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THE SADDLE MOUNTAINS: THE EVOLUTION OF AN ANTICLINE IN THE YAKIMA FOLD BELT

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ABSTRACT. The Yakima Fold Belt of the western Columbia Plateau is a series of generally east-west trending anticlinal ridges and synclinal valleys. The Saddle Mountains, typical of the anticlinal ridges, form the northern margin of one of the larger synclinal basins, the Pasco Basin. The Saddle Mountains uplift is an asymmetrical, north vergent anticline with a length of about 110 km. It varies from an open to tight fold and is divided into six segments based upon differences in geometry. The north flank is the locus of a high-angle reverse to thrust fault, the Saddle Mountains fault, that has at least 2.5 km of displacement. The anticlinal uplift is modified by numerous cross structures, two of which extend beyond the uplift: the northwest-trending Smyrna anticline and Hog Ranch-Naneum Ridge anticline.

Flows of the Columbia River Basalt Group, intercalated sedimentary deposits of the Ellensburg Formation, and suprabasalt sediments thin over the uplift and thicken into the synclines. Variations in thickness are used to determine the timing of deformation and age of major and minor structures. Both the east-trending Saddle Mountains uplift and northwest-trending Hog Ranch-Naneum Ridge anticline and possibly the Smyrna anticline were growing during the eruption of the Grande Ronde Basalt (17-15.5 Ma), but many secondary structures did not develop until after 12 Ma.

Thickness variations record paleostructural relief and thus provide a method of calculating the growth rate of the Saddle Mountains. These calculations indicate the uplift was growing at about 250 m/my during Grande Ronde time but slowed to less than 40 m/my by the end of the Miocene. Thickness variations and amount of uplift of suprabasalt sediments indicate this low average rate persisted at least until 3.5 Ma. This low average rate of uplift, projected to the present time, accounts for the present structural relief of the Saddle Mountains. Estimates of the rate of shortening are of the same order of magnitude as that of uplift.

Studies of other folds in the province show a similar pattern of evolution suggesting that the age, timing, and growth rate of the Saddle Mountains provide a model for anticlinal folds of the Yakima Fold Belt. The close correlation of growth rate of the folds with rate of magma supply of the Columbia River Basalt Group suggests that the Yakima Fold Belt resulted from the same tectonic processes that produced eruption of the Columbia River basalt.

INTRODUCTION

Location and setting.—The Columbia Plateau in Washington State can be subdivided (fig. 1) into three structural subprovinces (Myers and others, 1979): Blue Mountains subprovince, characterized by the northeast-trending Blue Mountains uplift; Palouse Hills subprovince, characterized by a generally undeformed, westward-tilting paleoslope; and Yakima Fold Belt subprovince, characterized by generally east-west-trending (70°-130°) asymmetric anticlinal ridges, the Yakima folds. Typical folds within the belt form asymmetric anticlinal ridges separated by synclinal valleys that in many areas are broad, flat basins. The Saddle Mountains anticlinal ridge (fig. 1) forms the northern boundary of one of the larger basins, the Pasco Basin, which is the structurally lowest part of the Columbia Plateau.

The Saddle Mountains uplift is defined as the ridge extending from about 25 km east-southeast of Ellensburg, Wash. to about 20 km southeast of Othello, Wash., a distance of 110 km. From Ellensburg to Foster Springs, the uplift trends southeast and is called the Boylston Mountains. The highest elevation is 1158 m above sealevel near McDonald Springs at the southern end of the Boylston Mountains; Wahatis Peak, at 823 m, is the highest point east of the Columbia River. The Columbia River crosses the Saddle Mountains at a spectacular water gap, Sentinel Gap.

Previous investigations.—The first published report on the Saddle Mountains was by Symons (1882), who summarized the results of a recon-

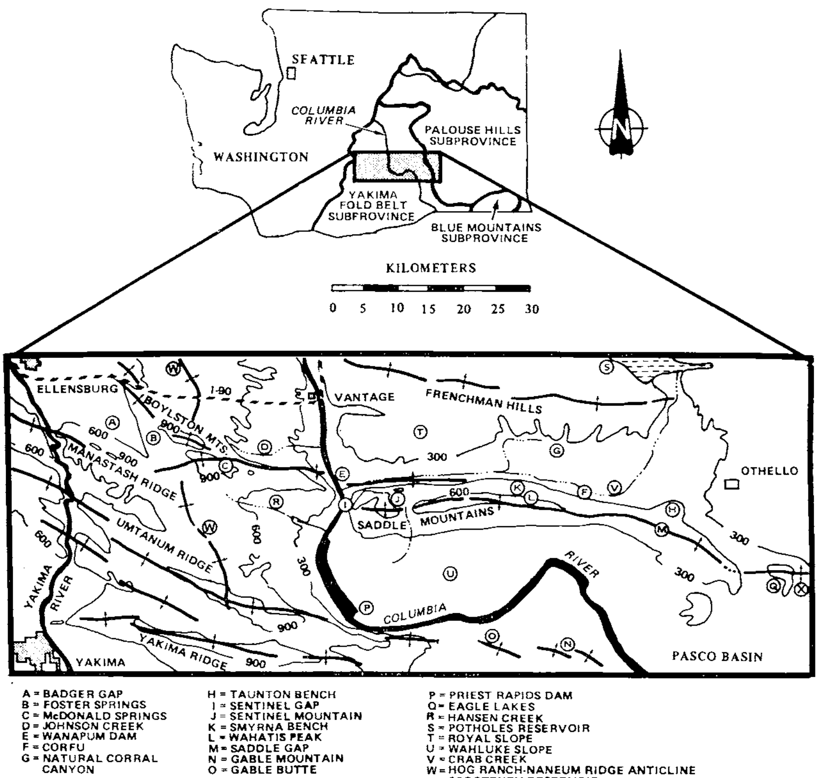


Fig. 1. Location map showing the Saddle Mountains uplift and features of the surrounding area in central Washington. Structural subdivisions of Columbia Plateau in Washington are shown; topographic contour interval is in meters.

naissance survey along the Columbia River. Russell (1893), Smith (1903), and Calkins (1905) established the anticlinal nature of the ridges and the general geometry of the Yakima Fold Belt.

The first detailed studies of the fold belt were undertaken in the 1950s and 1960s by Waters (1955, 1961) and Mackin (1961) and their students (Laval, ms; Schmincke, ms and 1967; Grolier, ms; Grolier and Bingham, 1971, 1978; and Bingham, Londquist, and Baltz, 1970). These studies concentrated on the stratigraphy, geometry, and development of the folds.

Since then, a refined stratigraphy of the Columbia River Basalt Group (Waters, 1961; Wright, Grolier, and Swanson, 1973; Swanson and others, 1979b), aided by X-ray fluorescence chemical analysis and field-determined paleomagnetic polarity, has allowed more detailed studies to be carried out. The most recent phase of study in the Saddle Mountains began with Taylor (ms), who mapped an area east of Sentinel Gap, and with Bentley (1977), who completed a reconnaissance study west of Sentinel Gap. Swanson and Helz (1979) published a map of the Ice Harbor dike system and adjacent area (Swanson and others, 1977) which included the eastern edge of the Saddle Mountains.

Purpose of the study.—The tectonic setting of the Columbia Plateau has been the subject of study because of nuclear waste management activities and the siting and construction of nuclear powerplants on the Hanford Site (ARHCO, 1976; WPPSS, 1977, 1981). Recently, several models have been proposed to account for the geometry and spacing of folds and associated faults in the Yakima Fold Belt (Davis, 1977, 1981; Bentley, 1980; Laubscher, 1981; Price, 1982). This study was undertaken to decipher the geologic evolution of the Saddle Mountains uplift.

Stratigraphy.—The stratigraphic nomenclature of the Columbia River Basalt Group (fig. 2) has been revised recently by Swanson and others (1979b); that revision introduced new names and formalized many of the names and relationships proposed by previous workers in south-central Washington. The Columbia River Basalt Group ranges in age from about 17.5 to 6 Ma (Watkins and Baksi, 1974; McKee, Swanson, and Wright, 1977; McKee, Hooper, and Kleck, 1981) and consists of five formations; only the Grande Ronde, Wanapum, and Saddle Mountains Basalts are exposed in the central plateau (fig. 2).

The oldest formation exposed in the Saddle Mountains is the Grande Ronde Basalt. The N_2 magnetostratigraphic unit (fig. 2) is the principal unit (Taylor, ms; this study), but the upper flow of the older R_2 magnetostratigraphic unit is exposed along Crab Creek near Sentinal Gap (Taylor, ms; Coe, Bogue, and Myers, 1978). Both the high-Mg and low-Mg Grande Ronde Basalt chemical types of Wright, Grolier, and Swanson (1973), informally named the Sentinel Bluffs sequence and the Schwana sequence, respectively (Myers and others, 1979), are present (Taylor, ms; this study).

Three members of the Wanapum Basalt are present in the Saddle Mountains: Frenchman Springs, Roza, and Priest Rapids. The Ginkgo, Sand Hollow, and Sentinel Gap flows of the Frenchman Springs Member are present in the Sentinel Gap area (Mackin, 1961), but more flows occur in the Pasco Basin (Reidel and Fecht, 1981). The Roza Member consists

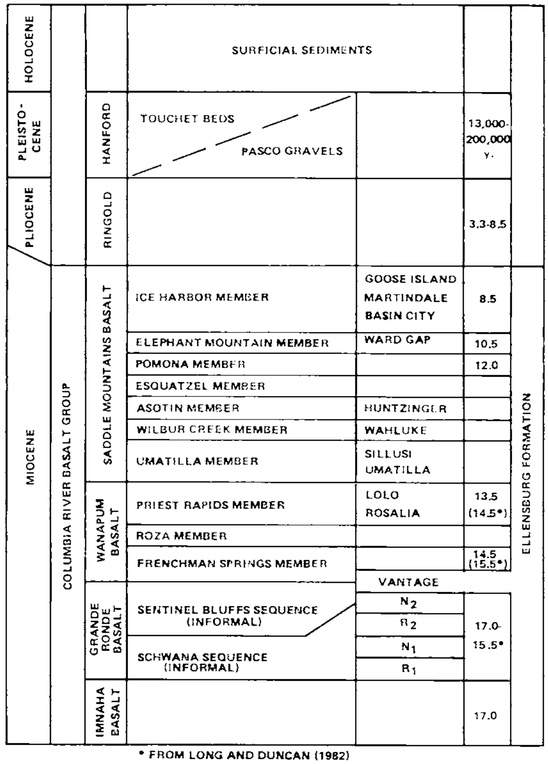


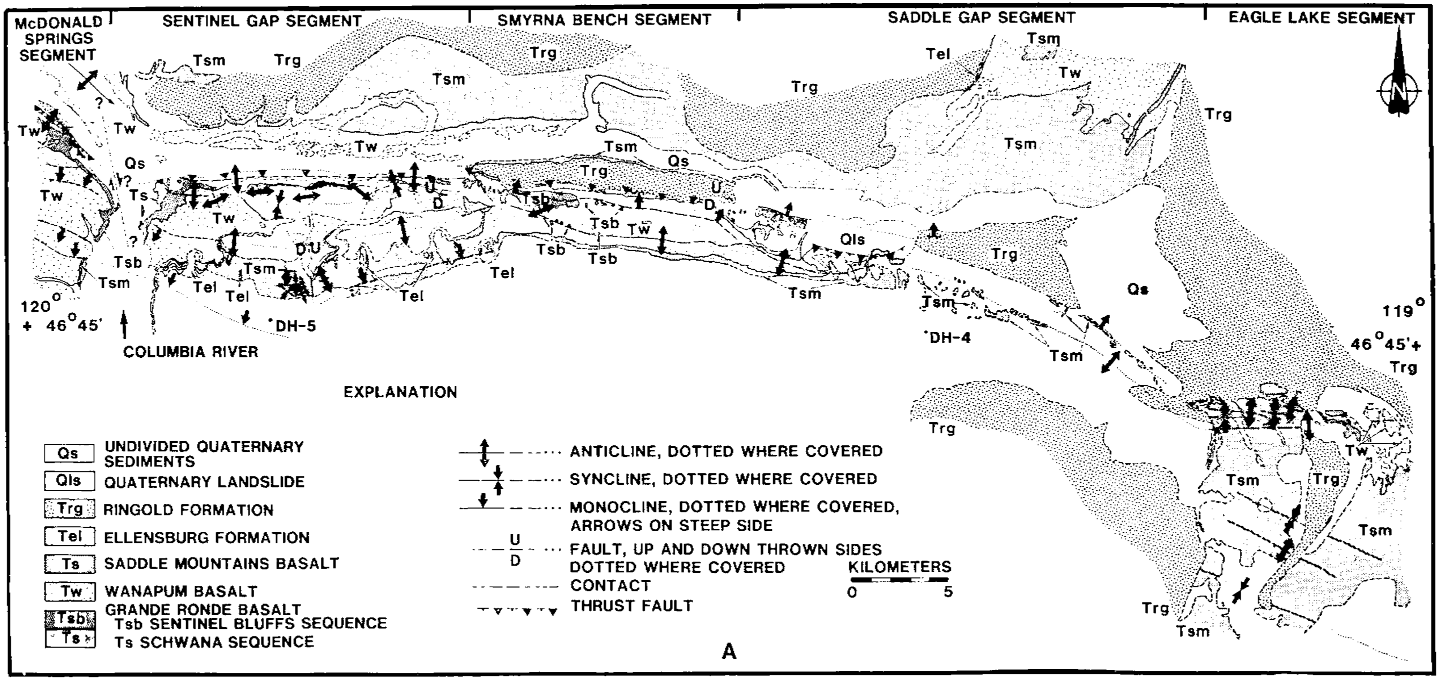
Fig. 2. Central Columbia Plateau stratigraphic nomenclature. Modified from Myers and others (1979) and Swanson and others (1979b). Formation names are shown in the third column from left, member names in the fourth column from left, flow names in the fifth column from left, and ages of members in millions of years in sixth column from left.

of one to two flows or flow lobes, while the Priest Rapids Member contains two distinct flows, the Rosalia and Lolo, which can be readily separated using chemical compositions.

