RHO-BW-SA-344 P

Structure and Evolution of the Horse Heaven Hills in South-Central Washington

Michael C. Hagood

Prepared for the U.S. Department of Energy
under Contract DE-AC06-77RL01030

Rockwell International
Rockwell Hanford Operations
Richland, Washington

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ABSTRACT

The Horse Heavens Hills uplift in south-central Washington consists of distinct northwest and northeast trends which merge in the lower Yakima Valley. The northwest trend is adjacent to and parallels the Rattlesnake-Wallula structural alignment (a part of the Olympic-Wallowa topographic lineament). The northwest trend and northeast trend consist of aligned or en echelon anticlines and monoclines whose axes are generally oriented in the direction of the trend. At the intersection, folds in the northeast trend plunge onto and are terminated by folds of the northwest trend.

The crest of the Horse Heaven Hills uplift within both trends is composed of a series of asymmetric, north vergent, eroded, usually double-hinged anticlines or monoclines. Some of these major anticlines and monoclines are paralleled to the immediate north by lower-relief anticlines or monoclines. All anticlines approach monoclines in geometry and often change to a monoclinal geometry along their length.

In both trends, reverse faults commonly parallel the axes of folds within the tightly folded hinge zones. Tear faults cut across the northern limbs of the anticlines and monoclines and are coincident with marked changes in the wavelength of a fold or a change in the trend of a fold.

Layer-parallel faults commonly exist along steeply-dipping stratigraphic contacts or zones of preferred weakness in intraflow structures. Most of these faults appear to reflect strain from folding.

Isopach maps of Columbia River basalt flows and Ellensburg Formation interbeds and paleodrainage maps of the ancestral Columbia River system indicate that deformation occurred simultaneously along and coincident with both trends of the Horse Heaven Hills uplift, the lower Yakima Valley syncline, the Piening syncline (within the Horse Heaven Plateau), and the Hog Ranch-Naneum Ridge anticline (within the lower Yakima Valley) since at least Roza time. Data are not available for determining the timing and location of deformation prior to Roza time, nor does the geologic record allow for a detailed description of the growth history after Columbia River Basalt Group time, except that the observed present structural relief along the Horse Heavens Hills uplift developed after Elephant Mountain time (10.5 m.y.B.P.).

Relief between the Horse Heaven Hills uplift and the lower Yakima Valley syncline developed at an average rate of less than ~70 m/m.y. during Wanapum and Saddle Mountains time (combined rate of vertical uplift and subsidence). Growth rates appear to decrease with age. Growth rates, extrapolated to the present, approximate the cumulative relief developed since Wanapum time and suggest that folds developed at a uniform rate since Columbia River Basalt Group time to the present. However, the data from this study do not preclude the variability of growth rates in post Columbia River Basalt Group time.

Data from this study suggest that tectonic models that directly or indirectly pertain to the origin of the Horse Heaven Hills uplift may be constrained by: (1) the predominance of monoclinal or near-monoclinal fold geometries and reverse faults along both the northwest and northeast trends; (2) preliminary data which suggest clockwise rotation has occurred along folds of both trends; (3) folds along both trends developing simultaneously and at similar rates (at least during Wanapum and Saddle Mountains time); (4) folds along the northwest trend of the Horse Heaven Hills uplift being genetically related to and forming simultaneously with at least certain folds along the Rattlesnake-Wallula structural alignment; (5) the uplift developing simultaneously with the north-northwest-trending Hog Ranch-Naneum Ridge anticline as well as other Yakima folds during at least Columbia River Basalt Group time. It is proposed that folds of both trends of the Horse Heaven Hills uplift were generated by the same tectonic processes.

