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Late Cenozoic Structure and Stratigraphy of South-Central Washington

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ABSTRACT

The structural framework of the Columbia Basin began developing before Columbia River Basalt Group (CRBG) volcanism. Prior to 17.5 Ma, the eastern part of the basin was a relatively stable area, with a basement of Paleozoic and older crystalline rock. The western part was an area of subsidence in which large volumes of sediment and volcanic rocks accumulated. The boundary between the two parts is a suture zone between the stable craton and accreted terranes.

Concurrent with eruption of the CRBG, anticlinal ridges of the Yakima Fold Belt (YFB) were growing under north-south compression. Topographic expression of these features, however, was later masked by the large volume of CRBG basalt flowing west from fissures in the eastern Columbia Basin. The folds continued to develop after cessation of volcanism (ca. 6 Ma), leading to as much as 1,000 m of structural relief in the past 10 million years. Rates of subsidence and fold growth in the Columbia Basin decreased from the Miocene to Recent. Shortening across the entire YFB probably does not exceed 25 km.

Post-CRBG evolution of the Columbia Basin is recorded principally in folding and faulting in the YFB and sediments deposited in the basins. The accompanying tectonism resulted in lateral migration of major depositional systems into subsiding structural lows.

Although known late Cenozoic faults are on anticlinal ridges, earthquake focal mechanisms and contemporary strain measurements indicate most stress release is occurring in the synclinal areas under north-south compression. There is no obvious correlation between focal mechanisms for earthquakes whose foci are in the CRBG and the location of known faults.

High *in situ* stress values help to explain the occurrence of microseismicity in the Columbia Basin but not the pattern. Microseismicity appears to occur in unaltered fresh basalt. Faulted basalt associated with the YFB is highly brecciated and commonly altered to clay. The high stress, abundance of ground water in confined aquifers of the CRBG, and altered basalt in fault zones suggest that the frontal faults on the anticlinal ridges probably have some aseismic deformation.

INTRODUCTION

The Columbia Basin is an intermontane basin between the Cascade Range and the Rocky Mountains that is filled by Cenozoic volcanic rocks and sediments. This basin forms the northern part of both the Columbia Plateau physiographic province (Fenneman, 1931) and the Columbia River flood-basalt province (Reidel and Hooper, 1989).

Within the Columbia Basin are four structural subdivisions or subprovinces (Fig. 1). The Yakima Fold Belt (YFB) is a series of anticlinal ridges and synclinal valleys in the western and central parts of the basin. Structural trends range from northwest to northeast but are predominantly east-west. The Palouse Slope forms the eastern subprovince of the basin; it shows little deformation, with only a few faults and low-amplitude, long-wavelength folds on an otherwise gently westward-dipping paleoslope (Swanson and others, 1980). A third subprovince, the Blue Mountains, forms the southern border of the Columbia Basin. It

is a northeast-trending anticlinorium that extends 250 km from the Oregon Cascades to the eastern part of the Columbia Basin. The easternmost part of the basin constitutes the fourth subprovince and will not be discussed in this paper.

In the central and western parts of the Columbia Basin, the Columbia River Basalt Group (CRBG) overlies Tertiary continental sedimentary rocks and is overlain by younger Tertiary and Quaternary fluvial and glaciofluvial deposits (Campbell, 1989; Reidel and others, 1989b; Smith and others, 1989; U.S. Department of Energy, 1988). In the eastern part, a thin (<100 m) sedimentary unit separates the basalt and underlying crystalline basement and a thin (<50 m) veneer of eolian sediments overlies the basalt (Reidel and others, 1989b).

In this paper, we discuss the Late Cenozoic structure and stratigraphy of the Columbia Basin. We focus largely on the period following eruption of the last voluminous flood-basalt flows of the Saddle Mountains Basalt, those of the Elephant Mountain Member (10.5 Ma). However, we

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Figure 1. The Columbia Basin. Shown are the areal extent of the Columbia River Basalt Group, the four major structural-tectonic subprovinces, the Pasco Basin, and the Olympic-Wallowa lineament.

trace the development of the Columbia Basin from before the CRBG eruptions to the present because tectonic events that occurred during this time are closely related.

STRATIGRAPHY

The generalized stratigraphy of the Columbia Basin is shown in [Figure 2](#) and summarized in [Table 1](#). Most of the rocks exposed in the basin are the CRBG, intercalated sedimentary rocks of the Ellensburg Formation, and younger sedimentary rocks that include the Ringold Formation, Snipes Mountain conglomerate, Thorp Gravel (not shown on [Fig. 2](#)), the Hanford formation, and other localized strata. In this report, the Hanford formation includes all deposits of cataclysmic Pleistocene floods, including those from glacial Lake Missoula and the Columbia River system.

Stratigraphy Older than the Columbia River Basalt Group

Rocks older than the CRBG are exposed along the margin of the Columbia Basin. Their stratigraphy is complex and varies widely in both age and lithology (Campbell, 1989). Along the northwest margin, a series of sedimentary basins formed in early Tertiary time (Tabor and others, 1984; Campbell, 1989). These basins are now separated by tec-

tonic "blocks" or uplifts that expose pre-Tertiary rocks and have a north-west-trending structural grain.

Along the northeast and east margins of the Columbia Basin, the CRBG laps onto Paleozoic rocks and Precambrian metasedimentary rocks interspersed with crystalline rocks. These include: Proterozoic metasedimentary rocks of the Windermere Group and Belt Supergroup, miogeosynclinal lower Paleozoic shallow marine rocks, rocks associated with the Kootenay arc, granitic rocks of the Idaho Batholith, and other Jurassic and Cretaceous intrusions (Stoffel and others, 1991). The structural grain of these rocks is north to northeast.

To the south and southwest, lower to middle Tertiary (Paleogene)

volcanic rocks and related volcanoclastic rocks directly underlie the CRBG. The rocks include tuffs, lahars, and tuffaceous sedimentary rocks interbedded with rhyolite, andesite, and basalt flows and breccias; these are primarily assigned to the Clarno and John Day Formations. Older (Permian-Cretaceous) volcanoclastic sedimentary rocks and metasedimentary rocks of accreted intra-arc and volcanic-arc origin are exposed along the southeast margin of the CRBG (Walker and MacLeod, 1991).

To the west, younger volcanic rocks erupted from the High Cascades cover the CRBG and obscure the older rocks. Rare inliers of older Paleozoic rocks, such as the Rimrock inlier, are exposed as erosional windows in younger volcanic rocks.

Sedimentary rocks related to those along the northwest margin are thought to be present under the interior of the Columbia Basin. However, units exposed along the north, east, and south margins of the CRBG probably contributed to the sedimentary package because they were extensively eroded by west-flowing rivers (Fecht and others, 1987) and their deposits accumulated in the subsiding western part of the basin.

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Table 1. Stratigraphic units and characteristics. Palouse Formation, Latah Formation, and other loess deposits not included

Unit	Age	Thickness	Distribution	Lithology	Stratigraphic trends	Tectonic implications
Columbia River Basalt Group	17.5 Ma–6 Ma	as much as 4 km in central Columbia Basin	Extent defines the Columbia Plateau	Tholeiitic flood-basalt flows	Older, more voluminous units cover entire area; younger, thinner units occur in eastern and central Columbia Basin	Records stability in the eastern Columbia Basin, subsidence in the central and western basin, and Miocene uplift of anticlinal ridges
Upper Ellensburg Formation (Fecht and others, 1987; Smith, 1988)	10 Ma–4.72 Ma ±0.28	as much as 350 m in Yakima Basin	Nile, Selah, Yakima, Kittitas, and Satus and Toppenish basins; also in Goldendale area	Basalt sidestream gravels, lahars, and volcaniclastic sediments derived from Cascade Range, siliciclastics deposited by Columbia River	Volcaniclastic sediments most common in west; siliciclastic sediments in east; gravels record channel system positions	Shifting channel deposits reflect displacement of river courses caused by ridge uplift and basin subsidence, especially Yakima River and Columbia River southwest of Pasco Basin
Snipes Mountain Conglomerate (Schminke, 1964; Fecht and others, 1987; Smith, 1988)	<8.5 Ma–8.5 Ma	30–150 m	Lower Yakima valley and across western Horse Heaven Hills; also east Toppenish basin	Quartzose gravel and siliciclastic sands; interbedded volcaniclastic sediments common in eastern Toppenish Basin	Linear channel tracts from Sunnyside Gap up Moxee and Yakima valleys and then across Horse Heaven Hills to Goldendale area	Records Columbia River course prior to diversion into Pasco Basin
Ringold Formation (Fecht and others, 1987; Lindsey, 1991a, b)	<8.5 Ma–>3.4 Ma	as much as 185 m	Pasco Basin, north side of Saddle Mountains, and Walla Walla basin	Fluvial gravels and sands, overbank deposits, lacustrine deposits, and alluvial fan deposits	Gravelly alluvial tracts mixed with basin-wide overbank systems dominate lower part of section; sharply overlain by a sandy alluvial system that, in turn, grades up-section into cyclic lacustrine deposits	Records initial post CRBG Columbia River deposits in Pasco Basin, shifting channel courses reflect syndepositional uplift on basin margins; large lakes reflect regional changes in river gradients
Lake deposits overlying Snipes Mountain Conglomerate (Smith, 1988)	<4.7 ±0.3 Ma	more than 30 m	Lower Yakima valley near Sunnyside and Granger and on Ahtanum Ridge	Laminated silts and fine-grained sandstone	Equivalent to upper Ellensburg Formation; laterally correlative with upper Ringold lake deposits(?)	Large lakes form as a result of regional gradient changes
Thorp Gravel (Watt, 1979; Bentley and Campbell, 1983; Campbell, 1983; Fecht and others, 1987; Smith, 1988)	<3.64 ±0.74 Ma to 3.7 ±0.2 Ma	as much as 200 m	Kittitas and Selah basins, and south into Yakima basin as far as Toppenish	Basaltic sidestream gravels and poly-mictic mainstream gravels deposited as an alluvial wedge off the Cascades	Old terraces of the Yakima River	Record uplift and erosion of Cascades and Yakima folds.
Pliocene and Pleistocene strata (U.S. Dept. of Energy, 1988; Baker and others, 1991)	<3.5–~1 Ma	as much as 10 m	Regional distribution in basins and on uplifts	Pedogenic carbonates, basaltic alluvium, eolian deposits, multilithologic quartzose gravels	Unconformably overlies middle Pliocene and older (>3.5 Ma) strata; discontinuous horizons in and around basins and uplifted on ridges	Deposited after post-3.5 Ma base-level change that led to regional incision of main rivers; records more recent uplift of anticlinal ridges
Hanford formation (Fecht and others, 1987; Baker and others, 1991)	<1 Ma–~12 ka	as much as 70 m	Pasco Basin, Toppenish, Yakima, and Walla Walla basins, and flood deposits throughout the Columbia Basin	Pebble to boulder gravel, sand, and laminated silts deposited by cataclysmic flood waters released from glacial Lake Missoula	Common throughout region, mostly below elevations of approximately 1200 ft	Strata locally offset by faults recording Pleistocene deformation
Quaternary alluvium (Baker and others, 1991)	<2 Ma	0 to 75 m	Regional	Locally derived alluvial and colluvial deposits	Laterally discontinuous strata common on basin margins and on uplifted ridges	Folded and faulted deposits record neotectonic deformation in region

Figure 2. Diagrammatic representation of the Columbia River Basalt Group and younger sedimentary units of the central Columbia Basin. Emphasis is on the post-basalt rocks. Not to scale.