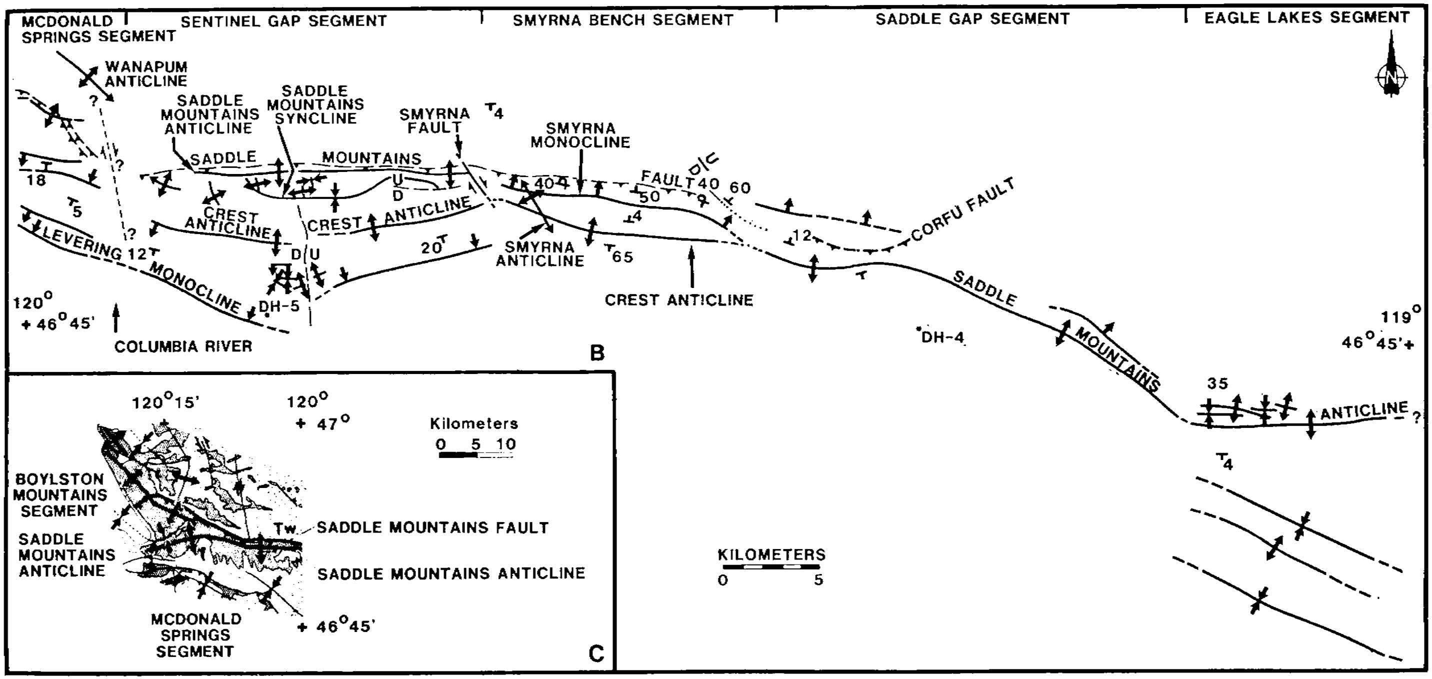
Only five members of the Saddle Mountains Basalt are present in the Saddle Mountains area: Wilbur Creek, Asotin, Pomona, Elephant Mountain, and Ice Harbor. The Wilbur Creek, Asotin, and Pomona Members consist of one flow each: Wahluke flow (ARHCO, 1976) of the Wilbur Creek Member, Huntzinger flow (Mackin, 1961) of the Asotin Member, and Pomona flow of the Pomona Member. The Elephant Mountain Member consists of two flows: the younger is the Ward Gap flow (Laval, ms), and the older is the Elephant Mountain flow. The Ice Harbor Member is represented locally by the Basin City flow (Swanson and Helz, 1979; this study).

Intercalated with these basalt flows are sedimentary interbeds of the Ellensburg Formation (fig. 2). Within the Pasco Basin, these beds are named for the confining basalt flows (Reidel and Fecht, 1981) and are primarily fluvial deposits.

Fig. 3



A. Generalized geologic map of the Saddle Mountains between 119° and 120° long.



B and C. Generalized tectonic map of the Saddle Mountains showing locations and names of faults and folds for (A); (C) is a geologic map by Swanson and others (1979a) of the Saddle Mountains uplift west of 120° long. (B) is the basic reference for later figures.

The Ringold Formation (Merriam and Buwalda, 1917) overlies the Columbia River Basalt Group and consists of a consolidated sequence of fine sand, silt, conglomerate, and fanglomerate (Newcomb, 1958; Grolier and Bingham, 1978). On the basis of paleomagnetic stratigraphy and fossil evidence, Packer and Johnston (1979) and Tallman, Lillie, and Fecht (1981) dated the Ringold Formation as Miocene-Pliocene (8.5-3.3 Ma).

Pleistocene catastrophic flood deposits, informally called the Hanford formation (Myers and others, 1979), cover the extreme eastern part of the Saddle Mountains. These glaciofluvial sediments were deposited as two facies: Pasco gravels (Brown, 1975) and Touchet beds (Flint, 1938). On the flanks of the Saddle Mountains, these sediments range from approx 200,000 y.B.P. (Tallman, Lillie, and Fecht, 1981) to the last major flood, dated at 13,000 y.B.P. (Mullineaux and others, 1977).

Methodology.—The equivalents of nine 7½-min. U.S. Geological Survey quadrangles were mapped at a scale of 1:24,000. Field work concentrated on the area just west of Sentinel Gap (long 120°) to just east of Othello (long 119°). Recognition and identification of basalt flows were based upon X-ray fluorescence chemical analyses, natural remanent magnetization, physical characteristics, and stratigraphic sequence. After preliminary mapping was completed (Myers and others, 1979, pl. 3), the area was reexamined to resolve inconsistencies in flow identification, check field maps, measure the thickness of individual flows and intercalated sedimentary units, and resolve problems. The result is a revised map of the area, presented in generalized form in figure 3.

STRUCTURE

Introduction.—Grolier (ms) and Grolier and Bingham (1978) divided the Saddle Mountains east of Sentinel Gap into three parts: a western part from Sentinel Gap to Smyrna Bench, here termed the Sentinel Gap segment (fig. 4); a central part along Smyrna Bench, here termed the Smyrna Bench segment; and an eastern part which is further subdivided in this study into the Saddle Gap segment, extending from Smyrna Bench to the

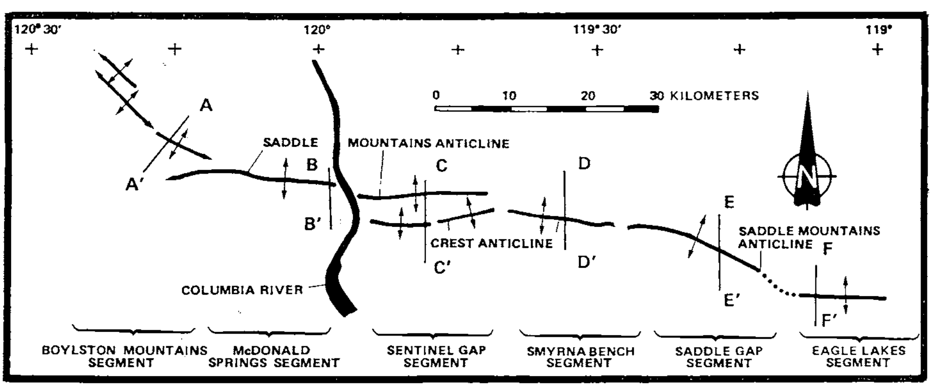


Fig. 4. Location of the six segments of the Saddle Mountains uplift and cross sections for figure 5.

Eagle Lakes area, and the Eagle Lakes segment, extending to the exposed eastern edge of the structure. Based on this study and mapping by Bentley (1977) west of 120° west longitude, the area from Sentinel Gap west to Foster Springs is named the McDonald Springs segment and from Foster Springs to the terminus of the structure near Interstate 90 is named the Boylston Mountains segment (see fig. 1). Information on the western part of the McDonald Springs and the Boylston Mountains segments is from Bentley (1977; *in* Swanson and others, 1979a) and reconnaissance examination during this study; data from 120° west longitude to the eastern extent of the structure are from my mapping.

The Saddle Mountains uplift.—The dominant structure of the Saddle Mountains is a generally east-trending north-vergent anticline. Variation along the length of the anticline is from an open to a tight fold and forms the basis for the six segments (fig. 4). Between Foster Springs and Smyrna Bench, the uplift is an asymmetrical, complex, tight fold; however, the general shape varies slightly on either side of Sentinel Gap (fig. 5, B-B′ and C-C′). It is a conjugate fold in the Smyrna Bench segment (fig. 5, D-D′) and an asymmetric, open fold in the Boylston Mountains segment (fig. 5, A-A′), Saddle Gap segment (fig. 5, E-E′), and Eagle Lakes segment (fig. 5, F-F′). The lowest amplitude occurs in the Boylston Mountains and Eagle Lakes segments and increases to the McDonald Springs area, the point of intersection with the north-northwest-trending Hog Ranch-Naneum Ridge anticline, and the junction of the McDonald Springs and Boylston Mountains segments.

Previous studies (Laval, ms; Grolier, ms; Grolier and Bingham, 1971) called the broad fold, which forms the present topographic crest in the Sentinel Gap segment, the Saddle Mountains anticline. I reserve this term for the hinge line, which is the oldest and dominant part of the uplift, and use the term Crest anticline for the topographic and structural crest, which is younger than the Saddle Mountains anticline. The use of these terms for various parts of the uplift implies age relationships. Later sections will provide the data for these distinctions.