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1.0 INTRODUCTION

1.1 PURPOSE

Several generally narrow, east-west-trending Yakima folds extend eastward from the Cascade Range into the central Columbia Basin. Two of these folds, the Rattlesnake Hills uplift and the Horse Heaven Hills uplift, abruptly change trend near the western margin of the Pasco Basin and continue southeast towards the Blue Mountains. The northwest-trending portions of the Horse Heaven Hills and Rattlesnake Hills uplifts are coincident with and parallel, respectively, a portion of the Rattlesnake-Wallula structural alignment (RAW), (Bingham et al. 1970; fig. 1) which is part of the Olympic-Wallowa topographic lineament (OWL), (Raisz 1945; fig. 2). The northwest trend of the Horse Heaven Hills uplift is part of another structural alignment, the Anderson Ranch-Wallula structural alignment (ARW; see fig. 1). The structural and evolutionary relationships of these two northwest- and northeast-trending structural trends at their intersections are unclear but are important to the understanding of the development of the Yakima folds. The purpose of this study is to describe the structure and evolution of one of these uplifts, the Horse Heaven Hills, at its abrupt structural transition. This was achieved by (1) delineating the structure within the two trends as they approach the intersection, (2) determining the timing and location of uplift within each trend, (3) comparing and contrasting Miocene vertical growth rates along folds within both trends, and (4) imposing constraints for tectonic models that pertain to the genesis of the Horse Heaven Hills uplift. These objectives can only be fulfilled if the stratigraphy of the area is first delineated.

1.2 REGIONAL GEOLOGIC SETTING

The Horse Heaven Hills uplift lies within the Columbia Plateau geologic province, which is an intermontane basin between the Cascade Range to the west and the Rocky Mountains to the east. The Columbia Plateau can be divided into three informal structural subprovinces (Myers et al. 1979; see fig. 2): (1) the Blue Mountains subprovince characterized by the northeast-trending Blue Mountains uplift, (2) the Palouse subprovince characterized by a generally undeformed, westward-tilting paleoslope, and (3) the Yakima Fold Belt subprovince characterized by generally east-west and northwest-southeast-trending folds such as the Horse Heaven Hills uplift.

Three of the five formations that make up the Miocene tholeiitic flood basalts of the Columbia River Basalt Group are known to underlie the Yakima Fold Belt subprovince. They are the Grande Ronde Basalt, the Wanapum Basalt, and the Saddle Mountains Basalt. Basalt flows of these three formations were erupted during a period of time spanning 17 to 6 m.y.B.P. (McKee et al. 1977; Long and Duncan 1982) from northwest-trending linear vent systems in the eastern portion of the Columbia Plateau (Waters 1961; Taubeneck 1970; Swanson et al. 1975; Price 1978). Intercalated with and