Columbia River Basalt Group and Ellensburg Formation

The CRBG consists of 174,000 km³ of tholeiitic flood-basalt flows that were erupted between 17.5 and 6 Ma. It now covers approximately 164,000 km² of eastern Washington and Oregon and western Idaho (Tolan and others, 1989). Eruptive units have volumes as great as 5,000 km³ (Reidel and others, 1989a; Reidel and Tolan, 1992). These flows are the structural framework of the Columbia Basin, and their distribution pattern reflects the tectonic history of the area (Reidel and others, 1989b).

Intercalated with, and in some places overlying, the CRBG are epiclastic and volcanoclastic sedimentary rocks of the Ellensburg Formation (Waters, 1961; Swanson and others, 1979a; Smith, 1988). Most volcanoclastic material

occurs in the western basin; in the central and eastern basin, epiclastic deposits of the ancestral Clearwater and Columbia Rivers form the dominant lithologies (Fecht and others, 1982, 1987).

Post-Columbia River Basalt Stratigraphy

Most post-CRBG sediments are confined to the synclinal valleys of the YFB. The sedimentary record is incomplete, but it is a direct reflection of the structural development of the Columbia Basin (Fecht and others, 1987). The upper Miocene to middle Pliocene record of the Columbia River system in the Columbia Basin is represented by the upper Ellensburg Formation, Ringold Formation, and Snipes Mountain conglomerate. The Thorp Gravel (≈ 3.7 Ma) river terrace deposits record the post-CRBG history of the upper Yakima River (Waitt, 1979; Campbell, 1983). Except for local deposits (for example, the "Pliocene-Pleistocene unit" and the "early Palouse soil" [U.S. Department of Energy, 1988]), there is a hiatus in the stratigraphic record between the end of the Ringold (3.4 Ma) and Thorp Gravel (≈ 3.7 Ma) deposition and the Pleistocene (1.6 Ma) deposits. Pleistocene to Holocene sediments overlying the CRBG include: flood gravels and slackwater sediments of the Hanford formation; terrace gravels of the Columbia, Snake, and Yakima Rivers; and, in eastern Washington, eolian deposits including the Palouse Formation (Keroher and others, 1966).

GEOLOGIC STRUCTURES OF THE COLUMBIA BASIN

Structural Setting

The major structural features that underlie the Columbia Basin are exposed along its west and north margins (Fig. 3). Major structures along the western margin have been discussed by Campbell (1988, 1989) and Tabor and others (1984); those along the north margin are discussed in the compilation by Stoffel and others (1991). All these features are older than the CRBG, and it is not clear how many of them extend under the CRBG. Those structural features that we consider important to understanding the Columbia Basin and are known to extend into or cross the Columbia Basin interior are summarized below.

The Olympic-Wallowa Lineament

The Olympic-Wallowa lineament (OWL) is a major topographic feature in Washington and Oregon that crosscuts the Columbia Basin (Raisz, 1945; Fig. 1). This feature parallels prebasalt structural trends along the northwest margin of the Columbia Basin, but it has not been linked to any individual structure (Campbell, 1989; Reidel and Campbell, 1989). Within the YFB, the OWL includes a zone of Miocene and post-Miocene deformation along Manastash Ridge and apparent bending of Umtanum Ridge, Yakima Ridge, and Rattlesnake Ridge (the ridge immediately south of Yakima Ridge) (Fig. 3).

The portion of the OWL that crosses the Columbia Basin is called the Cle Elum-Wallula deformed zone (CLEW;

Figure 3. Major geologic features in the Columbia Basin. Shown are the Hog Ranch-Naneum Ridge anticline, the Olympic-Wallula lineament (OWL), and major surface structures. Also shown are the inferred locations of major subbasalt structural features and the proposed edge of the continental craton.

Kienle and others, 1977). It is a 10-km-wide, moderately diffuse zone of anticlines that have a N50°W orientation (Fig. 3). As defined by G. A. Davis (*in* Washington Public Power Supply System, 1981a), the CLEW consists of three structural parts: (1) a broad zone of deflected or anomalous fold and fault trends extending south from the northwest part of Manastash Ridge (in the Cascade foothills near the edge of the CRBG) to Rattlesnake Mountain; (2) a narrow belt of topographically aligned domes and doubly plunging anticlines extending from Rattlesnake Mountain to Wallula Gap, where the OWL crosses the Columbia River (a zone commonly called the Rattlesnake-Wallula alignment or

RAW); and (3) the Wallula fault zone, extending from Wallula Gap southeast to the Blue Mountains.

Northwest of the CRBG margin, numerous northwest- and north-trending faults and shear zones of the Straight Creek fault system lie subparallel to the OWL (Tabor and others, 1984). The Snoqualmie batholith intrudes these faults but is not cut by them, indicating that any movement along the OWL at the western margin of the Columbia Basin must be older than the batholith, 17 to 19.7 Ma (Frizzell and others, 1984).

The structural significance of the OWL has been called into question by two recent geophysical studies. Neither a

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Table 2. Characteristics of anticlinal ridges; $\bar{x}$ = mean; σ = 1 standard deviation; R = range; NK = not known; best approximation. * structural relief on youngest basalt

Anticline	Length/ width	Relief* (maximum)	Trend	Number of segments	Segment length	Vergence	Amount of shortening	Geometry
Beezley Hills– Beezley Coulee	160 km/ 5 km	430 m	230°	4	$\bar{x}=40$ $\sigma=20$ R=30 to 70	S	NK; <2 km	Asymmetrical, monoclinial
Badger Hills– Moses Stool	50 km/ 5–15 km	300 m	220°	1	---	N	NK; <2 km	Asymmetrical, monoclinial
Frenchman Hills	100 km/ 5–10 km	200 m	90°–100°	7	$\bar{x}=14$ $\sigma=10$ R=7 to 35	N	NK; <2 km	Asymmetrical, gentle to open
Saddle Mountains	110 km/ 5–10 km	550 m	90°–115°	6	$\bar{x}=14$ $\sigma=10$ R=5 to 20	N	>3 km	Asymmetrical, gentle to open, box fold
Manastash Ridge–Thrall structure	55 km/ 5–10 km	370 m	120°	4	$\bar{x}=12$ $\sigma=2.5$ R=10 to 15	N	NK; >3 km	Asymmetrical, gentle to open,
Umtanum Ridge	110 km/ 3–10 km	520 m	90°–130°	9	$\bar{x}=11$ $\sigma=4.2$ R=5 to 17	N	1–3 km	Asymmetrical, tight to open, en echelon segments east end
Cleman Mountain	35 km/ 8 km	950 m	130°	2	$\bar{x}=18$ $\sigma=8$ R=13 to 23	S	NK; >1 km	Asymmetrical
Yakima Ridge	100 km/ 5–10 km	550 m	135°–225°	12	$\bar{x}=12$ $\sigma=8$ R=5 to 30	N	NK; >3 km	Asymmetrical, gentle to open, en echelon segments, box fold segments
Rattlesnake Mountain and "rattles"	85 km/ 5–20 km	800 m	310°	11	$\bar{x}=9$ $\sigma=6$ R=5 to 25	N	NK; >3 km	Asymmetrical, tight to open, faulted out hinge, doubly plunging
Rattlesnake– Ahtanum Ridge	100 km/ 5–8 km	610 m	238°–108°	11	$\bar{x}=9$ $\sigma=4$ R=5 to 18	N	NK; >1 km	Asymmetrical, gentle to open
Toppenish Ridge	85 km/ 4–8 km	500 m	118°–258°	5	$\bar{x}=17$ $\sigma=7$ R=10 to 28	N	NK; >1 km	Asymmetrical, tight to open
Snipes Mountain	13 km/ 1 km	150 m	110°	3	13 km	S	NK; <1 km	Asymmetrical, tight to open
Horse Heaven Hills	185 km/ 5–30 km E; 2–7 km W	335– 1100 m	115°–255°	21	$\bar{x}=17$ $\sigma=5$ R=5 to 20	N	>2 km; (0.67– 1.25 km)	Asymmetrical, tight to open, en echelon subsidiary crest folds, box folds
Columbia Hills	170 km/ 5–10 km	250– 365 m	255°	10	$\bar{x}=15$ $\sigma=6$ R=6 to 23	S	NK; >2 km	Asymmetrical, tight to open doubly plunging, en echelon subsidiary crest folds, box folds

seismic profiling survey by Jarchow (1991) nor a gravity survey by Saltus (1991) could find any obvious geophysical signature of the OWL below the CRBG.