The Saddle Mountains anticline shows distinct southeast and east trends. The intersection of the McDonald Springs and Boylston Mountains segments is a complex structural zone; the Saddle Mountains anticline begins just west of Foster Springs but the structural trend, as evidenced by the Saddle Mountains fault (fig. 3C), continues into the Boylston Mountains segment at the base of a series of en echelon folds (Swanson and others, 1979a). Beginning in the western part of the McDonald Springs segment, the Saddle Mountains anticline trends east for 20 km, turns to 135° at 120° west longitude, and then abruptly trends east again near the Columbia River, where the fold hinge is well exposed for over 2 km. East of Sentinel Gap, the fold hinge is exposed only near the Columbia River. The hinge line on the west side of the river is about 2.7 km north of the hinge line east of the river. This relation suggests that either a right-lateral strike-slip fault extends through Sentinel Gap with 2.7 km of offset, or the structure bends and evidence for the bend has been eroded away. My preferred interpretation is that of a fault because of the lack of

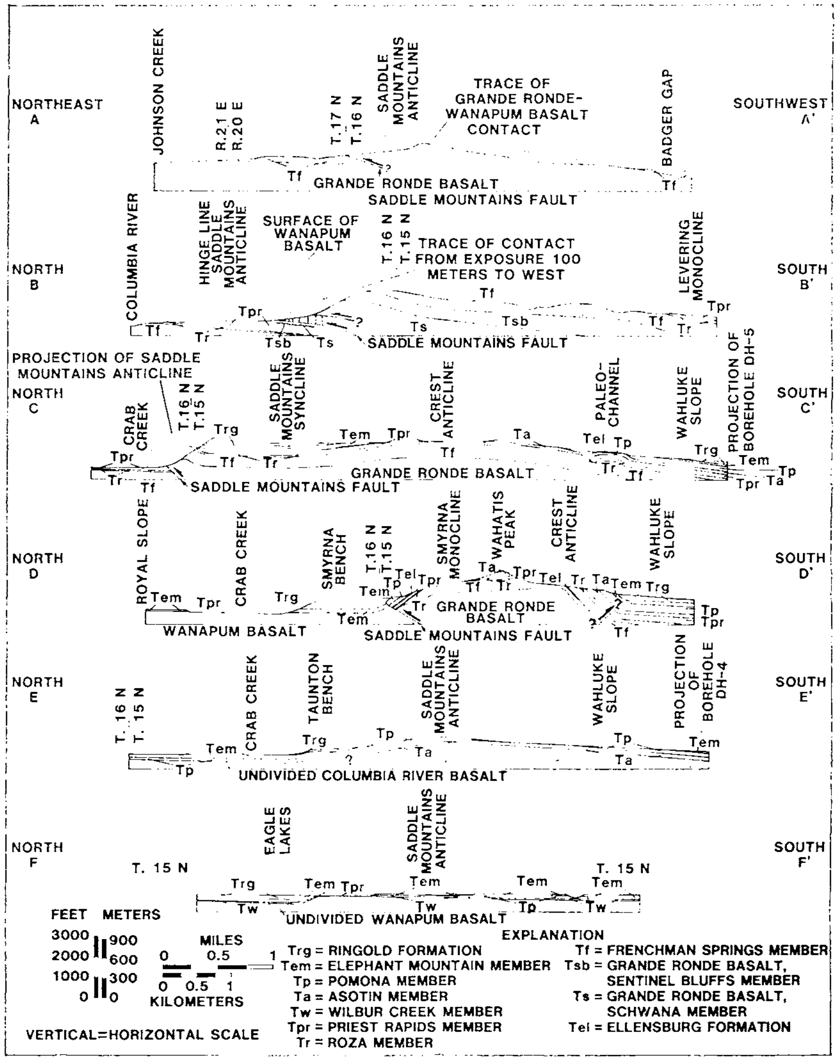


Fig. 5. Geologic cross sections of the six segments of the Saddle Mountains. (A-A′) Boylston Mountains segment, (B-B′) McDonald Springs segment, (C-C′) Sentinel Gap segment, (D-D′) Smyrna Bench segment, (E-E′) Saddle Gap segment, and (F-F′) Eagle Lakes segment. See figure 4 for location of cross sections.

rotation observed in paleomagnetic declinations between two sections of Grande Ronde Basalt on either side of the river (Reidel and Scott, unpub. data, 1983).

In the Smyrna Bench segment, only the Crest anticline is present, and it occurs along the south slope (fig. 5, D-D′). Starting at the junction between the Smyrna Bench and Saddle Gap segments, the Saddle Mountains anticline is sinuous and merges with the Crest anticline and Smyrna monocline. The Saddle Mountains anticline is complicated by the presence of a local thrust fault near the west end of the Saddle Gap segment. In the Saddle Gap segment, the anticline trends 110° but is poorly exposed and may be a series of east-trending en echelon folds. Erosion has dissected this area, and, along with poor exposure, the en echelon folds may be topographic rather than structural features. The en echelon nature of the crest of other folds, such as Horse Heaven Hills, argues for the possibility of en echelon folds in the Saddle Gap segment.

Where the Saddle Gap and Eagle Lakes segments join, the Saddle Mountains anticline changes strike from 110° to 90°. Offset of approx 500 m in a right-lateral sense is suggested. In the Eagle Lakes segment, the north limb dips steeply but is disrupted by a series of discontinuous, left-stepping en echelon folds several kilometers long (fig. 3). A broad, low-amplitude syncline separates the en echelon folds from the Saddle Mountains anticline. Amplitude decreases eastward to where the fold is covered by undeformed Ringold sediments at apparently its eastern terminus.

Saddle Mountains fault.—The Saddle Mountains fault occurs along the base of the north slope of the Saddle Mountains (Laval, ms; Grolier, ms; Grolier and Bingham, 1971, 1978; this study). The continuity of this fault east from the Boylston Mountains (Swanson and others, 1979a) is the basis for my inclusion of this segment into the Saddle Mountains uplift. At Foster Springs Bentley (1977) interprets the Saddle Mountains fault (figs. 1 and 3) as a high-angle reverse fault, but I have mapped two thrust faults there that repeat the Sentinel Bluffs sequence and the upper flows of the Schwana sequence. At the west side of Sentinel Gap (fig. 5, B-B′), the Saddle Mountains fault is a thrust fault, but east of Smyrna Bench, the basalt dips steeply on the north flank of the uplift, and the Elephant Mountain Member appears to be unfaulted, although this cannot be demonstrated because of poor exposure (Grolier and Bingham, 1971; this study). This suggests that either the Saddle Mountains fault does not extend east of Smyrna Bench, or deformation is less apparent to the east.

On the west side of Sentinel Gap, the fault zone (fig. 5, B-B′) is a complex series of thrust faults. The greatest deformation occurs in the hinge zone of the Saddle Mountains anticline, but, about 1 km south, folded Grande Ronde Basalt flows have been thrust north over east-striking, vertical flows of Grande Ronde Basalt that, in turn, are thrust over gently south-dipping flows of the Priest Rapids Member. The upper thrust fault terminates within the hinge zone, but the lower fault is continuous with the Saddle Mountains fault. The upper fault consists of a thick (~20 m) breccia with shear zones that strike 60° to 90° and dip 30° to 40° south. Vertical beds between the two faults consist primarily of shatter breccia but still retain primary structures. The lower fault, the Saddle Mountains fault, is not well exposed. There are ~550 m of vertical offset and a minimum of about 3 km of total shortening.

Within the hinge zone on the west side of Sentinel Gap, vertical faults, striking 45° to 90°, offset gently south-dipping shear surfaces that crosscut the vertical flows. Slickensides are predominantly vertical but locally are subhorizontal. Faults parallel the vertical beds and probably result from flexural-slip folding. Between individual flows above the two main faults are small slip surfaces subparallel to the flow contacts with generally low-angle (30°) dips.

On the east side of the gap, the Saddle Mountains anticline is overturned, and the Saddle Mountains fault is poorly exposed. An abrupt change in bedding dip from gently south to vertical occurs about 100 m above the Saddle Mountains fault in Crab Creek; this suggests the presence of several smaller thrust faults similar to the west side of Sentinel Gap and Foster Springs.

The base of the Saddle Mountains fault on the west side of Smyrna Bench is marked by a zone of tectonic breccia 1 m thick, but the zone of faulting is 400 m wide and involves deposits as young as those of the Ringold (5-3.5 Ma). Vertical to overturned flows of Wanapum Basalt and the Elephant Mountain Member, and sediments of the Ringold overlie gently dipping Elephant Mountain basalt. A minimum of 300 m of vertical offset occurs, but the amount of shortening cannot be estimated. Numerous east-striking reverse faults dip 40° to 50° south, generally with ~10 m offset.

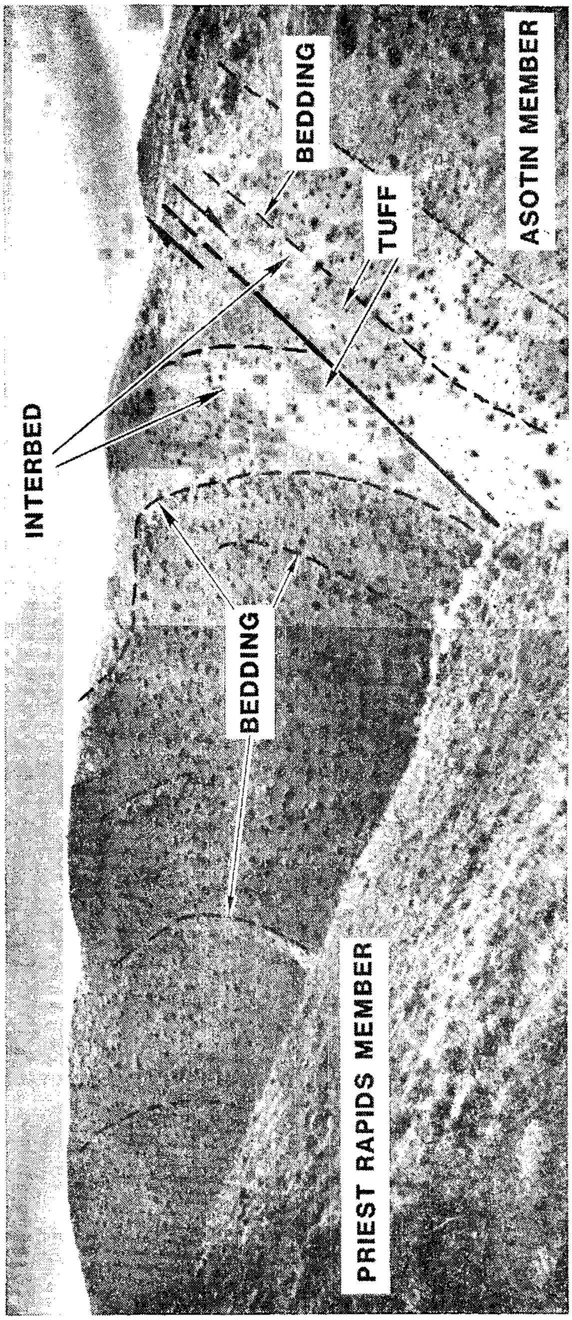
On the east side of Smyrna Bench, the Priest Rapids, Asotin, and Pomona Members are overturned (fig. 3) and dip 40° south. A high-angle reverse fault offsets a tuffaceous interbed (pl. 1) that occurs between the Priest Rapids and Asotin Members. Overturning abruptly ends at the junction with the Saddle Gap segment.

Minor Structures.—In addition to the Saddle Mountains anticline and fault, many minor folds and faults are present. These structures are secondary but are primarily responsible for differences in geometric shape among the segments and play an important role in the evolution of the Saddle Mountains. Minor structures are discussed by segments, concentrating on those I have mapped.

The south slope of the McDonald Springs segment is gently dipping with four monoclinal flexures (figs. 3 and 5, B-B′) having dips that are 18° or less. Only the southernmost monocline, the Levering monocline, has been mapped east of the Columbia River.

The Sentinel Gap segment is one of the most complex in the Saddle Mountains. The trace of the Crest anticline is separated by ~300 m, in a left-lateral sense, along a north-trending fault near the middle of the segment. The fault, however, apparently formed before eruption of the Pomona Member, because it does not offset the Pomona. The Crest anticline decreases in amplitude and may die out toward the fault suggesting it formed independently on either side of the fault. Several smaller folds are present on either side of the fault. West of the fault, two folds less than 4 km long, make a sharp bend from northwest to northeast. These folds are asymmetric with a south vergence. The bend coincides with a northwest-trending paleochannel eroded into the Asotin Member and filled with folded basalt of the Pomona Member. The paleochannel is an apparent zone of shear or faulting; movement began post-Asotin to pre-Pomona time (~13 Ma), with deformation continuing after the Pomona was emplaced. Age of youngest movement is not known.

PLATE 1



Overturned Priest Rapids Member at the east end of Smyrna Bench. Note the change from north-dipping to overturned south-dipping basalt and high-angle reverse fault offsetting tuffaceous interbed.

The Saddle Mountains syncline (Grolier and Bingham, 1971) parallels the Crest and Saddle Mountains anticlines. It is continuous from Sentinel Mountain (fig. 1) to within 1 km of Smyrna Bench, where it terminates against an east-trending fault. Several northwest-trending cross folds locally divide the syncline into two smaller basins (Schmincke, ms; this study, fig. 3B).

The Smyrna Bench segment has a conjugate fold geometry and is more tightly folded than the other segments. The Smyrna monocline on the north flank parallels the Crest anticline (fig. 3B). The monocline has a sharply defined hinge zone, in contrast to the more open hinge of the Crest anticline. The Smyrna monocline merges with the anticline east of Smyrna Bench but dies out west of the bench; the flows are locally overturned on the steeper north limb.

Two cross structures occur in the Smyrna Bench segment: Smyrna anticline and the Smyrna fault. The Smyrna anticline (Reidel, 1978) is oriented northwest and has nearly been obliterated by the east-trending folds; it now forms a structural high along the Saddle Mountains.