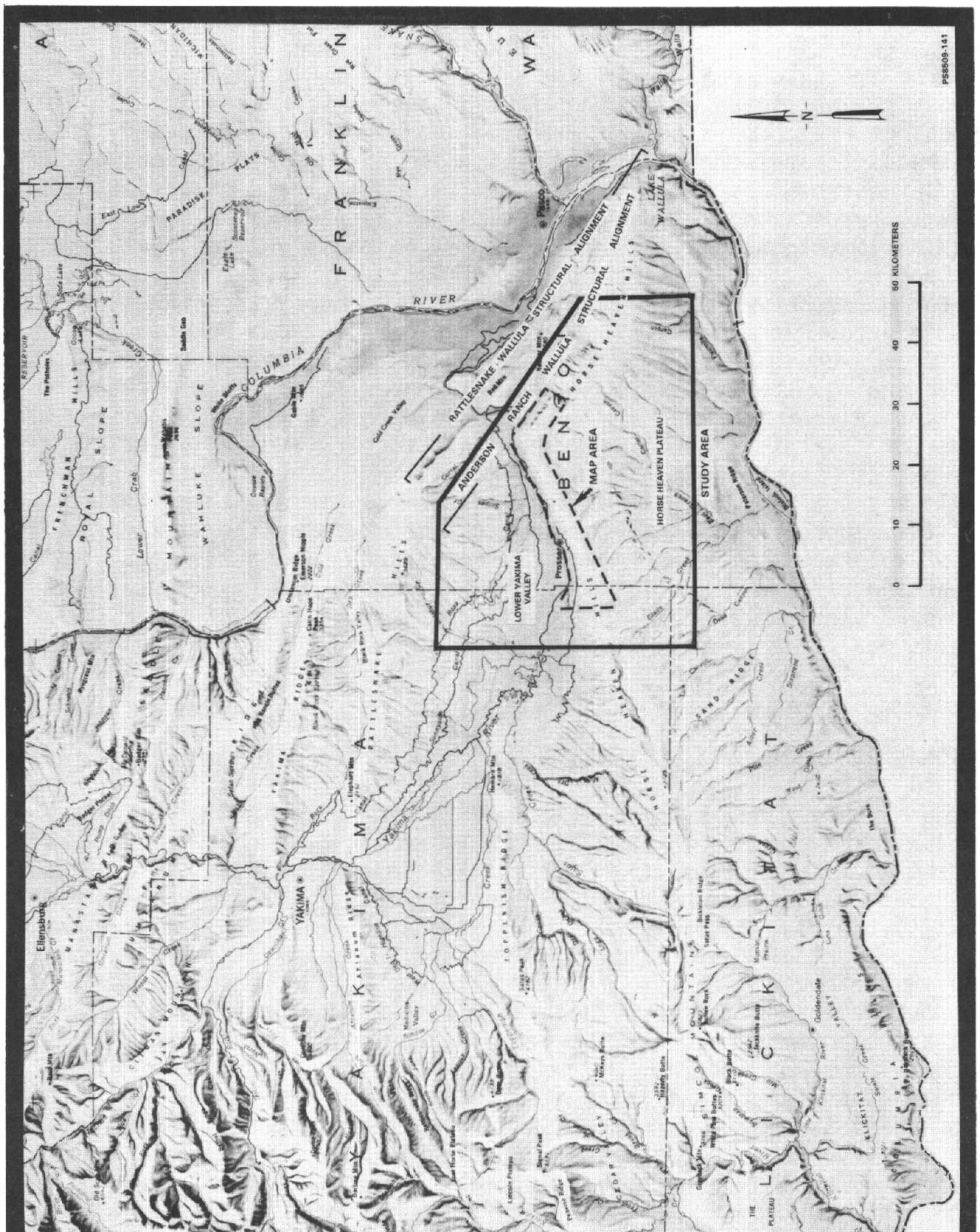


Figure 1. Location of Study Area and Map Area.