Hog Ranch–Naneum Ridge Anticline

The Hog Ranch–Naneum Ridge (HR–NR) anticline is a broad south-trending anticline in the CRBG that crosses the YFB at a nearly right angle. The anticline begins at the north basalt margin on Naneum Ridge (at the south end of the Stuart block and southwest of the city of Wenatchee), trends southeast for about 12 km and then turns south toward Prosser, WA, where it separates the Toppenish basin to the west from the Pasco Basin. This south-plunging structure passes through five Yakima folds and the OWL. A gravity gradient and a series of gravity highs delineate part of the anticline in the subsurface. The southern extension of the anticline appears to be a Bouguer gravity high near the Washington–Oregon border southeast of Prosser.

The HR–NR anticline was active in middle to late Miocene time, as demonstrated by thinning of basalt flows across it (Reidel and others, 1989b). However, the east-trending Yakima folds show no apparent offset by the cross structure (Campbell, 1989; Tabor and others, 1982; Kienle and others, 1977; Reidel and others, 1989b), nor is the HR–NR anticline offset where the OWL–CLEW crosses it. Growth of the HR–NR anticline continued from the Miocene to the present time and is now delineated by the highest structural points along the ridges that cross it.

White River–Naches River Fault Zone

The White River–Naches River Fault Zone (WR–NRFZ) (Fig. 3), a major fault zone that extends 90 km from Naches to Enumclaw, WA, separates two domains of dissimilar structure, stratigraphy, and topography (Campbell, 1988, 1989). To the northeast, structures strike N60°W; to the southwest, structures in pre-Tertiary rocks trend N5°E to

Table 3. Characteristics of major faults; NK = not known (best approximation)

Fault zone	Length	Trend	Horizontal offset	Vertical offset	Sense of movement; fault-plane dip	Age of last movement
CLEW	290 km	310°	0-4 km	0-800 m	mainly reverse	Quaternary; see Table 4
RAW (includes Wallula Fault Zone)	125 km	310°	0-4 km	0-800 m	mainly reverse/some possible strip-slip	Quaternary; see Table 4
Hite fault system	135 km	330°-335°	NK	NK; 0-900 m	vertical, en echelon, and strike-slip	Holocene (1936 Milton-Freewater earthquake); see Table 4
Frenchman Hills	100+ km	270°-280°	>300 m	-200 m	reverse, thrust; >45°S	>500,000 yr
Saddle Mountains	100 km	270°-285°	>2.5 km	600 m	reverse; >60°S	<3.4 Ma, Quaternary-Holocene?
Manastash-Hansen Creek	70 km	300°	<1 km	-300 m	reverse, thrust	>1 to 3.4 Ma
Umtanum	110 km	270°-310°	>300 m	1500 m	reverse, thrust; 30-70°S	<13,000 yr
Clemon Mountain	207 km	310°	NK	-900 m	reverse, thrust; N	Unknown
Yakima Ridge	120+ km	225°-45°	NK	-500 m	reverse, thrust; S, locally N	<1 Ma
Rattlesnake-Ahtanum Ridge	100 km	58°-315°	NK	-800 m	reverse, thrust; S	>13,000 yr
Toppenish Ridge	65-90 km	258°-298°	NK	-500 m	reverse, thrust; S	Holocene; see Campbell and Bentley (1981)
Horse Heaven Hills	200+ km	245°-295°	NK	-335-1100 m	reverse, thrust; S	Unknown
Columbia Hills	160 km	245°	NK; 1 km	-365 m	reverse, thrust; 70°N	Unknown
Northwest-trending faults	40-120 km	320°	<100 m	<100 m	strike-slip, vertical (dip reversal)	Holocene

N20°W. The WR-NRFZ probably extends under the basalt at least as far as Konnowoc Pass (Fig. 3) and either parallels or crosscuts the HR-NR anticline. The WR-NRFZ is the major structure trending into the Columbia Basin that can be demonstrated to be a fundamental structural boundary in rock below the CRBG.

Leavenworth Fault Zone

The Leavenworth fault is part of a fault zone that consists of a series of northwest-trending high-angle faults and associated tight folds that marks the southwest side of the Chiwaukum graben (Fig. 3). At the basalt margin, the fault passes southeast under the CRBG in alignment with the HR-NR anticline. The Leavenworth fault is assumed to continue under the basalt along the HR-NR anticline and to have been a factor in its development (Campbell, 1989). Saltus (1991), however, suggests it does not continue underneath the basalt.

Other Structures Marginal to the Columbia Basin

Other major structures including the Entiat fault, Methow, Republic, and Keller grabens, and numerous faults associated with the Kootenay Arc appear to die out or their magnitude is significantly reduced before reaching the basalt margin. Therefore, we do not consider them significant tectonic elements in the Columbia Basin.

Northwest-Trending Wrench Faults

A series of northwest-trending, dextral strike-slip wrench faults is present in the CRBG west of 120° longitude and the HR-NR anticline (Newcomb, 1969, 1970; Shannon & Wilson, Inc., 1973; Bentley and others, 1980; Swanson and others, 1979a, 1981; Anderson, 1987). These are conjugate and en-echelon faults and genetically related en-echelon folds that have a mean strike of N40°W. Many can be traced for more than 100 km but do not extend beyond the CRBG. These wrench faults cross and offset several Yakima folds, but they do not appear to have more than 100 m total displacement (Anderson, 1987).

The Yakima Folds

The YFB subprovince covers about 14,000 km² of the western Columbia Basin (Fig. 1) and formed as basalt flows and intercalated sediments were folded and faulted under north-south-directed compression. The reader is referred to Tables 2 and 3 and the recent compilation of structural features for the Columbia Basin by Tolan and Reidel (1989), which updates plate II-20 of Myers, Price and others (1979).

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 of the Saddle Mountains Basalt (Fig. 2), buried much of the

Figure 4. North-south and generally east-west cross sections through the central Columbia basin (modified from Reidel and others, 1989b).

central Columbia Basin. The main deformation is concentrated in the YFB; there is only minor deformation on the Palouse Slope.

The YFB consists of anticlinal ridges separated by synclinal valleys. The folds are typically segmented, and most have north vergence. However, some anticlines, such as Columbia Hills, Cleman Mountain, and a few segments of other ridges, have a south vergence. Fold length ranges from 1 to more than 100 km; fold wavelengths range from several kilometers to as much as 20 km (Table 2). The folds are segmented by crosscutting faults and folds (Reidel, 1984; Reidel and others, 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 HR-NR anticline (Fig. 3).

Anticlines of the Yakima Fold Belt have various trends, ranging from N50°W through east-west to N50°E. Abrupt changes in trend occur along individual anticlines at segment boundaries, giving these anticlines a disjointed appearance along their length. This is most apparent where anticlines cross the zone of the CLEW. On a regional scale, parts of the fold belt typically have dominant directional trends. The anticlines lying within the CLEW zone typically trend N50°W (Fig. 3). However, anticlines southwest of the CLEW have a dominant N50°E trend (Swanson and others, 1979b; Reidel and others, 1989b; Tolan and Reidel, 1989) (Fig. 3), and the trend of anticlines northeast of the CLEW, such as the Saddle Mountains and Frenchman Hills, is dominantly east-west. Anticlines that extend across the entire fold belt, such as Umtanum and Yakima Ridges, have varied trends that reflect the dominant trends of the areas they cross.

Although the faults are rarely exposed, nearly all the steep forelimbs of the asymmetrical anticlines are faulted. These frontal fault zones (Fig. 4) typically consist of imbricated thrusts (Bentley, 1977; Goff, 1981; R. D. Bentley in

Swanson and others, 1979b; Hagood, 1986; Reidel, 1984, 1988; Anderson, 1987) that are emergent at ground surface. The tops of lava flows at ground surface become the planes of low-angle thrust faulting. Where erosion provides deeper exposures, these frontal faults are shown to be steep reverse faults: the fault in the Columbia water gap in the Frenchman Hills dips 45 degrees south (Grolier and Bingham, 1971), and the fault in the Columbia Hills at Rock Creek, WA, dips 50–70 degrees north (Swanson and others, 1979b).

Hydrocarbon exploration boreholes provide direct evidence for the dips of these frontal faults. Reidel and others (1989b) have shown that the Saddle Mountains fault must dip more than 60 degrees where the Shell-ARCO BN 1-9 borehole was drilled (Fig. 3). Drilling through the Umtanum fault near Priest Rapids Dam suggests that this fault dips at least 30 degrees (Puget Sound Power and Light, 1982) but perhaps as steeply as 60 degrees southward under the ridge (Price, 1982; Price and Watkinson, 1989).

Total shortening across the YFB is less than 25 km (Reidel and others, 1989b), or about 5 percent of the fold belt width. Crustal shortening is difficult to estimate, however. Typically, shortening caused by folding is 1 to 1.5 km, but the amount of shortening caused by faulting is generally unknown. Estimates for shortening due to faulting alone range from several hundreds of meters to as much as 4 km (Table 3).

Typical synclines are structurally low areas formed between the gently dipping limb of one anticline and the steeply dipping limb of another. The steep limb was thrust up on the gently dipping limb of the neighboring anticline to form the syncline. Few synclines were formed by simple synclinal folding of the basalt.

THE PRE-MIDDLE MIOCENE COLUMBIA BASIN

The Columbia Basin as we now see it reflects structural elements that formed prior to flood-basalt volcanism. This

section of our paper provides an interpretation of the structural setting of the Columbia Basin prior to the eruption of the CRBG. Our interpretation is based on data from the last two decades of geophysical surveys and from deep hydrocarbon exploration boreholes in the Columbia Basin, both combined with our field observations.

The YFB and Palouse Slope overlie the two major pre-CRBG structural features of the Columbia Basin (Reidel and others, 1989b). The YFB lies on a large pre-basalt basin filled with as much as 7,000 m of continental sediments. The Palouse Slope subprovince overlies a crystalline basement high; only a thin (<100 m) discontinuous sediment package separates the basalt and basement.