Parallel to the Smyrna anticline is the Smyrna fault zone, which marks the transition from the Sentinel Gap segment to the Smyrna Bench segment. Shear is apparently distributed across at least a 100-m-wide zone, and right-lateral movement is suggested along the primary fault. Slickensides plunge up to 65° north. Dip direction locally changes from north to south across this fault, and several of the larger faults may have up to 100 m of offset. The fault zone is restricted to the north slope of the Saddle Mountains and cannot be traced north into Crab Creek.

The junction between the Smyrna Bench and Saddle Gap segments is marked by a change from a tight- to open-fold geometry (fig. 5, D-D′, E-E′) which Glass and Slemmons (1977) interpreted from air photographs as a fault. A local fault occurs at the east end of the Saddle Mountains fault, where bedding changes from overturned to north dipping, and the paleomagnetic declinations of the Pomona Member change across this zone (Reidel and others, 1984), but no fault can be shown to mark the junction of the two segments.

Two minor structures were observed in the Saddle Gap segment: a monocline occurs along the north flank and an east-trending thrust fault along the southern margin of the landslide near Corfu. The monocline terminates near Smyrna Bench, but Lewis (ms) has been able to trace it east through the landslide to Taunton Bench. The thrust fault is poorly exposed near the headwall of the landslide. It is less than 6 km long as indicated by unfaulted rock on either end of the landslide. Recent mapping by Reidel and Lewis (unpub. data) has shown that near vertical beds of Elephant Mountain, Pomona, and Asotin Members have been thrust north onto gently north-dipping Elephant Mountain basalt. Lewis (ms) interprets this fault to be a primary factor in controlling the Corfu landslide. This fault is a local feature that occurs at the change in fold geometry near the junction of the Smyrna Bench and Saddle Gap segments. I interpret this fault to have developed in a manner similar to that described by Price (1982) for the mechanical development of the Buck thrust at Umtanum Ridge. The Saddle Mountains anticline changes strike from 115° to 75° about a vertical axis. Because nearly horizontal flow layering cannot mechanically fold about a vertical axis, further shortening must proceed by thrusting of the rigid basalt flows north over the vertical fold axis with the thrust dying out away from the vertical hinge.

The junction between the Eagle Lakes and Saddle Gap segment is marked by a sharp change in strike and apparent offset of 500 m which coincides with the northern projection of the vent system for the Basin City flow. Swanson, Wright, and Helz (1975) interpreted the Basin City flow as filling a graben 15 m deep and 150 m wide in the Elephant Mountain Member. However, my detailed mapping shows that the Basin City flow fills an erosional channel cut into the Ward Gap flow and rests on the Elephant Mountain flow. No graben is present, but I interpret the channel to be controlled by a northwest-trending shear system that also probably controlled the Basin City dike system and offset the Saddle Mountain anticline. The difference in interpretations results from my recognition of remnants of the Ward Gap flow that are preserved only in the troughs of a series of broad (1-km fold wavelength), low-amplitude (<30 m) synclines that strike 130° across the area (fig. 3B).

LOCATION AND TIMING OF DEFORMATION

This section describes the thickness variations and lateral extent of basalt flows and sedimentary deposits and demonstrates how these data are used to determine the location and timing of deformation.

Thickness measurements were made principally using a surveying tape and occasionally using the Jacob's Staff method; all data were corrected for structural tilt. Except for flows not overlain by younger flows, all measurements were made where both the upper and lower contacts are exposed or well controlled. Where flows are not overlain by younger flows, thicknesses were used only where strong evidence could be found for the absence of erosion (that is, broad, planar dip slope, consistent flow top thickness). Erosion was determined by interpreting the nature of the primary flow features and in particular the scoraceous flow top. Continuous core from basalts in the Pasco Basin was used to help estimate normal thickness variations in the flow top. Areas where erosion has modified the thickness of the flows are not shown using data points on isopach maps but are used only as minimum thicknesses for helping control the location of isopach lines. Data points on the isopach maps are generally representative for the surrounding area, unless additional points are shown. Where control is poor due to significant erosion or cover by younger flows, no isopach lines are shown. Primary flow features such as invasive flows (Byerly and Swanson, 1978) and flow edges are based upon field criteria. Flow edges are shown as solid lines on isopachs where field data are definitive and dashed where control is less certain.

Grande Ronde Basalt.—The Grande Ronde Basalt is exposed principally near Sentinel Gap, but because the flows are poorly exposed elsewhere and similar in appearance, thickness variations are difficult to determine. Variations in the total thickness of the Grande Ronde cannot

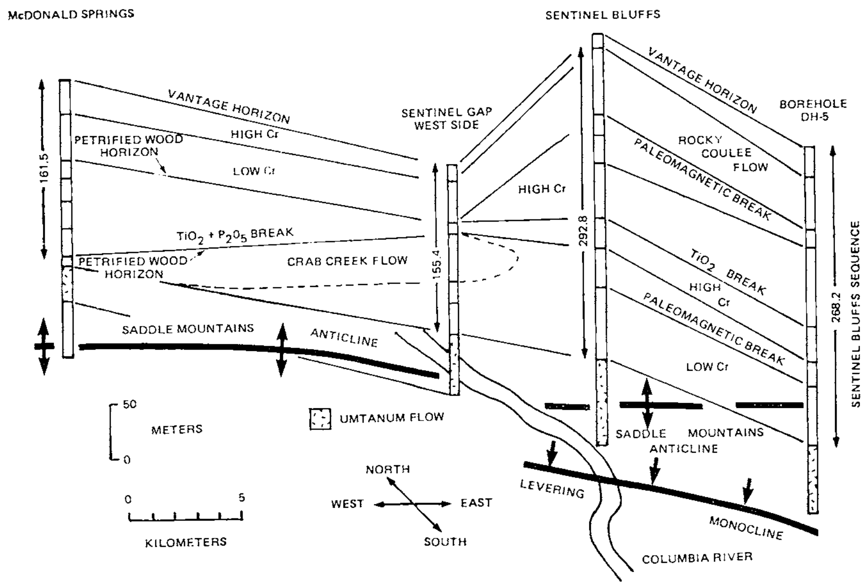


Fig. 6. Stratigraphic correlation of four measured sections of Grande Ronde Basalt in the Sentinel Gap area. McDonald Springs and Sentinel Gap West Side are from this study; Sentinel Gap East Side is from Taylor (1976), Long (1978), and this study; borehole DH-5 is from Myers and others (1979). The base of each stratigraphic section is positioned with respect to structures in figure 3B. Sentinel Bluffs sequence consists of all basalt above the Umtanum flow. Base of McDonald Springs section is on a fault that repeats entire sequence of flows.

be demonstrated because of the lack of a complete section, but thickness variations in the Sentinel Bluffs sequence (high-Mg chemical type, fig. 2) indicate that the Grande Ronde Basalt flows thin and some pinch out on the Saddle Mountains uplift (fig. 6). East of Sentinel Gap and several kilometers south of the fold hinge of the Saddle Mountains anticline, the Sentinel Bluffs sequence is ~293 m thick (Taylor, ms; Long, 1978; this study). Nine kilometers to the southeast, the Sentinel Bluffs sequence is 268 m thick (fig. 6, borehole DH-5), but along the fold hinge, it is only 155 m thick on the west side of Sentinel Gap and 162 m thick at McDonald Springs (fig. 6). Stratigraphic sections measured at the northeast side of Sentinel Gap are also thinner than at the southeast side of Sentinel Gap. The presence of a chemically distinct flow (fig. 6, Crab Creek flow) along the fold hinge both northeast and northwest of Sentinel Gap, but not in the Sentinel Gap section or in borehole DH-5, suggests that the Saddle Mountains uplift prevented this flow (and possibly others) from entering the Pasco Basin. Thus even more structural relief might be present in the Saddle Mountains.

The lateral extent and facies changes of the Vantage Member of the Ellensburg Formation also indicate that the Saddle Mountains anticline was a topographic high before eruption of the Wanapum Basalt. The Vantage within the Pasco Basin is interpreted to be thickest in a basin

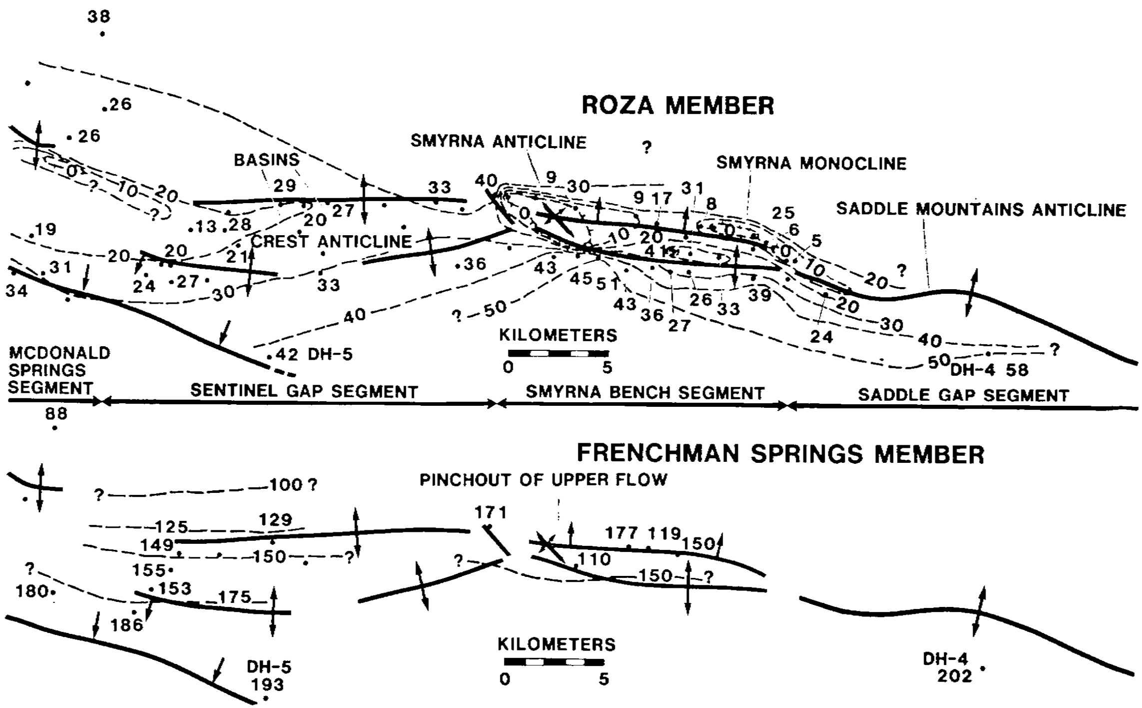


Fig. 7. Isopach maps of the Frenchman Springs and Roza members in the Saddle Mountains. Stippled pattern is area of nondeposition. Major structural axes are from figure 3B. Isopleths and data points are in meters. Actual and inferred original extent of Roza flow is shown; see text for description of thickness control.

formed where the regional westward-tilting paleoslope was disrupted by the Hog Ranch-Naneum Ridge anticline (Reidel and Fecht, 1981). The Vantage Member was deposited in a similar basin north of the Saddle Mountains. In the Saddle Mountains, the Vantage pinches out against the structure; it is 9 m thick on the west side of Sentinel Gap, 6 m thick on the east side, and thins to where it pinches out against the hinge zone of the Saddle Mountains anticline. In the Smyrna Bench segment, the Vantage is a saprolite, and the fluvial sandstone that typically occurs elsewhere has not been found east of a single, 6-m thick exposure at the northern boundary of the Sentinel Gap and Smyrna Bench segments.

Frenchman Springs Member.—The Frenchman Springs Member of the Wanapum Basalt (fig. 2) consists of three flows in the Saddle Mountains but is generally covered by younger flows. An isopach map of the Frenchman Springs (fig. 7) shows thicknesses ranging from 110 to 202 m in the Saddle Mountains. There are two areas where the basalt flows either thin or pinches out: a northwest-trending zone across the Smyrna anticline (Reidel, 1978) and an east-trending zone in the Sentinel Gap segment.

The best exposed cross section in the Saddle Mountains is at Sentinel Gap, where, in 6 km, the Frenchman Springs Member thins 64 m toward the hinge of the Saddle Mountains anticline. The thickness remains nearly constant from borehole DH-5 south into the Pasco Basin and thins gradually north of the Saddle Mountains. In the regional pattern, the Saddle Mountains represent an area of abrupt thinning superimposed on a broader pattern of gradual northward thinning. Exposures do not permit a more thorough examination of thickness variations.

The Frenchman Springs Member generally covers the Grande Ronde Basalt in the Smyrna Bench segment, so the total thickness is not available. The upper flow of the Frenchman Springs, however, pinches out on either side of the Smyrna anticline suggesting the anticline had structural relief at this time.