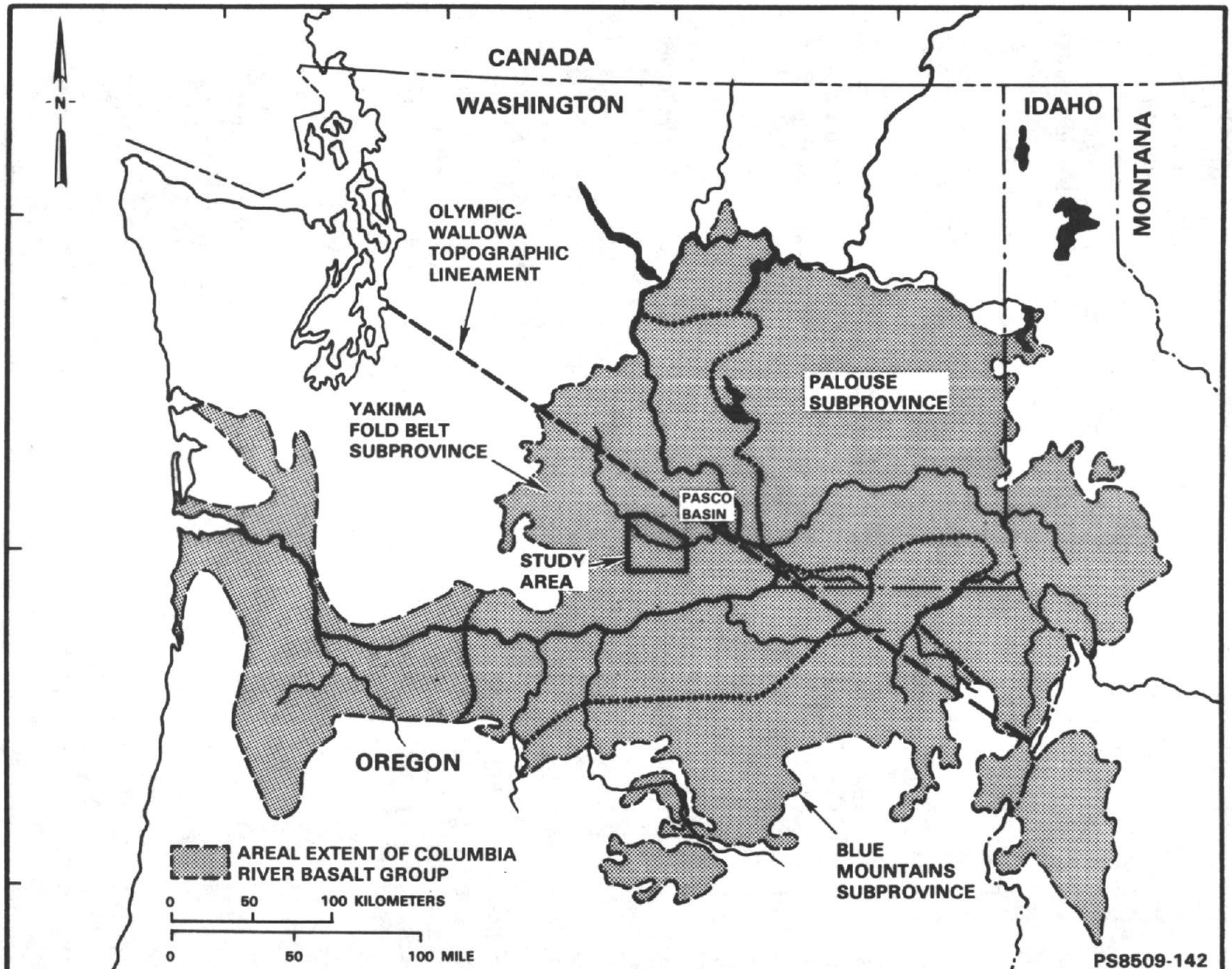


Figure 2. Structural Subprovinces of the Columbia Plateau (Myers et al. 1979) Shown in Relationship to the Extent of the Columbia River Basalt Group.

overlying the Columbia River Basalt Group in western and central portions of the Columbia Plateau are epiclastic and volcaniclastic sediments of the Ellensburg Formation that were derived from both within and outside the Columbia Plateau (Waters 1955; Mackin 1961; Schmincke 1964, 1967c; Swanson et al. 1979c). Overlying the Columbia River Basalt Group and Ellensburg Formation to the east of the lower Yakima Valley are remnants of Miocene and Pliocene fluvial and lacustrine sediments of the Ringold Formation (Myers et al. 1979; Tallman et al. 1981), and to the northwest of the lower Yakima Valley are Pliocene Thorp or Thorp-equivalent sediments (Waitt 1979; Campbell 1983). Pleistocene glaciofluvial deposits from catastrophic floods mantle portions of many of the basins within the Yakima Fold Belt (Baker and Nummedal 1978). Loess and dune sand of Pleistocene and Holocene age blanket much of the area as well.

1.2.1 Location and Physical Description

The study area covers portions of the lower Yakima Valley, Horse Heaven Hills, Horse Heaven Plateau, and Badger Coulee (see fig. 1). The Horse Heaven Hills are a series of ridges averaging 600 m in elevation. Approximately 450 m of topographic relief exists between these ridge crests and the lower Yakima Valley. The Horse Heaven Hills uplift is bordered to the north by the eastward-flowing Yakima River.

Any portion of the study area is accessible to within a few kilometers of certain roads. The Horse Heaven Hills uplift can be reached from major arterials such as Interstate 82 between Benton City and Prosser, Washington; State Highway 22 between Prosser and Mabton, Washington; and State Highway 221 between Prosser and Paterson, Washington. Secondary roads such as Webber Canyon Road, McBee Grade, Lincoln Grade, Ward Gap Road, and Byron Road all cross the ridge crest of the Horse Heaven Hills. Dirt roads along portions of the crest are usable with permission from the landowner. Irrigation ditch roads also provide good access to the northern base of the Horse Heaven Hills uplift, but permission for access is required from the appropriate irrigation districts.