The crystalline basement underlying the Palouse Slope (Fig. 4) has been penetrated by two boreholes (the Darcell and Basalt Explorer, Fig. 3). This basement is essentially metasedimentary rock composed of quartz, feldspar, and mica. It resembles the Addy Quartzite and certain Precambrian Belt Supergroup rocks. We interpret this basement to be part of the old continental craton that has remained fairly stable except along its west and south margins. Mohl and Theissen (1989) extended the southern boundary by extrapolating gravity data from Lewiston, ID, as far west as Pomeroy, WA (Mohl, 1985). The rock penetrated by the Darcell borehole (Fig. 3) indicates that the craton must also extend west and south from Pomeroy. We suggest that the trace of the southern cratonic margin is reflected at the surface by the Hite fault zone (Fig. 3), the major fault system that forms the western margin of the Blue Mountains between Pomeroy and Pendleton, OR, and has been the locus of many historic earthquakes (U.S. Department of Energy, 1988).

The YFB is underlain by a thick sequence of sediments that was first recognized in deep hydrocarbon exploration boreholes (Campbell and Banning, 1985). On the basis of seismic refraction survey data, Catchings and Mooney (1988) interpret this as a failed rift basin. Other studies using additional geophysical data sets (Rohay and Malone, 1983; Rohay and others, 1985; Glover, 1985; Zervas and Crosson, 1986), however, question this interpretation. These studies do not "see" any deep crust or mantle evidence for a failed rift basin.

The pre-CRBG basin above the crystalline basement is filled with deposits consisting primarily of Paleocene and Eocene continental sediments and some Oligocene volcanoclastic sediments (Campbell and Banning, 1985; Campbell, 1989). Reidel and others (1989b) interpreted the suture zone between the pre-CRBG basin and craton to coincide with the Ice Harbor dike swarm (Fig. 4). They also interpreted the location of the dike swarm to have been controlled by this fundamental crustal boundary. Reidel and others (1992) suggested that this boundary is the suture zone between the continental craton and accreted terranes. Furthermore, they suggested that the suture is oriented approximately N10°W and is marked at the surface by the Ice Harbor dikes and the boundary between the Saddle Gap and Eagle Lakes segments of the Saddle Mountains (Reidel,

1984, 1987). This location is also marked by the prominent aeromagnetic anomaly shown by Swanson and others (1979c) for the Ice Harbor dike swarm and that extends as far south as the east side of Wallula Gap. This boundary between craton and basin may cross the CLEW and intersect the structurally similar Hite fault boundary near Pendleton, OR.

The HR-NR anticline parallels the eastern margin of the pre-CRBG basin and appears to divide it into two parts. Campbell and Banning (1985) have interpreted pre-CRBG rocks under the HR-NR anticline as part of a horst, but results from a recent seismic profile (Jarchow, 1991) suggest that the HR-NR anticline may not involve basement. We suggest that the Pasco Basin is underlain by a northwest-trending graben between the HR-NR anticline and the suture zone. The western graben fault may only involve the basalt and sediment and not the basement rock. Tertiary sedimentary and volcanoclastic rocks west of the HR-NR anticline extend beyond the margin of the CRBG and form part of the Cascade Range. The western basin margin is not faulted, as implied by the rift model of Catchings and Mooney (1988); the pre-CRBG sedimentary rocks continue across the present Cascade Range and were arched upward with the Cascade Range to form the present western boundary of the Columbia Basin. This model is supported by geophysical studies (Rohay and Malone, 1983; Rohay and others, 1985; Glover, 1985; Zervas and Crosson, 1986) suggesting that the Columbia Basin is not a failed rift basin but perhaps simply a back-arc basin.

The Blue Mountains uplift forms the southern boundary of the pre-CRBG basin, although the boundary is not precisely located. The boundary may lie near the present Blue Mountains crest because a thick sequence of sedimentary rock lies north of the crest below the basalt near the Washington-Oregon border (Fox and Reidel, 1987). We interpret this boundary to coincide with Beeson and others' (1989) east-trending Columbia Transarc lowland (Fig. 3) that forms the low area extending along the Washington-Oregon border through the Columbia Gorge. The Columbia Transarc lowland and the pre-CRBG basin combine to produce an apparent northeast-trending trough through the Columbia Basin. The thickest pre-CRBG sediment package lies along this trend; in addition, more CRBG flows are found along the trough than elsewhere in the basin. The lowland was the main pathway for CRBG lavas flowing between the vent area and western Oregon and Washington (Reidel and Tolan, 1992).

THE MIDDLE MIOCENE COLUMBIA BASIN

Borehole, geophysical, and stratigraphic data (Bergstrom and others, 1987; Catchings and Mooney, 1988; Reidel and others, 1989b) indicate that the CRBG thins onto the Palouse Slope and thickens into the YFB (Fig. 4). The CRBG ranges from 500 to 1,500 m thick on the Palouse Slope, but it abruptly thickens to as much as 4,000 m in the Pasco Basin area (Reidel and others, 1982, 1989b). Regional thickness patterns for both the CRBG and underlying Ter-

Figure 5. Generalized evolution of the Columbia River system in the central Columbia Basin during the late Miocene and Pliocene (Modified from Fecht and others, 1987). (A) Snipes Mountain time approximately 10.0 to 8.0 Ma. (B) Approximately 8.0 to 6.0 Ma. (C) After 6.0 Ma.

approximately 1 cm/yr initially and decreased to 3×10^{-3} cm/yr in the late Miocene (Reidel and others, 1989b).

During the eruption of the CRBG, the anticlinal ridges were topographic highs against which the basalt flows thinned with elevation during emplacement (Reidel, 1984; Reidel and others, 1989b; Anderson, 1987). Flow thickness variations provide a means to estimate fold growth rates (Reidel, 1984). The ridges grew at about 0.25 mm/yr during initial eruption of the CRBG (17–15.6 Ma); the rate decreased to about 0.04 mm/yr during the waning phases (15.6–10.5 Ma) (Reidel, 1984; Reidel and others, 1989b).

By the end of the massive eruptions of the CRBG (10.5 Ma), most of the Columbia Basin was a shallow, bowl-shaped, nearly featureless plain. The massive eruptions had buried most of the structural and topographic relief. In the western part of the Columbia Basin, standing above the plain were only the anticlinal ridges not inundated by younger flows. Across this plain flowed the ancestral Columbia River and its main tributaries, including the Salmon–Clearwater, Yakima, and Palouse Rivers.

THE LATE MIOCENE TO MIDDLE PLIOCENE COLUMBIA BASIN

Post-CRBG tectonic history of the Columbia Basin is recorded in the Yakima folds and post-CRBG sediments. Alluvial-lacustrine sediments (Table 1) deposited primarily by the Columbia River system show that the Yakima folds were still growing and displacing river channels (Fecht and others, 1987). The structural evolution, as reflected in these

tertiary sedimentary rocks indicate that the pre-CRBG basin was subsiding relative to the Blue Mountains and Palouse Slope from at least the Paleocene or Eocene through the Miocene. By far the most significant regional tectonic activity was continued subsidence in the basin. The subaerial nature of the CRBG indicates that subsidence continued as long as basalt was being erupted and that basalt accumulation kept pace with subsidence (Reidel and others, 1982, 1989a, 1989b). Subsidence rates from 17 to 15.6 Ma were

Figure 6. Generalized interpretation of the paleogeography of the Pasco Basin during each of the three phases of the Ringold Formation deposition. The first phase (A) ended approximately 6.0 Ma; the second phase (B) approximately 5.0 Ma; and the third phase (C) approximately 3.4 Ma.

sediments, is interpreted from: (1) the lateral distribution of facies, (2) changes in depositional style, and (3) structural deformation.

Lateral Distribution of Facies

Changes in the facies distribution in post-CRBG sediments are one of the best records of the post-CRBG history of the Columbia Basin. Sand and gravel in fluvial channels mark the locations of major drainages. Lesser alluvial fans and sidestream alluvial sequences were deposited adjacent to the main rivers. Ridge uplift and basin subsidence caused lateral shifts in these depositional environments over time (Fecht and others 1987; Smith, 1988; Lindsey, 1991).

During the waning phase of CRBG eruptions (12.5–8.5 Ma), the Columbia River flowed south across the YFB. The post-CRBG pre-Ringold channel (upper Ellensburg Formation and Snipes Mountain Conglomerate) of the Columbia River passed across the western Pasco Basin, entering at Sentinel Gap (Reidel, 1984, 1987) and exiting near Sunnyside Gap (Fig. 5A). From there the river flowed southwest toward Goldendale. At about 8 Ma, the Columbia River began to shift eastward into the central Pasco Basin, occupying a water gap over the eastern end of Rattlesnake Mountain near Benton City (Fecht and others, 1987; Fig. 5B). By middle Ringold time (approximately 6 Ma), the Columbia River had shifted its position again, exiting the Pasco Basin at Wallula Gap (Fig. 5C), as it does now (Fecht and others, 1987).

B

C

Concurrent with the eastward shift in the Columbia River, alluvial wedges deposited in the Yakima River drainage system prograded eastward (Smith, 1988). These wedges are seen in the upper Ellensburg Formation and Thorp Gravel.

Changes in Depositional Style

Three major changes in depositional style are found in the Ringold Formation. Each is marked by rapid, apparently basin-wide transitions. The first change occurred at ap-

Figure 7. In this view to the west, the Ringold Formation overlies the Elephant Mountain Member of the Saddle Mountains Basalt, CRBG, in the Snively Basin area. This outcropping lies on the north side of the Rattlesnake Mountain structure and is part of the frontal fault zone. The Elephant Mountain Member has been thrust north onto the Ringold Formation.

proximately 6 Ma and is seen as a shift from gravelly braidplain and basin-wide paleosol systems of the lower part of the Ringold Formation (Fig. 6A) to the sandy alluvial systems of the middle part (Fig. 6B). The second shift in depositional style, which had occurred by 5.0 Ma, is marked by the replacement of sandy alluvial systems by widespread lacustrine conditions (Fig. 6C). Lacustrine deposits are found throughout the region, including the Yakima Valley (Smith, 1988) and north of the Saddle Mountains (Reidel, 1984, 1987). Lacustrine conditions and Ringold deposition ended with region-wide incision of the Columbia River system beginning approximately 3.4 Ma. Incision resulted in the removal of more than 100 m of Ringold section in the central part of the Pasco Basin. Many of the Pliocene and Pleistocene pedogenic carbonates in sediments overlying the Ringold Formation and found on the anticlinal ridges began to form following initiation of this incision.