Older Frenchman Springs flows are confined to the Pasco Basin and only younger ones reached the Saddle Mountains. Many flows have extensively pillowed bases only on the north side of the Saddle Mountains; these pillows indicate the presence of water and suggest that the north flank of the Saddle Mountains controlled drainage at this time.

Roza Member.—The Roza Member, like the Frenchman Springs, is exposed best in the Sentinel Gap and Smyrna Bench segments (fig. 7). Thinning occurs in three zones: Saddle Mountains anticline, Smyrna monocline, and Smyrna anticline. The Roza thins to 13 m in Sentinel Gap and to 10 m in the Saddle Gap segment approaching the Saddle Mountains anticline. In the Smyrna Bench segment, it thins and locally pinches out along the Smyrna monocline with the Priest Rapids Member directly overlying the Frenchman Springs. Two basins on the north side of the Sentinel Gap segment (fig. 3B, northwest-trending synclines) were also developing at this time; the Roza thickens into both basins and thins 7 to 9 m across the intervening anticline. West of Sentinel Gap the Roza has been eroded, and, except near Foster Springs, its original extent is speculative.

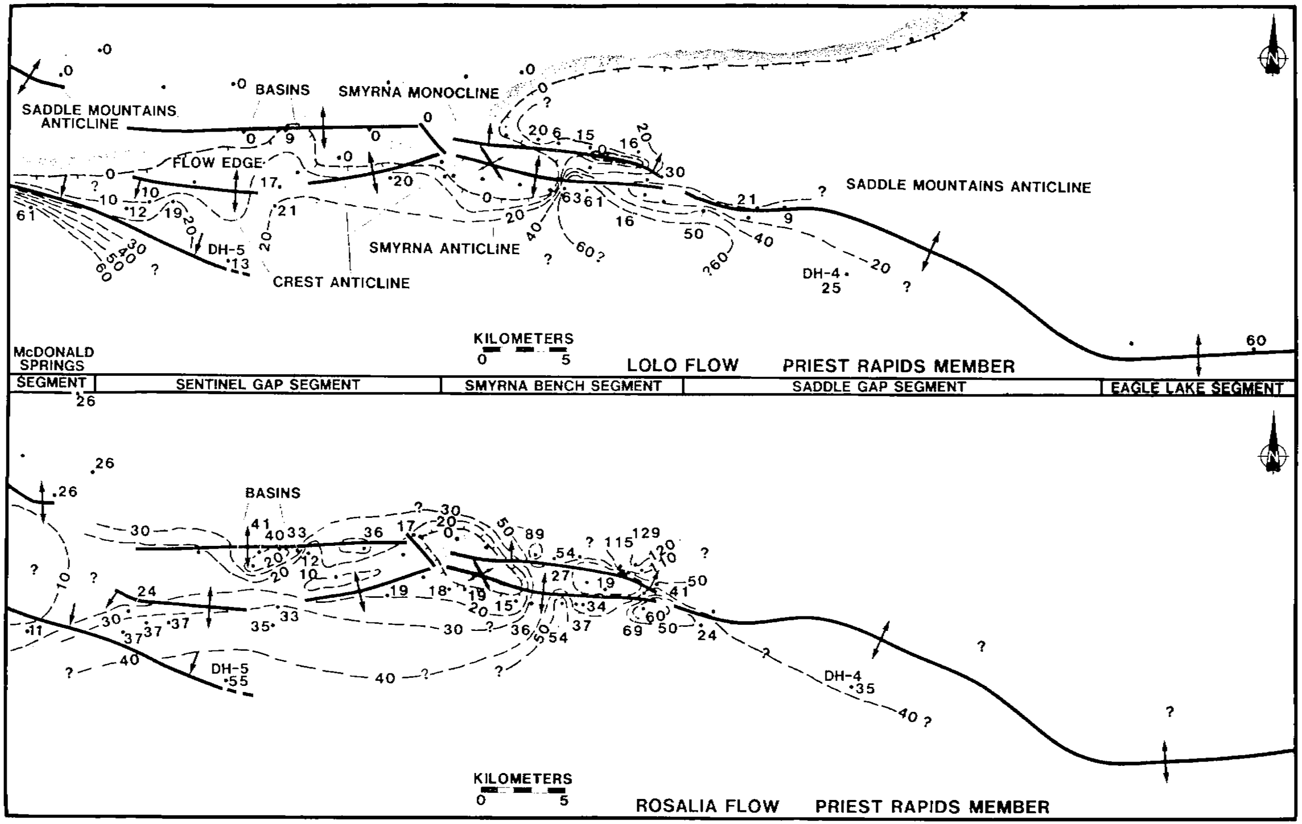


Fig. 8. Isopach maps of the Rosalia and the Lolo flows in the Saddle Mountains. Stippled pattern is area of nondeposition. Major structural axes are from figure 3B. Isopleths and data points are in meters. Actual and inferred original extent for both flows is shown; see text for description of thickness control.

The Roza thins to about 20 m across the Smyrna anticline where the anticline crosses the south flank of the Saddle Mountains uplift and is absent over a 4-km distance where the anticline crosses the north flank. Based upon the lateral extent and thickness of the Roza, the Smyrna anticline is interpreted to have been a broad (5- to 7-km wide), low-amplitude fold.

Priest Rapids Member.—Thickness variations in the flows of the Priest Rapids Member (fig. 8) are similar to those of the Roza Member. Both flows of the Priest Rapids Member thin and locally pinch out across the Saddle Mountains anticline in the Sentinel Gap and Saddle Gap segments, across the Smyrna monocline, and across the Smyrna anticline.

The Rosalia flow is absent over a 4-km distance where the Smyrna anticline crosses the north flank of the Saddle Mountains uplift and is less than 15 m thick over a 4-km distance where the anticline crosses the south flank; this occurs several hundred meters west of where the Roza thins and approximately where the upper Frenchman Springs flow pinches out. This suggests that the Smyrna anticline is a northwest-trending structure that disrupts the westward-tilting regional paleoslope; this is supported by the anomalous thickening of flows, up to 129 m in a 5-km wide area east of the Smyrna anticline, which resulted from ponding of basalt flows against this anticline as they flowed west. Thickening is greatest on the north side of the Saddle Mountains uplift but does not extend east of Smyrna Bench; this is interpreted as ponding against both the Smyrna anticline and monocline.

The Lolo flow is less extensive than the Rosalia flow but follows a similar pattern (fig. 8). In the Sentinel Gap segment, it pinches out south of the hinge line of the Saddle Mountains anticline and spread only into the easternmost northwest-trending basin. As shown in figure 8, the Saddle Mountains uplift apparently controlled the northern margin of the Lolo flow west of the center of the Smyrna Bench segment. The Lolo is covered by younger flows in the Eagle Lakes segment; one exposure, however, indicates it is at least 60 m thick, probably as the result of ponding against the Saddle Mountains anticline.

Wilbur Creek Member.—The Wahluke flow (fig. 2) of the Wilbur Creek Member is exposed north of the Saddle Mountains as an intracanyon flow (Grolier and Bingham, 1971; Swanson and others, 1977; this study) but is more extensive in the Eagle Lakes area (fig. 9). The eastern edge of the flow occurs at Scooteney Reservoir (fig. 1); its western edge is covered by younger flows and can only be approximated by the interpretation of aeromagnetic data (WPPSS, 1977; Myers and others, 1979; Zietz and others, 1971; and Swanson, Wright, and Zietz, 1979). Based on these data, Saddle Gap (fig. 1) is probably the western limit of the flow. Thickness data are sparse due to limited exposures, but near the western part of the Eagle Lakes segment, the flow apparently thins across the Saddle Mountains anticline. South of the Saddle Mountains, the Wahluke overflowed its channel but was directed farther south along the distal edge of the Umatilla Member (Reidel and others, 1980; Reidel and Fecht, 1981).

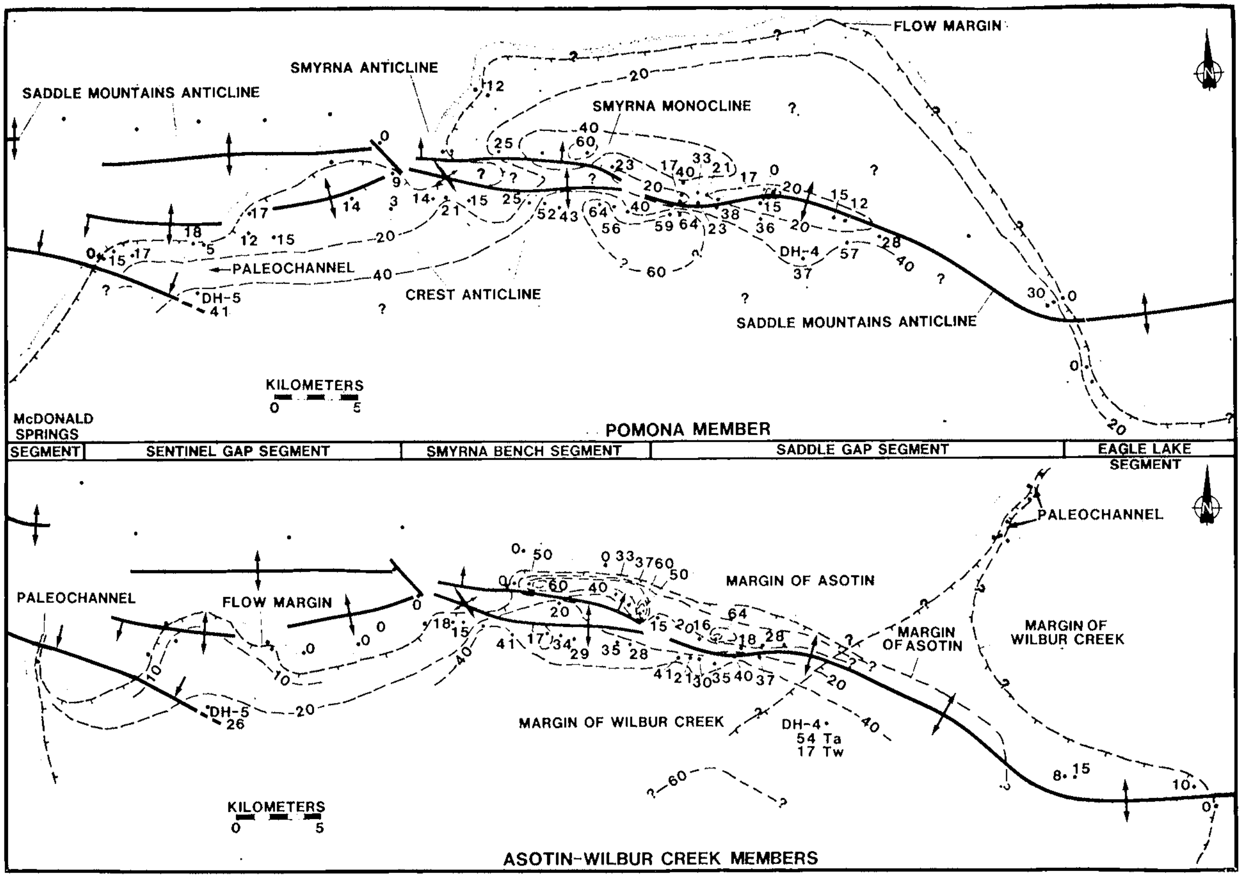


Fig. 9. Isopach maps of the Wilbur Creek, Asotin, and Pomona members in the Saddle Mountains. Stippled pattern is area of nondeposition. Major structural axes are from 3B. Isopleths and data points are in meters. Actual and inferred original extent for the flows is shown; see text for description of thickness control.

Asotin Member.—The Huntzinger flow of the Asotin Member occurs in the northern Pasco Basin (Reidel and others, 1980; Reidel and Fecht, 1981). Its distribution is irregular across the Saddle Mountains (fig. 9). The overall thickness variation is consistent with that of older flows. The Asotin thins toward the Saddle Mountains anticline, and in the Smyrna Bench segment, it thins across the Smyrna monocline. The Asotin pinches out on the northeast flank of the Smyrna anticline and thins where the anticline crosses the south slope of the Saddle Mountains uplift.

The westernmost exposure of the Huntzinger flow is a paleochannel in the McDonald Springs segment. The flow fills a north-trending channel of the paleo-Columbia River which is cut into the Priest Rapids Member. Pillowing of the flow throughout the channel suggests that the flow moved north up the channel as water flowed south.

The Huntzinger flow is nearly absent from the Sentinel Gap segment, occurring primarily as an invasive flow in a small embayment in the southwestern part of the segment. The Huntzinger is well exposed in the Smyrna Bench segment and the western part of the Saddle Gap segment. Along the northeastern flank of the Smyrna anticline, the Huntzinger is an intracanyon flow separated from the main body of the flow by a distance of 0.5 km. The trend is northward and is apparently an erosional channel cut into the eastern flank of the Smyrna anticline.