1.2.2 Methodology

To delineate the structure and stratigraphy exposed along the Horse Heaven Hills uplift, a bedrock outcrop map (scale 1:24,000) and a geologic map (scale 1:62,500) were constructed (map area, fig. 1; plate 1). Stratigraphic units were identified using (1) basalt lithologies, (2) stratigraphic positions, (3) basalt paleomagnetic polarities (using a fluxgate magnetometer), and (4) major oxide chemistry (as determined by x-ray fluorescence analysis (XRF)). In addition, subsurface stratigraphic units within the study area (generally located in the area adjacent to the Horse Heaven Hills uplift) were identified using borehole geophysical logs, drillers' logs, lithology of drill cuttings, and XRF analyses of drill cuttings.

To determine the timing and location of deformation in the study area, computer-generated isopach maps were constructed of individual Columbia River Basalt Group members and Ellensburg Formation interbeds using section-thickness data gathered from borehole geophysical logs, drillers' logs, and field sections. These isopach maps were later modified by the author to be more representative of the geology of the area.

Growth rates were calculated for the Horse Heaven Hills uplift by plotting cumulative paleorelief (determined from isopach maps) against radiometric age dates of certain Columbia River Basalt Group flows.

More background on some of these methods is presented in the appendixes.

1.2.3 Previous Work

Several geologic studies have encompassed portions, or all, of the study area, both in reconnaissance and in detail. Table 1 generally summarizes the various studies that include aspects of the structure of the Horse Heaven Hills uplift (and immediate area) and stratigraphy of the Columbia River Basalt Group and Ellensburg Formation within the study area. A major advancement in the study of the structure and stratigraphy of the Columbia River Basalt Group occurred when major oxide chemistry, paleomagnetics, and borehole geophysical logging were found useful in identifying basalt flows.

Table 1. Previous Work Pertinent to This Study which Encompasses All or Portions of the Study Area. (sheet 1 of 3)

Reference	Region	Major subject(s)	Special methods	Maps
Russell (1893)	Central Washington	Water resources, stratigraphy, structure		
Waring (1913)	South-central Washington	Water resources, stratigraphy, structure		Reconnaissance map showing location of water wells, springs, and approximate extent of geologic formations, scale, 1 in. = 13 mi
Shedd (1925)	Prosser and Pasco quadrangles	Stratigraphy		Geologic map, scale, 1:125,000
Warren (1941b)	South-central Washington	Hood River conglomerate		
Dennis (1938)	Horse Heaven Hills	Structure		
Mason (1953)	South-central Washington	Structure, lithology		
Laval (1956)	South-central Washington	Stratigraphy, structure		Geologic maps, scale, 1:62,500
Schmincke (1964)	South-central Washington	Stratigraphy, petrography	Major oxide analyses	

Table 1. Previous Work Pertinent to This Study which Encompasses All or Portions of the Study Area. (sheet 2 of 3)

Reference	Region	Major subject(s)	Special methods	Maps
Schmincke (1967a)	South-central Washington	Flow paths of the Columbia River Basalt Group, paleodrainage, paleoslopes	Basalt intraflow structures, sedimentary structures	
Schmincke (1967b)	South-central Washington	Fused tuffs, peperites	Major oxide analyses	
Schmincke (1967c)	South-central Washington	Stratigraphy petrography, chemistry	Major oxide analyses	
Newcomb (1970)	Columbia Plateau	Structure		Tectonic structure map, scale 1:500,000
Crosby et al. (1972)	Horse Heaven Plateau	Groundwater hydrology, subsurface stratigraphy, structure	Borehole geophysical logs	
Lobdell and Brown (1977)	Lower Yakima Valley	Groundwater hydrology, subsurface stratigraphy, structure	Borehole geophysical logs	
Bond et al. (1978)	Southwest Pasco Basin	Stratigraphy, structure	Major oxide analyses, paleomagnetics	Structure contour map, distribution map of limited Columbia River Basalt Group flows, geologic maps, scale 1:24,000

Table 1. Previous Work Pertinent to This Study which Encompasses All or Portions of the Study Area. (sheet 3 of 3)