These changes in depositional style are inferred to be related to regional factors that led to abrupt changes in gradient in the Columbia River system. The limited evidence available suggests gradients could have been influenced by: (1) changes in uplift rates where the Columbia River crossed the southern extension of the HR-NR anticline; (2) increased Cascadian volcanism in the Columbia River Gorge between 6 and 3 Ma (Tolan and Beeson, 1984; Tolan and others, 1984); (3) upstream changes in detrital input into the Columbia River system; and (4) headward erosion as base level dropped in the lower Columbia River. It is not yet possible to determine precisely which of these factors

(or combinations of factors) influenced the Columbia River.

Distribution of Deformed Post-CRBG Sediments

Uplifted and faulted Ringold and coeval sediments flank most ridges in the central Columbia Basin (Fig. 7; Reidel, 1984, 1987; Reidel and others, 1989b). The elevations at which they are found reflect the amount of structural development on the ridges after the sediments were deposited. Deformed Pliocene and Pleistocene sediments also are found on many ridges.

QUATERNARY AND YOUNGER DEFORMATION IN THE COLUMBIA BASIN

Probably all geologic structures of the Columbia Basin had developed their present relief by the end of the Pleistocene. Evidence for continued growth of the YFB is mainly in the frontal fault zones. Although not common, evidence of Pleistocene faulting has been found at many locations across the YFB (Fig. 8; Table 4). Young faults have been described at Toppenish

Ridge, at Union Gap in Ahtanum Ridge, on Gable Mountain along Umtanum Ridge, in the Columbia Hills anticline, and along the CLEW (Table 4). Age relations are generally poorly constrained, however, but they suggest that faulting has continued since the last cataclysmic flood (approximately 13,000 yr B.P.). The minimum age of this faulting is not known, but no seismically active faults have yet been identified. Younger glaciofluvial sediments of the Hanford formation locally record some of the youngest deformation in the Columbia Basin.

Toppenish Ridge

Campbell and Bentley (1980, 1981) describe a 0.5- to 2.2-km-wide zone of nearly 100 surface ruptures along a 32-km-long segment of the north flank of Toppenish Ridge (Fig. 9). The scarps are subparallel to the ridge trend and range from 0.1 km to 3 km in length. The lowest scarp (Mill Creek) is a thrust fault (Fig. 10), but all other are high-angle normal faults. Individual ruptures have displacements as great as 4 m; organic material in the ruptures yields ^{14}C ages of 505 ± 160 yr and 620 ± 135 yr (Campbell and Bentley, 1981).

Ahtanum Ridge

A Quaternary or younger fault was exposed during highway construction near Union Gap on Ahtanum Ridge (Figs. 8 and 11). A high-angle reverse fault offsets Yakima River terrace gravels by at least 7 m, juxtaposing them against the basalt of Ginkgo, Frenchman Springs Member (N. P. Campbell, in Washington Public Power Supply System, 1981). A questionable U-Th caliche age of 30,000 yr

Figure 8. Location of Quaternary-Holocene faults and possible Quaternary-Holocene faults in the Columbia Basin. See Tables 4 and 5 for descriptions of the faults.

was obtained for the terrace gravels (Campbell, 1983). The fault gouge appears to be capped by undeformed 13,000-yr-old slackwater flood sediments, but exposures 1 km to the east reveal faulted slackwater sediments (N. P. Campbell, unpub. data, 1992).

Umtanum Ridge-Gable Mountain

Glaciofluvial deposits 13,000 years old are offset as much as 6.5 cm by the central Gable Mountain fault (Puget Sound Power and Light, 1982) at the east end of Umtanum Ridge (Fig. 8). This tear fault has a component of reverse movement; it shows increasing offset in progressively older units.

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Table 4. Quaternary-Holocene faults in the Columbia Basin; NK = not known; see Fig. 8 for locations

Fault	Primary structural feature	Age of last movement	Sense of movement	Amount of movement	Location	Source of information
1. Central Ferry	Palouse Slope	Pleistocene?	sinistral oblique-slip	1 to 1.5 m	center sec. 22, T12N, R40E	Foundation Services, Inc. (1980, p. 25)
2. Thom Hollow	Hite Fault System	early Holocene?	strike-slip	not determined	SW¼NE¼ sec. 2, T4N, R35E	Shannon & Wilson, Inc. (1979, p. 28)
3. Buroker	Wallula Fault System	Pleistocene to early Holocene?	thrust fault with component of sinistral strike-slip	>1 m	sec. 31, T7N, R37E	Shannon & Wilson, Inc. (1979, p. 16-17); Foundation Services, Inc. (1980, p. 41-44)
4. Little Dry Creek	Wallula Fault System	Pleistocene?	normal	0.5 m	NE¼ sec. 11, T4N, R35E	Shannon & Wilson, Inc. (1979, p. 33-34)
5. Barrett	Wallula Fault System	late Pleistocene to Holocene?	dextral oblique-slip	varied, 2 to 50 cm	SW¼SE¼ sec. 25, T6N, R34E	Shannon & Wilson, Inc. (1979, p. 35)
6. Milton-Freewater	Wallula Fault System	Holocene (1936)	dextral strike-slip	ground breakage not located	SE¼ sec. 18, T5N, R35E	Shannon & Wilson, Inc. (1979, p. 36)
7. Promontory Point	Wallula Fault System	Pleistocene?	normal	NK	sec. 10, T6N, R37E	Shannon & Wilson, Inc. (1979, p. 40); Foundation Services, Inc. (1980, p. 40-41)
8. Wallula (near Warm Springs Canyon)	Wallula Fault System	Pleistocene?	strike-slip or oblique-slip	NK	sec. 12, T6N, R32E	Farooqui (1979, p. 8-9)
9. Umapine	Wallula Fault System	Pleistocene?-Holocene	oblique-slip	NK	sec. 15, T5N, R34E	Mann (1991) and Lewis
10. Wallula (near Vansycle Canyon)	Wallula Fault System	early Holocene	not determined	NK	sec. 3, T6N, R32E	Glass (1977, p. 2R K8-K9); Farooqui (1979, p. 9-10)
11. Finley Quarry	Cle Elum-Wallula lineament-Domain II	Pleistocene?	reverse	NK	sec. 3, T7N, R30E	Farooqui and Thoms (1980, p. 4-8)
12. Central Gable Mountain	Gable Mountain Anticline (Yakima fold)	late Pleistocene?	reverse	~6 cm	sec. 19, T13N, R27E	Puget Sound Power and Light Company (1981, p. 34-45)
13. Mill Creek thrust fault and numerous unnamed faults	Toppenish Ridge (Yakima fold)	Holocene	both normal and reverse	as much as 4 m	Area between lat. 46°15'-46°19'N, long. 120°22'-122°40'W	Campbell and Bentley (1981, p. 519-524)
14. Union Gap	Ahtanum Ridge (Yakima fold)	Pleistocene?	reverse	approximately 7 m	T12N, R19E	Washington Public Power Supply System (1981, p. 2.5K-53); Geomatrix Consultants, Inc. (1988, p. 47-54)

Columbia Hills

On the western side of the Columbia Basin, Anderson and Tolan (1986) report a Holocene fault cutting Pleistocene slackwater flood sediments on the south side of the Columbia Hills anticline near Goldendale.

CLEW

Quaternary deformation has been reported at 15 localities along the CLEW (Washington Public Power Supply System, 1981; U.S. Department of Energy, 1988; Tolan and Reidel, 1989) between Kennewick and Milton Freewater,

OR (Table 4). The widespread distribution of Quaternary faulting in the Columbia Basin, however, suggests that the CLEW does not have any more or fewer Quaternary faults than other parts of the YFB.

Other Localities

Undocumented and (or) unpublished data for other Quaternary or younger faults include the following (Table 5, Fig. 8): Manastash Ridge (Geomatrix Consultants, Inc., 1988), Boylston Mountains (R. D. Bentley, Central Wash. Univ., oral commun., 1983), Cleman Mountain (Geomatrix

Figure 9. Holocene fault on Toppenish Ridge near Yakima, WA. View southeast along the north flank of Toppenish Ridge at the fault scarp. The fault scarp offsets the CRBG, alluvium, and loess. Note the diverted gully.

Figure 10. Trench through the Mill Creek thrust fault at base of the north limb of Toppenish Ridge. This fault places pumicite of the upper Ellensburg Formation over fan gravels and a wedge of soil on the left side of the photograph.

Consultants, Inc., 1988; N. P. Campbell, unpub. data), Yakima Ridge (R. D. Bentley, oral commun., 1990), Medicine Valley (Geomatrix Consultants, Inc., 1988), Hog Ranch–Naneum Ridge anticline (R. D. Bentley, oral commun., 1986), Tamarack Springs (Campbell, 1983), Frenchman Hills and Smyrna Bench, Saddle Mountains (Geomatrix Consultants, Inc., 1990; West and Shaffer, 1989; Shaffer and West, 1989; S. P. Reidel, unpub. data), Wenas Valley (West, 1987), Kittitas Valley (Geomatrix Consultants, Inc., 1989), and Ahtanum Ridge (N. P. Campbell, unpub. data; Geomatrix Consultants, Inc., 1989).

There appears to be no pattern of faulting in the YFB that would suggest that Quaternary-Holocene faulting is more concentrated in one part of the basin than in another. Rather, the distribution seems to suggest that the entire fold belt has continued to develop in a pattern similar to that of the Pliocene and Miocene.

CONTEMPORARY STRESS AND STRAIN

Regional Stress Indicators

In situ stress for the Columbia Basin has been determined from geodetic surveys and earthquake focal mechanism solutions. Geodetic surveys (Prescott and Savage, 1984) across the Pasco Basin suggest north-south shortening at a rate of -0.27 ± 0.22 microstrain/yr. The principal strain directions are $N3^\circ W \pm 34^\circ$ at 0.06 ± 0.013 microstrain/yr and $N87^\circ E \pm 34^\circ$ at -0.024 ± 0.014 microstrain/yr. This rate is not statistically significant at the 95 percent confidence level, however, and the measurements are within the error limits of the recording instruments.