In the Saddle Gap segment, the Huntzinger flow thins across the Saddle Mountains anticline but pinches out in the eastern part of the segment. It is not present in the Eagle Lakes segment.

Pomona Member.—The Pomona Member in the mapped area consists of one flow, but, in several nearby areas, there are two flow lobes (as in borehole DH-4, Reidel and others, 1980). Thickness variations in the Pomona follow the same basic pattern as in previous flows; the flow thins toward or over the Saddle Mountains and Smyrna anticlines. Exposures are not present along most of the Smyrna monocline.

The western margin of the Pomona (Schmincke, 1967; this study) occurs in the southwestern part of the Sentinel Gap segment near the western edge of the Huntzinger flow (fig. 9). Nine kilometers to the east, the Pomona fills a structurally controlled paleochannel in the Huntzinger.

Erosion has removed the Pomona from all but the north and south flanks of the uplift in the Smyrna Bench segment. The flow pinches out against the northeast flank of the Smyrna anticline and thins across the anticline on the southern flank of the Saddle Mountains uplift. The Pomona is anomalously thick east of the anticline.

The eastern margin of the flow occurs at the junction between the Saddle Gap and Eagle Lakes segments, along the projection of the Basin City dike system, and at an offset in the Saddle Mountains anticline. Natural Corral Canyon (fig. 1) is located at the northwestern margin, and the northeastern margin occurs near the margins of the Lolo and the Elephant Mountain flows and at the intersection of the westward- and southward-tilting paleoslopes.

Elephant Mountain Member.—The Elephant Mountain Member is the youngest member present in the Saddle Mountains and consists of two flows. The lower flow is the more extensive of the two (Reidel and others, 1980), but both flows thin and pinch out along the flanks of the Saddle Mountains uplift (fig. 10). For the most part, the exact extent of thinning and lava encroachment onto the Saddle Mountains uplift cannot be determined due to erosion. Several localities in the Sentinel Gap, Saddle Gap, and Eagle Lakes segments, however, provide exposures from which interpretations of the extent of this member on the Saddle Mountains can be made.

The farthest advance of the Elephant Mountain onto the Saddle Mountains from the south can be documented both at Sentinel Gap and in the east-central part of the Sentinel Gap segment. Only the older flow is present on the northern side, where it occurs in two basins and pinches out against the Crest anticline. The Jericho "flow lobe," north of the Saddle Mountains along the Columbia River (Grolier and Bingham, 1978), may represent the paleo-Columbia River channel.

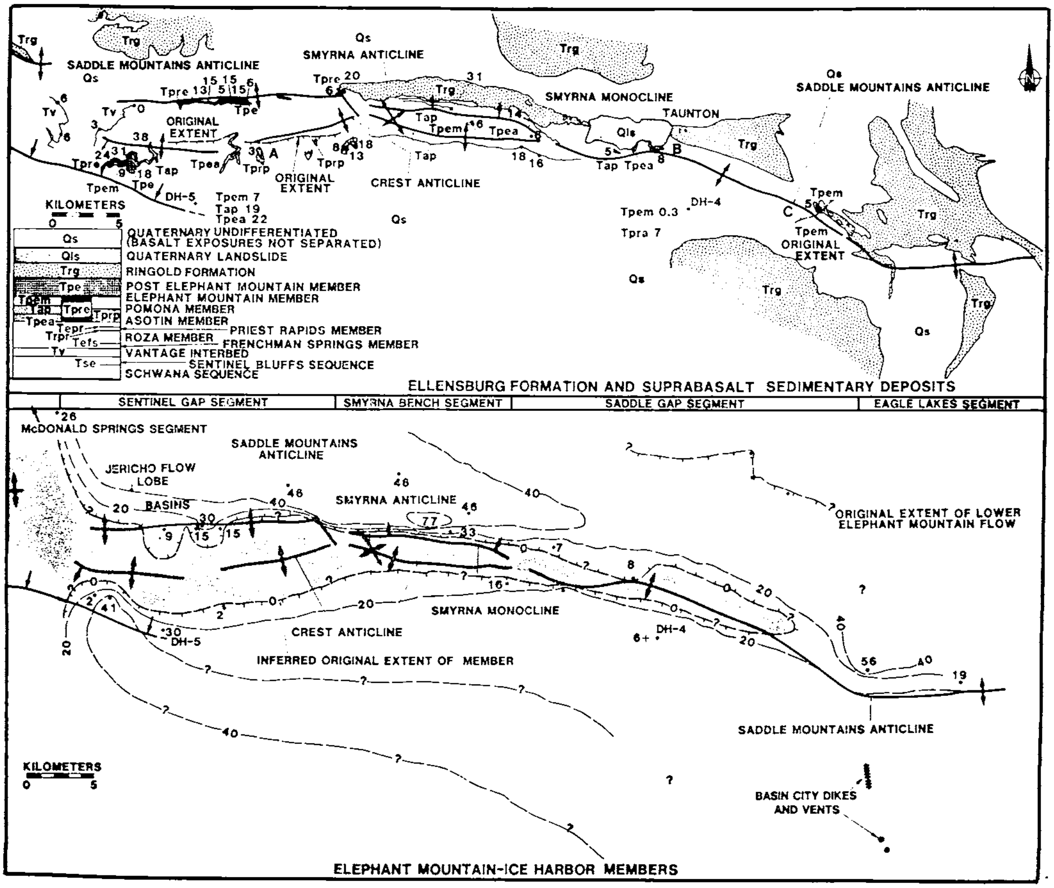
The Elephant Mountain Member covered at least part of the Smyrna anticline, but thinning across the anticline cannot be documented. The older flow ponded against the northern side of the Saddle Mountains, where it is more than 50 m thick. Its northern margin occurs at about the same location as that of the Lolo flow and Pomona Member.

The Elephant Mountain is present near the crest of the Saddle Mountains uplift only in the Eagle Lakes and eastern part of the Saddle Gap segments. On the eastern side of the Saddle Gap segment, a conglomerate from a stream marginal to the flow occurs at the westernmost point where the Elephant Mountain covered the Saddle Mountains anticline.

Ice Harbor Member.—The Ice Harbor Member occurs primarily in the southeastern Pasco Basin (Grolier and Bingham, 1971; Swanson, Wright, and Helz, 1975), but the northernmost exposures of the Basin City flow occur 6 to 10 km south of the crest of the Saddle Mountains in the Eagle Lakes segment (fig. 10). This occurrence aligns with several feeder dikes and an interpreted linear, fault-controlled stream channel. Thicknesses of the Basin City flow were not measured. The Ice Harbor dike system projects near the eastern margin of the Pomona Member and the interpreted edge of the Huntzinger flow near the junction between the Saddle Gap and Eagle Lakes segments. This projection suggests that the Ice Harbor dike system lies on a more regional zone of deformation, which may have been active through much of the Miocene. This may be a zone of strike-slip faulting similar to that described by Bentley (1980) for areas to the west.

Ellensburg Formation and suprabasalt sediments.—Sedimentary deposits of the Ellensburg Formation occur between many of the basalt flows and were typically laid down by south- and southwest-flowing streams (Schmincke, ms; Reidel and Fecht, 1981; Fecht, Reidel, and Tallman, 1982). The Ellensburg Formation chiefly consists of subarkosic sandstone, water-laid tuff, basaltic conglomerate, and fine siltstone and claystone (Schmincke, ms; Grolier and Bingham, 1978; Reidel and Fecht, 1981; Fecht, Reidel, and Tallman, 1982; this study). The Vantage Member contains an additional saprolite facies. Current directions indicate that the rivers were flowing south and southwest (Schmincke, ms). Near Sentinel Gap, the Vantage Member and the Beverly Member, which includes sediments deposited between the Priest Rapids and Elephant Mountain Members (Grolier and Bingham, 1971), show transport directions of 160° to 190°; the Beverly Member north of the Saddle Mountains near Smyrna Bench indicates a 225° transport direction (Schmincke, ms). A decrease in grain size and thickness of the Vantage Member from Sentinel Gap to Smyrna Bench suggests that the ancestral Columbia River was following a course through Sentinel Gap close to the present one (Schmincke, ms).

Other rivers apparently followed westward courses *along* the Saddle Mountains at this time. These rivers are interpreted to have been diverted from their erosional channels by lava flows into marginal channels that followed courses between flow margins and the flank of the Saddle Mountains anticline. One example (site A, fig. 10) occurs on the southeast side of the Sentinel Gap segment, where sandstone was deposited by a westward-flowing stream between the margin of the Huntzinger flow and the



flank of the uplift. A second example (site B, fig. 10) occurs in the Saddle Gap area where a sequence of sandstone, siltstone, and claystone occurs along the northern margin of the Pomona Member. A third example (site C, fig. 10) occurs on the eastern part of the Saddle Gap segment, where a conglomerate occurs on the edge of the Elephant Mountain Member. In these examples and in many others, invasive relationships such as those described by Byerly and Swanson (1978) were not observed, and the contact between the basalt flows north or south of the channel has no sediment.

In other areas along the Saddle Mountains uplift, sedimentary deposits thin and pinch out against the Saddle Mountains anticline. At these localities, many flows are invasive into the sedimentary deposits, and bases of flows are generally pillowed. Here time between flows was sufficient to allow streams to fill the paleo-Pasco Basin with sediments and gradually bury the ridges (Reidel and Fecht, 1981; Fecht, Reidel and Tallman, 1982).

The youngest recognized deposits of the Ellensburg Formation uncomformably overlie the basalt at an elevation of 548 m near Sentinel Gap. These deposits are composed chiefly of quartzite and rounded basalt, apparently deposited by the ancestral Columbia River. Their age is about 8.5 Ma (Ice Harbor age), based upon maximum elevation and estimates of the rate of uplift.

The Ringold Formation (Newcomb, 1958; Brown and McConiga, 1960; Mackin, 1961) overlies the Saddle Mountains Basalt. Its age at Taunton Bench (fig. 10) is estimated at between 5 to 3.5 Ma (Packer and Johnston, 1979; Tallman, Lillie, and Fecht, 1981). At Taunton Bench the section consists of stream channel conglomerates, point bar sandstones, fine-grained flood-plain overbank deposits, and lacustrine deposits (Principle, ms). At Smyrna Bench, the Ringold consists of basaltic fanglomerates intercalated with finer grained fluvial sediments. Between Smyrna Bench and the Columbia River, most of the Ringold has been removed by catastrophic flooding during the Pleistocene. Thick sections of basaltic fanglomerate preserved in the basins in the Sentinel Gap segment are similar to that at Smyrna and Taunton Benches described by N. P. Campbell (*in* Rigby and Othberg, 1979). These basaltic fanglomerates are interpreted to result from erosion of the Saddle Mountains as they were uplifted. West of Sentinel Gap, the Ringold is fine grained and unconformably overlies vertical flows of Wanapum Basalt.

The Ringold Formation is locally present higher on the Saddle Mountains, occurring on the crest as far west as the junction of the Saddle Gap and Eagle Lakes segments and along the flanks of the structure as far

← Fig. 10. Isopach maps of the Elephant Mountain and Ice Harbor members and of the Ellensburg Formation and suprabasalt sediments. Stippled pattern is area of nondeposition for Elephant Mountain Member. Major structural axes are from figure 3B. Isopleths and data points are in meters. Actual and inferred original extent of the two flows of the Elephant Mountain Member is shown; see text for description of thickness control.

west as the McDonald Springs segment. The Ringold has been folded and faulted along with the basalts in most localities.

North of the Saddle Mountains, the Ringold Formation is interpreted to record local ponding and diversion of rivers flowing south and southwest, a drainage pattern similar to that suggested by Schmincke (ms) for the Ellensburg Formation.

DISCUSSION

Age and timing of deformation.—Age of deformation and growth rate of the folds provide valuable information for the development of tectonic models for the Columbia Plateau. Derivation of a tectonic model is beyond the scope of this paper; however, information presented here provides constraints that must be considered in the development of tectonic models.

Previous studies have provided a wide range of interpretations of the age and growth rate of the Yakima folds. Waters (1955) argued that the anticlines near Yakima, Wash., formed over one long episode of deformation rather than a shorter period. Mackin (1961) and Grolier (ms) concluded that the Saddle Mountains did not begin growing until after Priest Rapids time. Schmincke (ms and 1967) also concluded that deformation began after Priest Rapids time but was more pronounced during Saddle Mountains time. Bentley (1977) indicated that deformation occurred 14 to 12 Ma near Priest Rapids Dam and Yakima, but the majority of the ridges rose 6 to 1.5 Ma. Swanson and Wright (1978) interpret the generally east-trending folds to have begun forming during Saddle Mountains time, while some, such as the Hog Ranch-Naneum Ridge anticline, which crosscuts the fold belt, were probably active as early as Grande Ronde time. Beeson and Moran (1979) provide evidence for the development of anticlines in the western part of the fold belt during Grande Ronde time. Barrash, Bond, and Vankatakrishman (1983) proposed a three-stage deformation process with the development of the anticlines during stage two (10-4 Ma).