Reference	Region	Major subject(s)	Special methods	Maps
Brown (1978)	Horse Heaven Plateau	Groundwater hydrology, subsurface stratigraphy, structure	Borehole geophysical logs	
Brown (1979)	Eastern and southern parts of the Pasco Basin	Groundwater hydrology, subsurface stratigraphy, structure		Structure contour map on top of the Columbia River Basalt Group
Myers et al. (1979)	Pasco Basin	Surface stratigraphy, subsurface stratigraphy, structure, tectonics	Major oxide analyses, paleomagnetics, borehole geophysical logs, geophysical methods	Isopach maps of Columbia River Basalt Group and Ellensburg Formation. Structure contour maps on top of Columbia River Basalt Group units, geologic maps, scale 1:62,500
Swanson et al. (1979a)	Eastern Washington and northern Idaho	Subsurface stratigraphy, structure	Borehole geophysical logs	Structure contour maps on top of Columbia River Basalt Group units
Swanson et al. (1979b)	Eastern Washington and northern Idaho	Stratigraphy structure	Major oxide analyses, paleomagnetics	Geologic maps, scale 1:250,000

2.0 STRATIGRAPHY

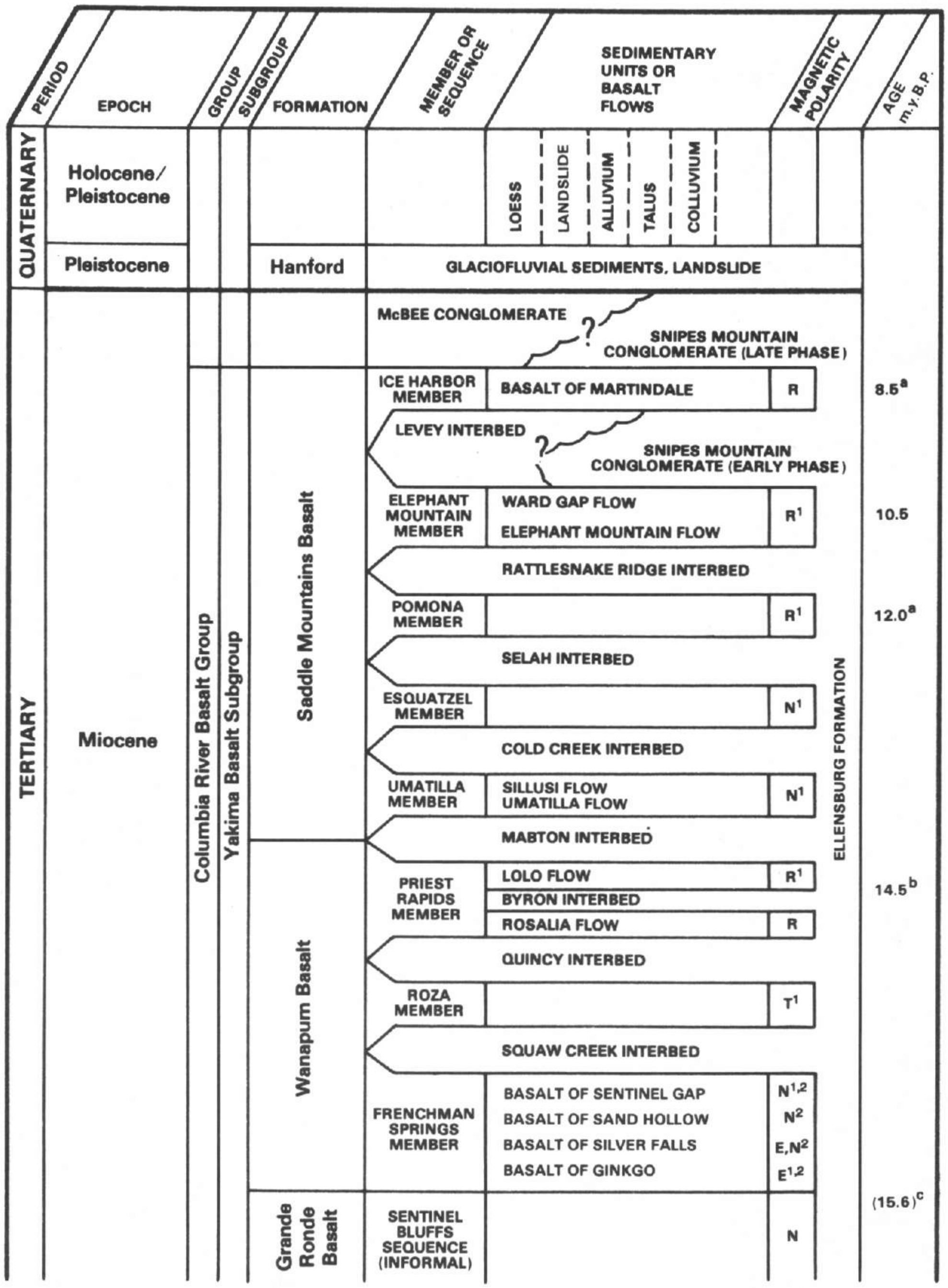
This section focuses on the surface and subsurface stratigraphy of the Columbia River Basalt Group and Ellensburg Formation in the study area. The stratigraphy is important to delineating structures and reconstructing the evolution of the Horse Heaven Hills uplift. The stratigraphy of the study area is shown in figure 3. Pliocene sediments are absent in the study area such that either the Columbia River Basalt Group or Ellensburg Formation is unconformably overlain by Pleistocene or Holocene deposits. The surface stratigraphy was generally determined from field mapping along the Horse Heaven Hills uplift (see plate 1), while the subsurface stratigraphy was determined from borehole data (see appendix B). The stratigraphic nomenclature for the study area generally follows the usage of Swanson et al. (1979c) and Myers et al. (1979). Radiometric age dates for the Columbia River Basalt Group (fig. 3) are from McKee et al. (1977), Watkins and Baksi (1974), and Long and Duncan (1982). The magnetostratigraphy was compiled from several studies (fig. 3; Reitman 1966; Van Alstine and Gillett 1981; Sheriff 1984; Beeson et al. 1985).