Focal mechanism solutions are more definitive, and they indicate that the maximum principal stress is generally north-south and the minimum principal stress is near vertical (U.S. Department of Energy, 1988). Seismicity occurs in three stratigraphic zones: the CRBG, the sub-basalt sedimentary rocks, and the crystalline basement. Most of the seismicity is concentrated in the CRBG and the crystalline basement. No seismic events have been associated with known faults; seismicity tends to be concentrated in the synclinal areas (Fig. 12; U.S. Department of Energy, 1988).

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Table 5. Localities of suspected Quaternary-Holocene faults in the Columbia Basin; NK = not known; see Fig. 8 for locations

Fault	Primary structural feature	Age of last movement	Sense of movement	Amount of movement	Location	Source of information
15. Unnamed	Service anticline	Late Pleistocene?	strike-slip	NK	SE 1/4 SW 1/4 sec. 28, T6N, R28E	Foundation Services, Inc. (1980, p. 48-49)
16. Luna Butte	Columbia Hills (Yakima Fold)	Early Holocene	dextral strike-slip	NK	sec. 8, T3N, R18E	Anderson and Tolan (1986, p. 82)
17. Kittitas Valley (3 faults)	Kittitas Basin (Yakima Fold)	Pleistocene?	normal	2 m?	Area between lat. 47°00'–47°10'N, long. 120°25'–120°45'W	Waitt (1979)
18. Smyrna Bench	Saddle Mountains (Yakima Fold)	Late Pleistocene-Holocene?	normal-reverse	6 m?	T15–16N, R25–27E	Geomatrix Consultants, Inc. (1990); West and Shaffer (1989)
19. Frenchman Hills (2 segments)	Frenchman Hills (Yakima Fold)	Holocene	reverse	2 m?	T17–18N, R27–29E	Geomatrix Consultants, Inc. (1990); Shaffer and West (1988)
20. West Canal	Frenchman Hills (Yakima Fold)	Pleistocene	reverse	1–3 m	T18N R23E	Grolier and Bingham (1971); Geomatrix Consultants, Inc. (1990)
21. Pinto	Pinto Ridge	Pleistocene	NK	NK	lat. 47°30'N, long. 119°15'W	Geomatrix Consultants, Inc. (1990)

The only association between seismicity and faults is on the east flank of the Smyrna anticline on the Saddle Mountains (Reidel, unpub. data). This is a segment boundary between the Smyrna Bench and Saddle Gap segments of Reidel (1984, 1987). Seismicity occurs north of the Saddle Mountains on the west side of a suspected deep fault marking the boundary and on the south side of the Saddle Mountains on the east side of the boundary. A time analysis of the microseismicity shows that this deep suspected fault controls the pattern of earthquake occurrence.

Geodetic measurements and, in particular, the pattern of seismicity indicate that the maximum stress in the Columbia Basin is horizontal, north-south compression (Fig. 13). The intermediate stress is horizontal and east-west, and the minimum stress is vertical. These data are consistent with geologic evidence (Reidel and others, 1989b) suggesting that the Columbia Basin has been under north-south compression since at least the Miocene and that the same stress pattern continues today.

Contemporary Stress in the Cold Creek Syncline

Core diskings and spalling in coreholes drilled in the Cold Creek syncline, central Columbia Basin, indicate high *in situ* stress (U.S. Department of Energy, 1988). Core diskings (Fig. 14) occurs when drill core fractures into thin disks during drilling. Borehole spalling or breakout is also an indicator of high deviatoric stress and suggests that the *in situ* stress is not distributed lithostatically. Spalling occurs in the direction of least horizontal compression. The consistent east-west (Fig. 15) orientation of borehole spalling also indicates that the maximum horizontal compression is oriented generally north-south.

Stress Magnitude at Depth

Hydraulic fracturing is currently the most widely used method to directly determine the magnitude of *in situ* stress. Hydraulic fracturing tests were conducted in boreholes at about 1 km depth in the upper

Figure 11. Roadcut along Interstate Highway 90 at Union Gap in which a Holocene fault is exposed. Frenchman Springs Member, Saddle Mountains Basalt, CRBG, is thrust south over terrace gravel of the Yakima River. Vertical re-bar is for a retaining wall along the highway.

Figure 12. Locations of all microseismic events recorded from March 1969 to January 1989 in the central Columbia Basin.

part of the Grande Ronde Basalt in the Cold Creek syncline (U.S. Department of Energy, 1988). The results indicated that the maximum horizontal stress ranges from 52.6 to 67.4 MPa (7,630–9,780 lbf/in²) and the minimum horizontal stress ranges from 30.3 to 35.7 MPa (4,400–5,180 lbf/in²). The ratio of average horizontal stress $[(\sigma_H + \sigma_h)/2]$ to the vertical stress (σ_v) ranges from 1.41 to 2.14, with a mean value of 1.77 ± 0.20 . This ratio is close to the higher end of known stress conditions at comparable depths at other locations (Fig. 16). The mean orientation of induced fractures, and thus the direction of the maximum horizontal stress, is consistent with north-south compression (Paillet and Kim, 1987).

In Situ Stress, Faults, and Microseismicity

Given the high *in situ* stress conditions in the central Columbia Basin, Kim and others (1986) suggested that move-

ment is possible on an east-striking reverse fault that dips 60 to 65 degrees and has an effective friction angle of 33 degrees or less along the fault plane. A comparison of shear strengths (Byerlee, 1978) to test results on the properties of CRBG joint surfaces (U.S. Department of Energy, 1988) suggests that slip could occur on a fault plane in the present stress field.

The regional pattern of Quaternary and Holocene faulting indicates that the hypothesis of Kim and others (1986) is correct, but the pattern of microseismicity is inconsistent with the fault distribution. Microseismicity occurs in synclinal areas where the CRBG is typically fresh, unaltered, and competent. Microseismicity is apparently absent from frontal faults on anticlinal ridges. This suggests that the ridges are deforming aseismically or that they are not moving and have locked up.

Figure 13. Stress orientation in the Pacific Northwest (modified from Zoback and others, 1992).

It is difficult to imagine why the strong, competent rock in the synclines would continually exhibit widespread microseismic activity while the incompetent, weak, altered basalts in the presence of abundant groundwater in the CRBG aquifers would not move and apparently be locked up. The regional high *in situ* stress must be acting on the anticlinal ridges. Some insight into this problem comes from examining the frontal fault zones on the anticlinal ridges. The faults are marked by highly brecciated basalt; fault gouge is commonly altered to clay. We suggest that *in*

situ stress is relieved by microseismicity (seismic creep) in the competent basalt of the synclines, and that there is a component of aseismic movement in the fault zones where the incompetent basalt gouge is lubricated by ground water.

SUMMARY AND CONCLUSIONS

The Columbia Basin is the product of deformation that began early in the Tertiary, prior to the eruption of the CRBG, and continues today. The Columbia Basin has two fundamental parts important to the post-CRBG geologic history

Figure 14. Disking in core from borehole DC-6, Hanford Site.

of the Columbia Basin, the Palouse Slope and the YFB. The Palouse Slope is a stable, undeformed area overlying the old continental craton. The YFB overlies a large prebasalt basin that has been subsiding since the early Tertiary. The basin is divided by the HR-NR anticline. The edge of the old continental craton is a suture zone that lies at the junction of the two structural subprovinces and is presently marked by the Ice Harbor dike swarm of the CRBG.

The pattern of deformation in the Columbia Basin has been dominated by north-south compression, and the YFB is the principal product of this stress. This deformation has also controlled the location of the Columbia River system

Figure 15. Generalized pattern of borehole spalling in the Cold Creek syncline. Redrawn from U.S. Department of Energy (1988).

since the late Miocene, as well as the depositional pattern of the post-basalt sediments.

The rate of deformation in the Columbia Basin has declined since the mid-Miocene, that is, the rate of basin subsidence and ridge growth have both declined. The present rate of ridge growth is estimated at 0.04 mm/yr, and subsidence in the basin is estimated to be 3×10^{-3} mm/yr.

Microseismicity, high *in situ* stress conditions, and areas of Quaternary and Holocene faulting indicate that the basin is still experiencing north-south compression. Although known late Cenozoic faults are found on anticlinal ridges, earthquake focal mechanisms and strain measurements suggest that most present-day stress release is occurring in the synclinal areas. No earthquake events have been shown to be related to known faults. The high *in situ* stress in the Cold Creek syncline explains the microseismicity in that area, but the absence of microseismicity associated with the anticlinal ridges may result from a component of aseismic slip on weakened fault zones lubricated with ground water.

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REFERENCES CITED

- Anderson, James Lee, 1987, The structural geology and ages of deformation of a portion of the southwest Columbia Plateau, Washington and Oregon: University of Southern California Doctor of Philosophy thesis, 283 p.
- Anderson, James Lee; Tolan, T. L., 1986, Ages of wrench faulting in interridge basins, southwest Columbia Plateau, Washington and Oregon [abstract]: Geological Society of America Abstracts with Programs, v. 18, no. 2, p. 82.

Beeson, M. H.; Tolan, T. L.; Anderson, James Lee, 1989, The Columbia River Basalt Group in western Oregon—Geologic structures and other factors that controlled flow emplacement patterns. *In* Reidel, S. P.; Hooper, P. R., editors, *Volcanism and tectonism in the Columbia River flood-basalt province: Geological Society of America Special Paper 239*, p. 223-246.

Bentley, R. D., 1977, Stratigraphy of the Yakima basalts and structural evolution of the Yakima ridges in the western Columbia Plateau. *In* Brown, E. H.; Ellis, R. C., editors, *Geological excursions in the Pacific Northwest: Western Washington University*, p. 339-390.

Bentley, R. D.; Anderson, James Lee; Campbell, N. P.; Swanson, D. A., 1980, Stratigraphy and structure of the Yakima Indian Reservation, with emphasis on the Columbia River Basalt Group: U.S. Geological Survey Open-File Report 80-200, 85 p., 1 pl.