Studies in specific areas have suggested an even later age of deformation. Bingham, Londquist, and Baltz (1970) concluded that most of the deformation near Smyrna Bench occurred after the Elephant Mountain Member was emplaced (10.5 Ma). Taylor (ms) argued that growth of the Saddle Mountains near Sentinel Gap probably began after Priest Rapids time and reached its greatest intensity after the eruption of the Elephant Mountain Member, a conclusion also reached by Thoms, Anderson, and Bentley (1977).

As shown in the present study, the thickness variations and lateral extent of individual flows indicate that the Saddle Mountains uplift was growing by at least late Grande Ronde time (16-15.5 Ma). Growth was primarily along the present east trend, but cross folds with a northwest trend were also growing. The age and duration of growth of the major structures are summarized in figure 11. Initial growth of the Saddle Mountains was along the present hinge area in the McDonald Springs and Sentinel Gap segments and along the Smyrna monocline in the Smyrna Bench seg-

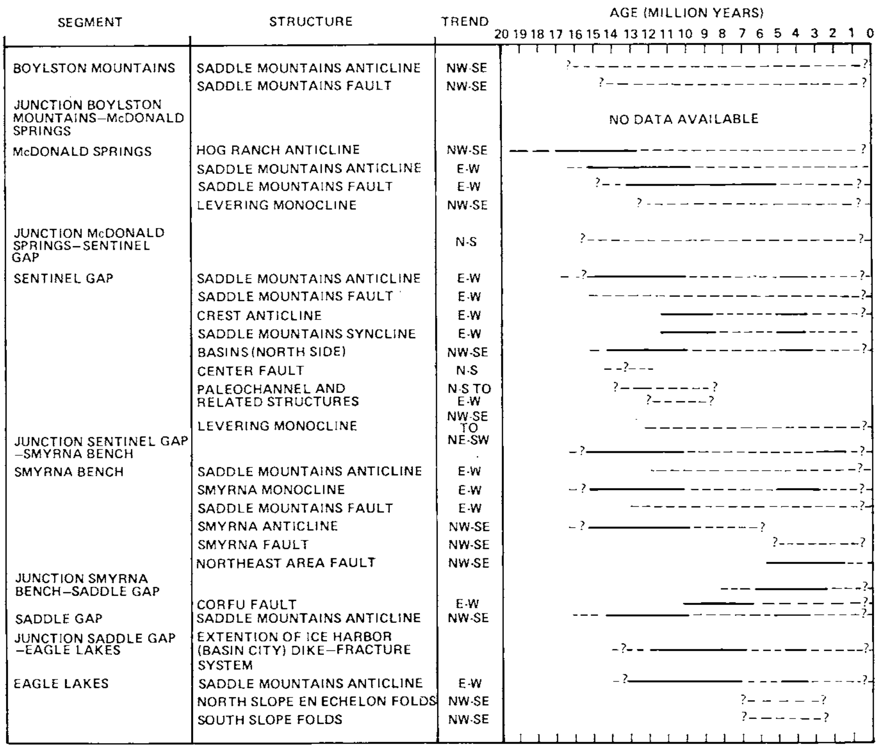


Fig. 11. Interpreted ages of major and minor structures in the Saddle Mountains uplift. Solid line indicates good to excellent control on age; dashed line indicates less certain age constraints.

ment. No evidence of growth along the Crest anticline exists prior to 12 Ma, as indicated by the lack of thickness variations in flows prior to the Pomona Member. The Saddle Mountains anticline was probably also growing in the Saddle Gap and Eagle Lakes segments by at least late Grande Ronde or Wanapum time, although the lack of exposure of these flows does not permit a firm conclusion.

Most minor structures apparently postdate the Pomona (about 12 Ma). The lack of variations in flow thickness across these structures indicates development at the time of or after the Pomona had been emplaced. Some minor structures may be older, however, such as the cross fault in the Sentinel Gap segment that does not displace the Pomona.

Several lines of evidence indicate that the folding and faulting continued well after the Miocene. The presence of folded and faulted Ringold Formation indicates that deformation continued into at least the Pliocene (5-3.5 Ma) and probably later. Shallow microearthquake swarms (Malone, Rothe, and Smith, 1975) also suggest that growth of the Saddle Mountains uplift might be continuing. The composite focal mechanisms indicate that principal compression is oriented north-south and is compatible with continued growth.

The age and degree of development of the various segments suggest that the geometric differences between segments represent stages in the structural evolution. The least deformed segments — Boylston Mountains, Eagle Lakes, and Saddle Gap segments — are the least evolved segments structurally. The most evolved segments are Smyrna Bench and Sentinel Gap. The degree of structural complexity increases from the east and west edges toward the center.

Of special interest are the boundaries of the segments. The distinct geometric differences among the segments and the narrow boundary zones suggest the presence of tear faults or strike-slip faults. Most areas, however, do not permit a straightforward interpretation. Areas of apparent offset include the junctions between the Smyrna Bench-Sentinel Gap segments, the McDonald Springs-Sentinel Gap segments, and the Eagle Lakes-Saddle Gap segments. A zone of strike-slip faulting occurs between the Smyrna Bench and Sentinel Gap segments, but it is confined only to the northern flank of the Saddle Mountains. About 2.7 km of right-lateral offset is interpreted to occur in the hinge zone of the Saddle Mountains anticline in the McDonald Springs-Sentinel Gap area. A strike-slip fault is probably also present in the Saddle Gap-Eagle Lakes area, where the Saddle Mountains anticline is offset. No apparent offset is present elsewhere; the change in trend at the junctions of the Boylston Mountains-McDonald Springs and the Smyrna Bench-Saddle Gap segments could also be explained by tear faults. Structural offsets limit the displacement of these segments to about 1 km or less, but they may be controlled by preexisting basement structures as suggested by the projection under the plateau of major Eocene structures (Ewing, 1980), such as the Chiwaukum and

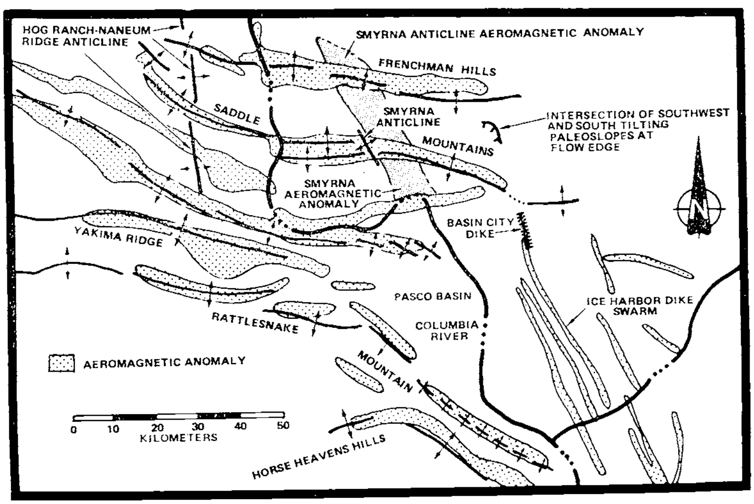


Fig. 12. Aeromagnetic anomaly map of the Saddle Mountains and vicinity. Areas of anomalies associated with the Smyrna anticline and Basin City dike are shown. Aeromagnetic map modified from WPPSS (1977) and geologic structures from Myers and others (1979, pl. 3-1) Swanson and others (1977, 1979a), and this study.

Methow grabens and the Wenatchee Mountains. The only direct connection to a basement structure is the Hog Ranch-Naneum Ridge anticline, which has been traced over 100 km north into the Wenatchee Mountains (Swanson and others, 1979a). The Smyrna anticline and the junction of the Saddle Gap and Eagle Lakes segments are also apparently controlled by basement structures. The Smyrna anticline is at least 30 km long as estimated from its aeromagnetic signature (fig. 12), which is the result of basalts ponding on its eastern side. The junction of the Eagle Lakes-Saddle Gap segments lies along the projection of the Basin City dike system and the intersection of southwest- and west-dipping paleoslopes (fig. 12). Both these features trend toward the Chiwaukum and Methow grabens and may be controlled by the reactivation of basement faults along a northwest or north structural trend.

Rate of uplift.—Fold growth followed by periodic emplacement of basalt flows recorded the topographic (structural) relief of the Saddle Mountains, which is now preserved in the thickness variations of the basalt flows. Most flows covered the uplift, and only a few pinched out on the flanks, thus the relief at several "instants" of geologic time can be determined with a high degree of confidence. This record of structural relief at specific instants of time allows the rate of uplift to be calculated.

Several assumptions are necessary to use the thickness data to calculate the rate of uplift. First, it is necessary to assume that these are low viscosity lava flows whose flow tops are an indicator of paleohorizontality. A second assumption is that thickness variations record existing topogra-

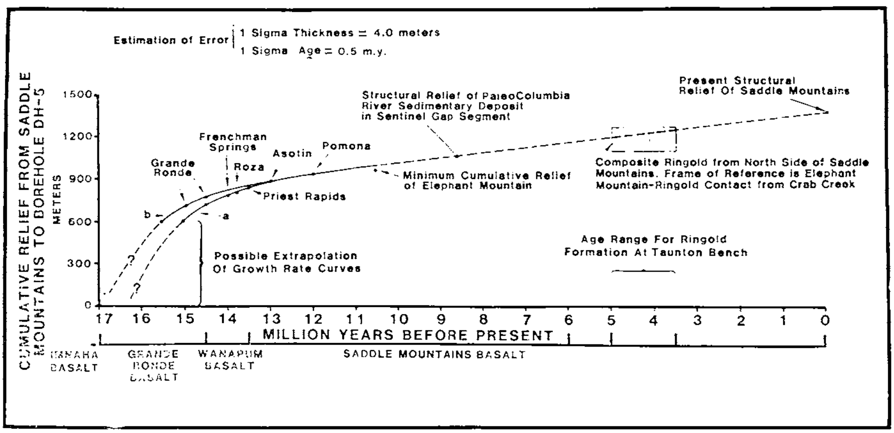


Fig. 13. Long-term uplift rate of the Saddle Mountains uplift. Solid lines and dots show regions of control; dashed lines show areas of extrapolation. Cumulative relief is measured from 600 m point which is the Schwana-Sentinel Bluffs contact (Grande Ronde Basalt High-Mg-Low-Mg contact); below 600 m point are the extrapolated lines. Grande Ronde Basalt age for curve A — Watkins and Baksi (1974) and curve B — Long and Duncan (1982); other ages are from ARHCO (1976), McKee, Swanson, and Wright (1977), McKee, Hooper, and Kleck (1981), and Watkins and Baksi (1974). Error for age dates estimated from McKee, Hooper, and Kleck (1981) and Long and Duncan (1982); error for thicknesses estimated from 1τ for thickness variations of Pomona, Elephant Mountain, Priest Rapids, and Roza members from five closely spaced boreholes in Cold Creek syncline of Pasco Basin (see text).

phy and structure and do not represent normal variations in the flow or erosion. Third, folding or faulting has not altered the original flow thickness since the time of emplacement; and fourth, a reference plane can be found that can be used to distinguish between uplift and subsidence. These assumptions can either be shown to be valid or are reasonable in light of what is presently known about the Columbia River basalt. The Columbia River Basalt Group consists of flood basalts, and based on its mode of eruption (Waters, 1961; Shaw and Swanson, 1970; Swanson and Wright, 1978), the basalt flows were of low viscosity with characteristics that include nearly planar upper and lower surfaces and uniform thicknesses for many kilometers (Shaw and Swanson, 1970, p. 272). The presence of faulting, folding, and erosion can be determined in the field, but a certain amount of normal thickness variation must occur. This normal thickness variation was estimated using five closely spaced boreholes from an undeformed, broad, flat region on the Cold Creek syncline of the Pasco Basin. One standard deviation in thickness variation for the Elephant Mountain, Pomona, Priest Rapids, and Roza Members was calculated to be 3.5, 3.4, 4.0 and 4.3 m, respectively. This is interpreted to represent normal variations in the basalt flows and was used to estimate error in figure 13. The regional southwest-dipping paleoslope that has been stable since late Miocene (Swanson and Wright, 1976) provides a regional frame of reference in which to distinguish uplift on the anticlinal ridges from subsidence in the synclines. Reidel, Cross, and Fecht (1983) projected this regional paleoslope into the Pasco Basin and found its intercept with the south flank of the Saddle Mountains to be near borehole DH-5. The flow thicknesses in borehole DH-5 are also intermediate between those in the Saddle Mountains and boreholes in the Cold Creek syncline (Reidel, Cross, and Fecht, 1983). Thus it is concluded that borehole DH-5 provides the best available data to use as a reference for determining uplift.

