of Rattlesnake Mountain.

This locality provides an excellent view of the north flank of one of the largest of the Yakima anticlines, Rattlesnake Mountain (Fig. 19). All basalt flows encountered in boreholes at Hanford thin onto Rattlesnake Mountain; this is interpreted to mean that Rattlesnake Mountain was growing during the eruption of the Columbia River basalt. The present relief developed in the last 10.5 m. y. but geologic and geophysical data show that even more structural relief on Rattlesnake Mountain is buried by the younger flows (Reidel et al., 1989b). The prominent bench just below the crest marks the Wanapum-Saddle Mountains Basalt contact and is erosional. A sedimentary unit, the Mabton interbed, which has eroded back into the hillside, marks the contact. The main fault runs along the base of the mountain but sediments cover the fault. 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. This is typical on most Yakima folds where the ridge is segmented and each segment is defined by a distinct structural style. The structurally higher segments are usually the result of the development of a second thrust fault where the basalt ramps up onto steeply dipping basalt.

Stop 16. Snively Basin View. Farther to the northwest along the Rattlesnake trend, Snively Basin has over 4 km of shortening but is lower in elevation. Here the thrust fault wedges are 'stretched' out rather than stacked.
Stop 17. Umtanum Ridge view at Priest Rapids Dam. Continue along SR 240 over the Columbia River until you see the turn off for Priest Rapids Dam. Drive down the road and park where you have a good view of the ridge. Umtanum Ridge extends about 110 km from near the western margin of the Columbia Basin to the Palouse Slope. The structural relief gradually decreases eastward where it becomes a series of en echelon anticlines developed along the dying ridge. In the Priest Rapids Dam area the north limb is over turned and dips 40 degrees to the south (Fig. 20). An upper thrust, the Buck thrust and a lower thrust, the Umtanum thrust define the overturned portion of the fold (Price and Watkinson, 1989). The Buck thrust merges with the Umtanum thrust fault to the east as the overturned portion becomes steeply dipping to the north. Drilling has constrained the fault to between 30 and 60 degrees to the south.

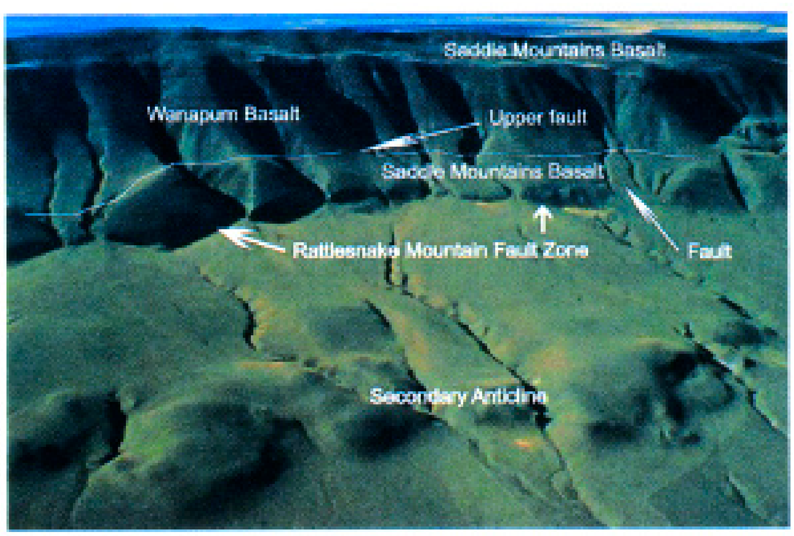
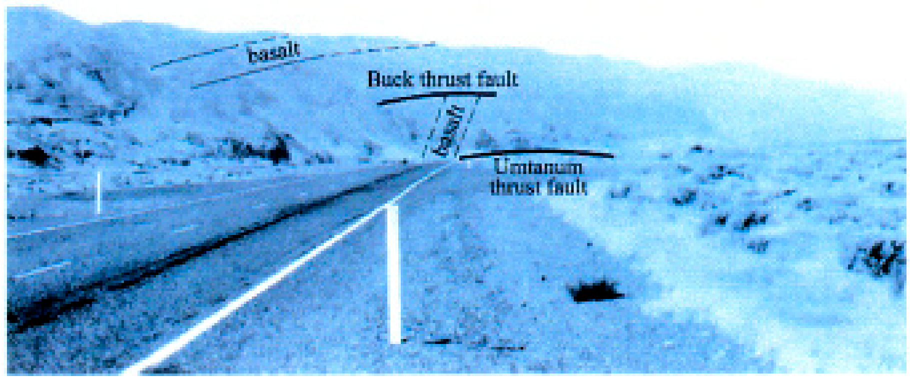


Figure 19. Main geologic features on Rattlesnake Mountain.

Figure 20. View of Umtanum Ridge structure from SR 240 east of Priest Rapids Dam.



E N D   O F   F I E L D   T R I P   G U I D E

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