Bergstrom, K. A.; Kunk, J. R.; Mitchell, T. H.; Rohay, A. C., 1987, Deep structure of the Pasco Basin, south-central Washington: Rockwell Hanford Operations RHO-BW-SA-664 P, 17 p.

Byerlee, J., 1978, Friction of rocks: *Pure and Applied Geophysics*, v. 116, no. 4-5, p. 615-626.

Campbell, N. P., 1983, Correlation of late Cenozoic gravel deposits along the Yakima River drainage from Ellensburg to Richland, Washington: *Northwest Science*, v. 57, no. 3, p. 179-193.

Campbell, N. P., 1988, Structural geology along the northwestern Columbia River basalt margin, Washington: Washington Division of Geology and Earth Resources Open File Report 88-5, 108 p., 8 pl.

Campbell, N. P., 1989, Structural and stratigraphic interpretation of rocks under the Yakima fold belt, Columbia Basin, based on recent surface mapping and well data. *In* Reidel, S. P.; Hooper, P. R., editors, *Volcanism and tectonism in the Columbia River flood-basalt province: Geological Society of America Special Paper 239*, p. 209-222.

Campbell, N. P.; Banning, D. L., 1985, Stratigraphy and hydrocarbon potential of the northwestern Columbia Basin based on recent drilling activities: Rockwell Hanford Operations SD-BWI-TI-265, 54 p.

Campbell, N. P.; Bentley, R. D., 1980, Late Quaternary faulting Toppenish Ridge; south-central Washington [abstract]: *Geological Society of America Abstracts with Programs*, v. 12, no. 3, p. 101.

Campbell, N. P.; Bentley, R. D., 1981, Late Quaternary deformation of the Toppenish Ridge uplift in south-central Washington: *Geology*, v. 9, no. 11, p. 519-524.

Figure 16. Worldwide horizontal/vertical stress ratio plotted versus depth (from U.S. Department of Energy, 1988).

Catchings, R. D.; Mooney, W. D., 1988, Crustal structure of the Columbia Plateau—Evidence for continental rifting: *Journal of Geophysical Research*, v. 93, no. B1, p. 459-474.

Farooqui, S. M., 1979, Evaluation of faulting in the Warm Springs Canyon area, southeast Washington: Shannon & Wilson, Inc. [Portland, OR], 22 p.

Farooqui, S. M., and Thoms, R. C., 1980, Geologic evaluation of selected faults and lineaments, Pasco and Walla Walla Basins, southeast Washington: Shannon & Wilson, Inc., 40 p.

Fecht, K. R.; Reidel, S. P.; Tallman, A. M., 1982, Evolution of the Columbia River system in the central Columbia Plateau of Washington from the Miocene to the present [abstract]: *Geological Society of America Abstracts with Programs*, v. 14, no. 4, p. 163.

Fecht, K. R.; Reidel, S. P.; Tallman, A. M., 1987, Paleodrainage of the Columbia River system on the Columbia Plateau of Washington State—A summary. *In* Schuster, J. E., editor, *Selected papers on the geology of Washington: Washington Division of Geology and Earth Resources Bulletin 77*, p. 219-248.

Fenneman, N. M., 1931, *Physiography of western United States*: McGraw-Hill Book Co., 534 p.

Foundation Sciences Inc., 1980, Reconnaissance of parts of the Walla Walla and Pullman, Washington, and Pendleton, Oregon 1° x 2° AMS quadrangles: Foundation Sciences Inc. report for U.S. Army Corps of Engineers, 83 p., 3 pl.

Fox, T. P.; Reidel, S. P., 1987, Stratigraphy of the Standard Kirkpatrick No. 1, Gilliam County, Oregon—New insight into Tertiary tectonism of the Blue Mountains: *Oregon Geology*, v. 49, no. 2, p. 15-22.

- Frizzell, V. A., Jr.; Tabor, R. W.; Booth, D. B.; Ort, K. M.; Waitt, R. B., 1984, Preliminary geologic map of the Snoqualmie Pass 1:100,000 quadrangle, Washington: U.S. Geological Survey Open-File Report 84-693, 43 p., 1 pl., scale 1:100,000.
- Geomatrix Consultants, Inc., 1988, Seismotectonic evaluation of the northern Cascade mountains geomorphic province for Bumping Lake, Tieton, Keechelus, Kachess, Cle Elum, and Clear Lake dams: Geomatrix Consultants, Inc. (San Francisco, CA., under contract to) U.S. Bureau of Reclamation, 154 p., 12 pl.
- Geomatrix Consultants, Inc., 1989, Seismotectonic evaluation—Northwest Rocky Mountains—Okanogan Uplands geomorphic province; Final report: Geomatrix Consultants, Inc. (under contract to U.S. Bureau of Reclamation), 124 p., 4 pl.
- Geomatrix Consultants, Inc., 1990, Seismotectonic evaluation, Walla Walla section of the Columbia Plateau geomorphic province; Final report: Geomatrix Consultants, Inc. (under contract to) U.S. Bureau of Reclamation, 1 v. 6 pl.
- Glover, D. W., 1985, Crustal structure of the Columbia Basin, Washington from borehole and refraction data: University of Washington Master of Science thesis, 71 p.
- Goff, F. E., 1981, Preliminary geology of eastern Umtanum Ridge, south-central Washington: Rockwell Hanford Operations RHO-BWI-C-21, 99 p., 2 pl.
- Glass, C. E., 1977, Remote sensing analysis of the Columbia Plateau. In Washington Public Power Supply System, WPPSS nuclear project no. 1—Preliminary safety analysis report: Washington Public Power Supply System Docket no. 50-460, Preliminary safety analysis report, Amendment 23, v. 2B, Appendix 2R, Subappendix 2R K, 19 p.
- Grolier, M. J.; Bingham, J. W., 1971, Geologic map and sections of parts of Grant, Adams, and Franklin Counties, Washington: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-589, 6 sheets, scale 1:62,500.
- Hagood, M. C., 1986, Structure and evolution of the Horse Heaven Hills in south-central Washington: Rockwell Hanford Operations RHO-BW-SA-344 P, 190 p., 1 pl.
- Jarchow, C. M., 1991, Investigations of magmatic underplating beneath the northwestern Basin and Range Province, Nevada, seismic data acquisition and tectonic problems of the Columbia Plateau, Washington and the nature of the Mohorovicic discontinuity worldwide: Stanford University Doctor of Philosophy thesis, 258 p.
- Keroher, G. C.; and others, 1966, Lexicon of geologic names of the United States for 1936–1960: U.S. Geological Survey Bulletin 1200, 3 v.
- Kim, Kunsoo; Dischler, S. A.; Aggson, J. R.; Hardy, M. P., 1986, The state of in situ stresses determined by hydraulic fracturing at the Hanford site: Rockwell Hanford Operations RHO-BW-ST-73 P, 1 v.
- Lindsey, K. A., 1991, Revised stratigraphy for the Ringold Formation, Hanford site, south-central Washington: Westinghouse Hanford Company WHC-SD-EN-EE-004, 12 p.
- Mann, G. M.; Lewis, S. D., 1991, Structure and correlations to seismicity along the Olympic–Wallowa lineament [abstract]: *Eos* (American Geophysical Union Transactions), v. 72, no. 44, supplement, p. 315-316.
- Mohl, G. B., 1977, Bouguer gravity investigation of the cratonic margin—Southeastern Washington: Washington State University Master of Science thesis, 67 p.
- Mohl, G. B.; Thiessen, R. L., 1985, Gravity measurements in south-eastern Washington and implications as to the location of the cratonic margin [abstract]: *Geological Society of America Abstracts with Programs*, v. 17, no. 4, p. 257.
- Myers, C. W.; Price, S. M.; and others, 1979, Geologic studies of the Columbia Plateau—A status report: Rockwell Hanford Operations RHO-BWI-ST-4, 541 p., 53 pl.
- Newcomb, R. C., 1969, Geologic map of the proposed Paterson Ridge pumped-storage reservoir, south-central Washington: U.S. Geological Survey Open-File Report, 8 p., 2 pl.
- Newcomb, R. C., 1970, Tectonic structure of the main part of the basalt of the Columbia River Group, Washington, Oregon, and Idaho: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-587, 1 sheet, scale 1:500,000.
- Paillet, F. L.; Kim, Kunsoo, 1987, Character and distribution of borehole breakouts and their relationship to in situ stresses in deep Columbia River basalts: *Journal of Geophysical Research*, v. 92, no. B7, p. 6223-6234.
- Prescott, W. H.; Savage, J. C., 1984, Crustal deformation near Hanford, Washington: U.S. Geological Survey Open-File Report 84-797, 247 p.
- Price, E. H., 1982, Structural geometry, strain distribution, and mechanical evolution of eastern Umtanum Ridge and a comparison with other selected localities within Yakima fold structures, south-central Washington: Rockwell Hanford Operations RHO-BWI-SA-138; Washington State University Doctor of Philosophy thesis, 199 p., 6 pl.
- Price, E. H.; Watkinson, A. J., 1989, Structural geometry and strain distribution within eastern Umtanum fold ridge, south-central Washington. In Reidel, S. P.; Hooper, P. R., editors, *Volcanism and tectonism in the Columbia River flood-basalt province*: Geological Society of America Special Paper 239, p. 265-281.
- Puget Sound Power and Light Company, 1981, Skagit/Hanford nuclear project, preliminary safety analysis report: Puget Sound Power and Light Company, 7 v.
- Raisz, Erwin, 1945, The Olympic–Wallowa lineament: *American Journal of Science*, v. 243-A, no. 5, p. 479-485.
- Reidel, S. P., 1984, The Saddle Mountains—The evolution of an anticline in the Yakima fold belt: *American Journal of Science*, v. 284, no. 8, p. 942-978.
- Reidel, S. P., 1988, Geologic map of the Saddle Mountains, south-central Washington: Washington Division of Geology and Earth Resources Geologic Map GM-38, 5 plates, scale 1:48,000, with 28 p. text.
- Reidel, S. P.; Campbell, N. P., 1989, Structure of the Yakima Fold Belt, central Washington. In Joseph, N. L.; and others, editors, *Geologic guidebook for Washington and adjacent areas*: Washington Division of Geology and Earth Resources Information Circular 86, p. 275-303.
- Reidel, S. P.; Fecht, K. R.; Hagood, M. C.; Tolan, T. L., 1989b, The geologic evolution of the central Columbia Plateau. In Reidel, S. P.; Hooper, P. R., editors, *Volcanism and tectonism in the Columbia River flood-basalt province*: Geological Society of America Special Paper 239, p. 247-264.
- Reidel, S. P.; Fecht, K. R.; Lindsey, K. A.; Campbell, N. P., 1992, Post-Columbia River basalt structure and stratigraphy of south-central Washington [abstract]: *Geological Society of America Abstracts with Programs*, v. 24, no. 5, p. 78.
- Reidel, S. P.; Hooper, P. R., editors, 1989, *Volcanism and tectonism in the Columbia River flood-basalt province*: Geological Society of America Special Paper 239, 386 p., 1 pl.