Figure 13 is a plot of the cumulative relief that developed on the Saddle Mountains uplift in the Sentinel Gap segment. Cumulative relief is based upon comparing the thickness of the flows in borehole DH-5 to thicknesses as near to the axes of the Saddle Mountains anticline as possible. This is a measure of the maximum topographic (structural) relief at that time relative to the projected plane of reference (the extension of the westward-tilting regional paleoslope, Reidel and Fecht, 1981; Reidel, Cross, and Fecht, 1983).

The ages of the Grande Ronde, Wanapum, and Saddle Mountains Basalts are relatively well constrained, but the ages for each of the members are not. Dates for the Pomona and Elephant Mountain Members are reasonably well known (McKee, Swanson, and Wright, 1977). The age of the Asotin Member has been estimated at about 13 to 12.7 Ma using data from ARHCO (1976). The Wanapum Basalt was erupted over about 1 my (Watkins and Baksi, 1974), but no accurate estimates of the ages of the members are available. Because the Wanapum Basalt consists of four members (Swanson and others, 1979b), of which only three are present in the Pasco Basin, it is assumed that eruptions of different members occurred at about 250,000-yr intervals. The Grande Ronde Basalt was erupted over a

2-my period (McKee, Hooper, and Kleck, 1981; Long and Duncan, 1982; Watkins and Baksi, 1974), but individual flows have not been dated and only thicknesses for Sentinel Bluffs flows (fig. 6) can be measured. Age determinations by Long and Duncan (1982) suggest that these exposed flows were deposited over a 500,000-yr period but also suggest that the Grande Ronde Basalt is older than indicated by Watkins and Baksi (1974). As a result, a range of values (curves a and b) is given in figure 13. Both curves have been extrapolated to approximately the beginning of the Grande Ronde eruptive period. The extrapolation is based upon the assumption that the rate of uplift was nearly uniform or decreasing slightly with time through the eruption of the Grande Ronde Basalt.

The shape of the curve indicates that the Saddle Mountains uplift was undergoing relatively rapid growth (~250 m/my) in late Grande Ronde time but slowed by more than 80 percent (40 m/my) by Elephant Mountain time. The present amount of structural relief on the Saddle Mountains at Sentinel Gap is 550 m (measured using the top of the Priest Rapids Member); extrapolation of this curve to account for this structural relief produces a slope of about 40 m/my.

Because fold growth during the time of basalt eruptions is measured by thinning of individual flows across the uplift, each point on the Miocene portion of figure 13 is assumed to represent an initially horizontal basalt flow that was folded and then buried by the next flow. The cycle repeated itself throughout the Miocene with each new flow that was emplaced. This part of the growth-rate curve is therefore independent of the fold geometry and thus provides the best available measure of the rate at which the rocks were being deformed and the uplift was growing.

The portion of the curve from Elephant Mountain time (10.5 Ma) to the present does not represent the same cycles that occurred when the basalts were emplaced, and therfore this part of the curve is dependent upon the development of the fold geometry. Estimates of uplift rates, using the Ringold Formation, are consistent with figure 13. The Elephant Mountain-Ringold contact in Crab Creek north of the Saddle Mountains is used as the frame of reference, because age equivalent Ringold may not be present in borehole DH-5. Lower Crab Creek also lies on the projection of the regional paleoslope (Reidel, Cross, and Fecht, 1983). If the Ringold Formation overlying the Elephant Mountain Member in the Sentinel Gap segment is assumed to be the same age as at Taunton Bench (5.0-3.5 Ma), then the present structural relief of the unit can be explained using an average uplift rate of 40 m/my, a figure consistent with the extrapolated curve from Miocene to present. Ringold sediments in the Saddle Gap segment also provide a close fit to this curve. The shape of the fold when the Ringold Formation was deposited appears to have been one in which compression would still produce significant uplift. This diagram (fig. 13), which is consistent with observed folding of the Ringold Formation, suggests uplift continued into the Pliocene and probably Pleistocene at a low rate (40 m/my).

Based upon an analysis of microearthquake swarms in the Saddle Mountains, Rohay and Davis (1983) modeled the seismicity on an assumed (for analysis purposes) 45° planar fault and estimated seismic deformation to be 0.02 to 0.04 mm/yr. Their study suggests that the extrapolated rates of 40 m/my (0.04 mm/yr), based on geologic data, provide a reasonable approximation of current uplift rates.

Calculations for the eastern part of the Sentinel Gap segment and the Smyrna Bench segment indicate rates similar to figure 13. Decreasing structural relief to the east coupled with less variation in thickness across the structure suggests slightly lower overall uplift rates in those segments.

Figure 13 indicates that the amount of uplift decreases with time. Greatest uplift occurs in Grande Ronde time and slows until about 12 Ma, about the time that the westward-tilting paleoslope became a stable feature (Swanson and Wright, 1976). It is interesting to note that the Miocene portion of this curve correlates with estimates on the volume and rate of magma supply of the Columbia River Basalt Group made by Swanson and Wright (1978) and Reidel and others (1982), suggesting a connection between volcanism and deformation.

A key point in interpreting figure 13 is the importance of separating topographic relief from total structural relief. During eruption of the basalts, the topographic relief is the relief measured at the surface at any one time, but total structural relief is an accumulation of structurally produced topographic relief throughout the growth history of the uplift. During eruption of the basalt, topographic relief was always small, but total structural relief increased with continued growth of the uplift. Figure 13 suggests that more structural relief developed between Grande Ronde time and Elephant Mountain time than in the next 10.5 my. It also suggests that the greatest amount of structural relief developed during Grande Ronde time. The failure to recognize this process of continually burying structural relief led many workers to conclude erroneously that the greatest deformation occurred after 10.5 Ma, the eruption of the last major basalt flow to cover many ridges (for example, Barrash, Bond, and Vankatakrishnan, 1983).

Amount and rate of shortening.—Good exposures on the western side of Sentinel Gap allow the amount of shortening to be measured accurately. Minimum total shortening from folding plus displacement on the lower (Saddle Mountains) and the upper thrust faults is 3017 m as measured from cross sections (fig. 5, B-B′). If the point of flexure from steeply to gently dipping beds on the south flank is taken as the limit to the original fold, then shortening is calculated to be about 35 percent.

Shortening is related to folding, but the relationship between fold amplification and shortening is not linear. In a general horizontal compression fold model, the fold grows vertically until steepening of the limbs results in diminished vertical growth. If faulting follows folding in Yakima folds as Price (1982) suggests, then shortening from faulting should begin after most of the vertical uplift has occurred. In the Saddle Mountains, however, structural relief was continually being buried by each new flow. Continued compression would cause folding of the surface layers and faulting of the deeper layers. During basalt volcanism, the surface expression of the Saddle Mountains anticline was that of a gentle, low-amplitude fold, but at depth, the amount of shortening increased in older rock. This hypothesis implies that faulting and folding occur simultaneously, and, although topographic relief is low, total structural relief is substantial. The net effect of this is that horizontal displacement becomes apparent at the surface only after the last flow to be emplaced has been folded substantially.

The youngest flow on the northwest side of Sentinel Gap is Rosalia flow of the Priest Rapids Member. Measured from this flow, which is the surface of the Wanapum Basalt on the cross section (fig. 5, sec. B-B′), at least 2500 m of shortening due to faulting alone has occurred. The rate of shortening is 185 m/my, if deformation continued at a constant rate from the late Miocene to the present, as suggested by the uplift calculations.

Short-term strain rates (rates approximated between data points of fig. 13) cannot easily be determined. The nature of Miocene structures buried by the basalt, deformation of the Pliocene and Quarternary sediments, and present patterns of strain release place some constraints on short-term strain rates. The absence of fault scarps buried by basalt, Ringold Formation, and Quarternary sediments, and the presence of folded basalt flows and sediments in most areas, suggest low-magnitude displacements with a short periodicity. Rohay and Davis (1983) estimate seismic deformation due to shortening to be 0.02 to 0.04 mm/yr. Savage, Lisowski, and Prescott (1981) estimate ~1.0 mm/yr of net shortening of trilateration lines of the Hanford net in which the lines are about 20 km in length. These studies, combined with the Miocene pattern, suggest that short-term rates are approaching the long-term rates (the average rate based upon data points of fig. 13) and that deformation was probably a long continuous process rather than a few "short" bursts of activity alternating with long periods of quiescence.

THE EVOLUTION OF THE SADDLE MOUNTAINS AND APPLICATION TO OTHER ANTICLINES OF THE YAKIMA FOLD BELT

The Saddle Mountains record a long, complex deformational history which is probably as old as the Columbia River Basalt Group. Studies conducted on other folds in the Yakima Fold Belt near the central Columbia Plateau yield similar results for age and rates of vertical growth (for example, see Reidel, Cross, and Fecht, 1983). Based on these studies I propose that the geologic history and evolution of the Saddle Mountains can be used as a general model for anticlines of the Yakima Fold Belt and can provide constraints on broader tectonic models.

In figure 14, a series of generalized cross sections through an idealized anticline of the Yakima Fold Belt is shown depicting the evolutionary history as interpreted from the Saddle Mountains. Initially (fig. 14A), the basalt begins to buckle under north-south compression. The extent or lack of basement involvement is not known, but the assumption is made that folding began prior to or simultaneously with the oldest basalt flows. As folding continues, the basalt becomes more deformed, but the uplift is repeatedly buried by younger basalt flows (fig. 14B). Therefore deformation of the basalt flows increases with depth and age. At some point, the layers

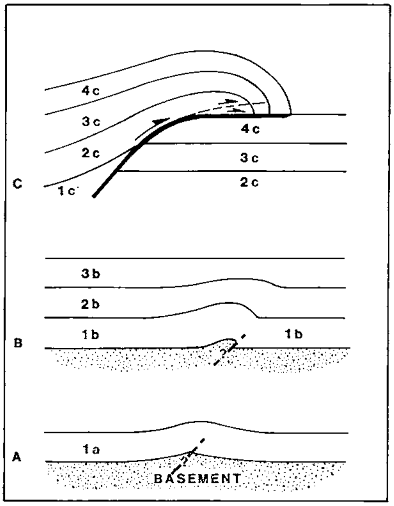


Fig. 14. Cross-sectional model showing the evolution of a Yakima fold. A — emplacement of the first lava flow and deformation under a north-south compressional stress field; B — continued deformation of the basalt as younger basalt flows are emplaced; C — present stage in which deformation continued after the last flows were emplaced (see text for complete description).

can no longer fold and begin to deform by faulting. Faulting occurs in the core of the fold, but the surface layers still deform by folding. In this stage, the greatest amount of deformation and structural relief is buried by the younger basalt flows, and the structural relief at the surface is only a small part of the total structural relief. Once eruptions cease, the uplift is no longer buried by younger flows, and structural and topographic relief develop together (fig. 14C). As deformation continues, faulting eventually becomes the principal means of shortening, and the surface layers are also faulted. The fault angle at depth is interpreted to be approx 45° based upon the angle of the Frenchman Hills fault exposed 20 km to the north along the Columbia River (Grolier and Bingham, 1971). The fault angle at the surface, however, is controlled by the dip of the basalt flows north of the uplift, because this surface must eventually become the principal fault plane as the uplift rides out over it. Imbricate faults may also develop, as on the west side of Sentinel Gap. Conjugate folds as in the Smyrna Bench segment or complex folds as in the Sentinel Gap segment are the most evolved stages observed here.

This model for anticlines in the Yakima Fold Belt can also be shown to be consistent with the regional tectonic framework of the Columbia Plateau. Fold growth in the Yakima Fold Belt occurred under north-south compression, while basalt eruption to the east in the Palouse subprovince was occurring under dominately east-west extension. East-west extension is compatible with north-south compression, but the geographic separation is unusual. The separation appears to be related to the rock directly underlying the basalt. In the Palouse subprovince the basalt overlies crystalline basement while the Yakima Fold Belt overlies several thousand meters of sediments as indicated by the Roza gap and Whiskey Dick wells drilled by Shell Oil Company. This difference may explain the lack of folding to the east, but it also suggests a fundamental crustal difference between the two subprovinces.

The correlation between the rate of fold growth and rate of magma supply suggests that the tectonic process responsible for the Columbia River basalt may be the same process producing north-south compression and deformation in the Yakima Fold Belt.

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