2.1 GRANDE RONDE BASALT

The Grande Ronde Basalt (Swanson et al. 1979c) composes up to 85% by volume ~275,000 km^3 of the Columbia River Basalt Group, (Reidel et al. 1982). The upper portion of the Grande Ronde Basalt was penetrated by two boreholes within the study area, the Horse Heaven Test well (see fig. B-11) and the Moon #1 well (see fig. B-10), which are both located on the Horse Heaven Plateau (fig. 4). Chemical analyses (see table A-1 in appendix A and table 2 of text) and borehole geophysical logs indicate that these boreholes penetrated part of the Sentinel Bluffs sequence of Myers et al. (1979). From other studies, it has been shown that the Sentinel Bluffs sequence consists entirely of high MgO flows (Long and Landon 1981). From inspection of drill cuttings from the Moon #1 well and interpretations of the borehole geophysical logs of the Moon #1 well and the Horse Heaven Test well, it appears that the Vantage Member of the Ellensburg Formation does not overlie the Grande Ronde Basalt at these two well sites, or that the Vantage Member interbed is too thin to identify.

2.2 WANAPUM BASALT

The Wanapum Basalt (Swanson et al. 1979c) consists of three members within the study area. These are (from oldest to youngest) the Frenchman Springs, Roza, and Priest Rapids Members. The Wanapum Basalt is separated from the overlying Saddle Mountains Basalt by the Mabton interbed and from the underlying Grande Ronde Basalt by the Vantage Member where present. Distinct lithologic, chemical, and paleomagnetic differences that occur among the members aid in their identification. However, a lack of a significant variation in the K_2O content of these members makes their identification on natural gamma geophysical logs very difficult. Figure 5 is an example of a natural gamma log taken from Landon (1985). The mean concentrations of K_2O were added from Reidel and Fecht (1981), and Long and Landon (1981). Stratigraphic contacts were defined by Landon (1985).



N = normal magnetic polarity
R = reversed magnetic polarity
T = transitional magnetic polarity
E = excursional magnetic polarity

[1] magnetic polarities from Van Alstine and Gillett (1981)
[2] magnetic polarities from Beeson et al. (1985)

[a] K-Ar dates from McKee et al. (1977)
[b] K-Ar dates from Watkins and Baksi (1974)
[c] Ar-Ar dates from Long and Duncan (1982)

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Figure 3. Stratigraphy of the Study Area, after Fecht et al. (1985), Swanson et al. (1979c), and Myers et al. (1979).