- Reidel, S. P.; Long, P. E.; Myers, C. W.; Mase, J., 1982, New evidence for greater than 3.2 km of Columbia River basalt beneath the central Columbia Plateau [abstract]: *Eos* (American Geophysical Union Transactions), v. 63, no. 8, p. 173.
- Reidel, S. P.; Tolan, T. L., 1992, Eruption and emplacement of flood basalt—An example from the large-volume Teepee Butte member, Columbia River Basalt Group: *Geological Society of America Bulletin*, v. 104, no. 12, p. 1650-1671.
- Reidel, S. P.; Tolan, T. L.; Hooper, P. R.; Beeson, M. H.; Fecht, K. R.; Bentley, R. D.; Anderson, J. L., 1989a, The Grande Ronde Basalt, Columbia River Basalt Group: Stratigraphic descriptions and correlations in Washington, Oregon, and Idaho. In Reidel, S. P.; Hooper, P. R., editors, *Volcanism and tectonism in the Columbia River flood-basalt province*: Geological Society of America Special Paper 239, p. 21-53.
- Rohay, A. C.; Glover, D. W.; Malone, S. D., 1985, Time-term analysis of upper crustal structure in the Columbia Basin, Washington: Rockwell Hanford Operations RHO-BW-SA-435 P, 19 p.
- Rohay, A. C.; Malone, S. D., 1983, Crustal structure of the Columbia Plateau region, Washington: Rockwell Hanford Operations RHO-BW-SA-289 P, 20 p.
- Salus, R. W., 1991, Gravity and heat flow constraints on Cenozoic tectonics of the western United States Cordillera: Stanford University Doctor of Philosophy thesis, 244 p.
- Shaffer, M. E.; West, M. W., 1989, Quaternary faulting in the Frenchman Hills anticline, Yakima fold belt, central Columbia Basin, Washington [abstract]: *Geological Society of America Abstracts with Programs*, v. 21, no. 5, p. 142.
- Shannon & Wilson, Inc., 1973, Geologic studies of the Columbia River Basalt structures and age of deformation in the Dalles-Umatilla region, Washington and Oregon, Boardman Nuclear Project: Shannon & Wilson, Inc. (Portland, Ore., under contract to) Portland General Electric Company, 1 v., 2 plates.
- Shannon & Wilson, Inc., 1979, Geologic reconnaissance of Walula Gap, Washington—Blue Mountains—LaGrande, Oregon region:
- Smith, G. A., 1988, Neogene synvolcanic and syntectonic sedimentation in central Washington: *Geological Society of America Bulletin*, v. 100, no. 9, p. 1479-1492.
- Smith, G. A.; Bjornstad, B. N.; Fecht, K. R., 1989, Neogene terrestrial sedimentation on and adjacent to the Columbia Plateau: Washington, Oregon, and Idaho. In Reidel, S. P.; Hooper, P. R., editors, *Volcanism and tectonism in the Columbia River flood-basalt province*: Geological Society of America Special Paper 239, p. 187-198.
- Stoffel, K. L.; Joseph, N. L.; Waggoner, S. Z.; Gulick, C. W.; Korosec, M. A.; Bunning, B. B., 1991, Geologic map of Washington—Northeast quadrant: Washington Division of Geology and Earth Resources Geologic Map GM-39, 3 sheets, scale 1:250,000, with 36 p. text.
- Swanson, D. A.; Anderson, J. L.; Bentley, R. D.; Byerly, G. R.; Camp, V. E.; Gardner, J. N.; Wright, T. L., 1979b, Reconnaissance geologic map of the Columbia River Basalt Group in eastern Washington and northern Idaho: U.S. Geological Survey Open-File Report 79-1363, 26 p., 12 pl.
- Swanson, D. A.; Anderson, J. L.; Camp, V. E.; Hooper, P. R.; Taubeneck, W. H.; Wright, T. L., 1981, Reconnaissance geologic map of the Columbia River Basalt Group, northern Oregon and western Idaho: U.S. Geological Survey Open-File Report 81-797, 33 p., 6 pl.
- Swanson, D. A.; Wright, T. L.; Camp, V. E.; Gardner, J. N.; Helz, R. T.; Price, S. M.; Reidel, S. P.; Ross, M. E., 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 Geologic Investigations Map I-1139, 2 sheets, scale 1:250,000.
- Swanson, D. A.; Wright, T. L.; Hooper, P. R.; Bentley, R. D., 1979a, Revisions in stratigraphic nomenclature of the Columbia River Basalt Group: U.S. Geological Survey Bulletin 1457-G, 59 p.
- Swanson, D. A.; Wright, T. L.; Zietz, Isidore, 1979c, Aeromagnetic map and geologic interpretation of the west-central Columbia Plateau, Washington and adjacent Oregon: U.S. Geological Survey Geophysical Investigations Map GP-917, 1 sheet, scale 1:250,000.
- Tabor, R. W.; Waitt, R. B., Jr.; Frizzell, V. A., Jr.; Swanson, D. A.; Byerly, G. R.; Bentley, R. D., 1982, Geologic map of the Wenatchee 1:100,000 quadrangle, central Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1311, 1 sheet, scale 1:100,000, with 26 p. text.
- Tabor, R. W.; Frizzell, V. A., Jr.; Vance, L. A.; Naeser, C. W., 1984, Ages and stratigraphy of lower and middle Tertiary sedimentary and volcanic rocks of the central Cascades, Washington—Application to the tectonic history of the Straight Creek fault: *Geological Society of America Bulletin*, v. 95, no. 1, p. 26-44.
- Tolan, T. L.; Beeson, M. H., 1984, Intracanyon flows of the Columbia River Basalt Group in the lower Columbia River Gorge and their relationship to the Troutdale Formation: *Geological Society of America Bulletin*, v. 95, no. 4, p. 463-477.
- Tolan, T. L.; Beeson, M. H.; Vogt, B. F., 1984, Exploring the Neogene history of the Columbia River—Discussions and geologic field trip guide to the Columbia River Gorge: *Oregon Geology*, v. 46, no. 8, p. 87-97.
- Tolan, T. L.; Reidel, S. P., compilers, 1989, Structure map of a portion of the Columbia River flood-basalt province. In Reidel, S. P.; Hooper, P. R., editors, *Volcanism and tectonism in the Columbia River flood-basalt province*: Geological Society of America Special Paper 239, plate, scale 1:580,000.
- Tolan, T. L.; Reidel, S. P.; Beeson, M. H.; Anderson, J. L.; Fecht, K. R.; Swanson, D. A., 1989, Revisions to the estimates of the areal extent and volume of the Columbia River Basalt Group. In Reidel, S. P.; Hooper, P. R., editors, *Volcanism and tectonism in the Columbia River flood-basalt province*: Geological Society of America Special Paper 239, p. 1-20.
- U.S. Department of Energy, 1988, Consultation draft site characterization plan, reference repository location, Hanford site, Washington: U.S. Department of Energy DOE/RW-0164, 9 v.
- Waitt, R. B., Jr., 1979, Late Cenozoic deposits, landforms, stratigraphy, and tectonism in Kittitas Valley, Washington: U.S. Geological Survey Professional Paper 1127, 18 p.
- Walker, G. W.; MacLeod, N. S., 1991, Geologic map of Oregon, U.S. Geological Survey, 2 sheets, scale 1:500,000.
- Washington Public Power Supply System, 1981a, Late Cenozoic tectonics of the Pacific Northwest with special reference to the Columbia Plateau: Washington Public Power Supply System nuclear project number 2, Final Safety Analysis Report, Amendment 18, Appendix 2.5N, p. 2.5N-1-2.5N-44.
- Washington Public Power Supply System, 1981b, WPPSS nuclear project no. 2—Final safety analysis report, Amendment 18: Washington Public Power Supply System Docket no. 50-397, Final Safety Analysis Report, Amendment 18, 3 v.

- Waters, A. C., 1961, Stratigraphic and lithologic variations in the Columbia River basalt: *American Journal of Science*, v. 259, no. 8, p. 583-611.
- West, D. O., 1987, The Wenatchee Valley fault—Holocene normal faulting or gravitational sliding in the Yakima fold belt, Columbia Plateau? [abstract]: *Geological Society of America Abstracts with Programs*, v. 19, no. 6, p. 463.
- West, M. W.; Shaffer, M. E., 1989, Late Quaternary tectonic deformation in the Smyrna Bench and Saddle Gap segments, Saddle Mountains anticline, Yakima fold belt, central Columbia Basin, Washington [abstract]: *Geological Society of America Abstracts with Programs*, v. 21, no. 5, p. 157-158.
- Zervas, C. E.; Crosson, R. S., 1986, An observation and interpretation in Washington: *Seismological Society of America Bulletin*, v. 76, no. 2, p. 521-546.
- Zoback, M. L.; Zoback, M. D.; Adams, J.; Bell, S.; Suter, M.; Suarez, G.; Jacob, K.; Estrabrook, C.; Magee, M., 1992, Stress map of North America: *Geological Society of America DNASG Continental-Scale Map 005*, 4 sheets, scale 1:5,000,000.

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