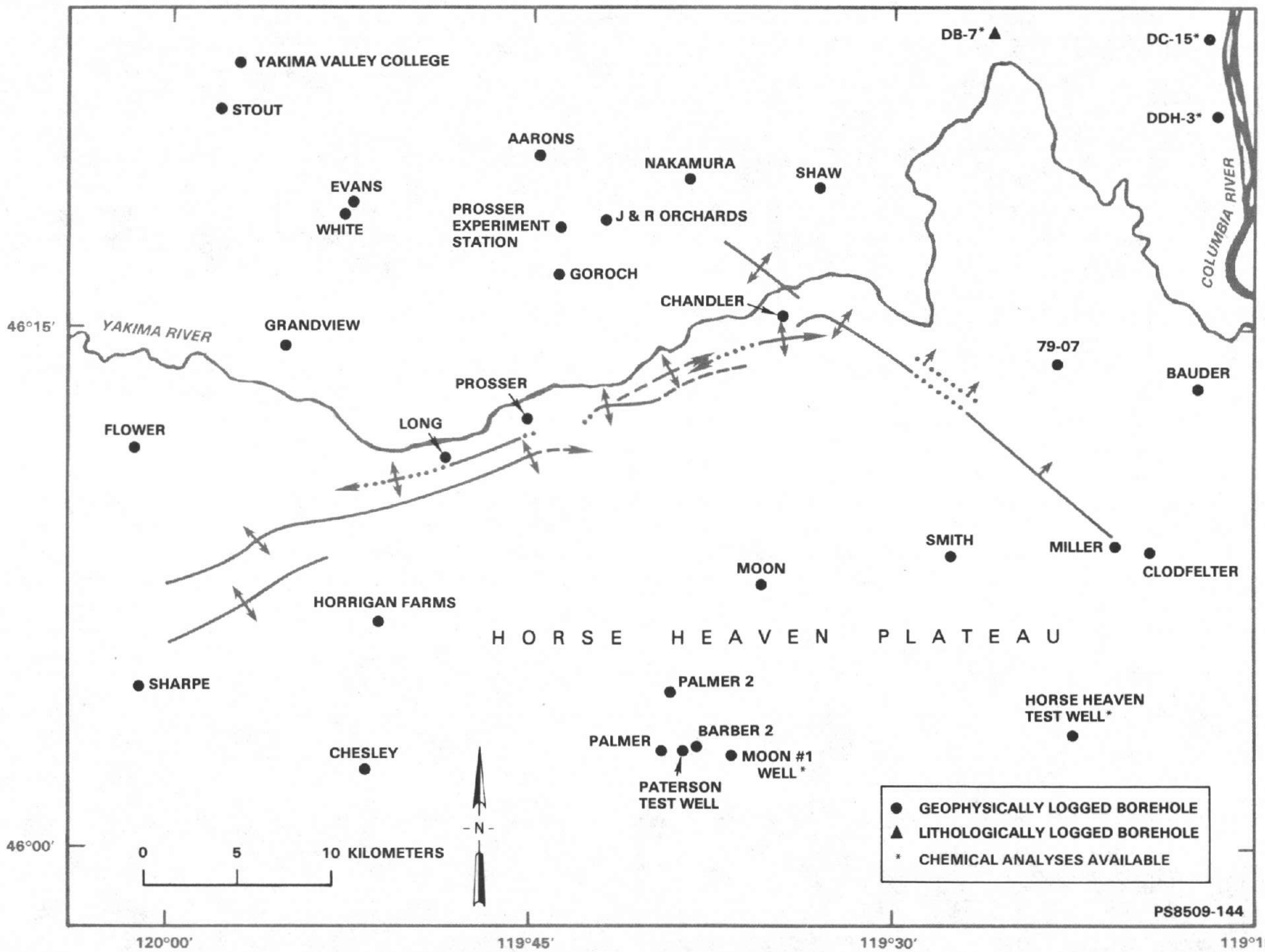


Figure 4. Names and Locations of Geophysically Logged and Lithologically Logged Boreholes Used in This Study.

Table 2. Average Major Oxide Composition of Columbia River Basalt Group Flows Found in the Study Area.

Location	Number of samples used in average	Composition																			
		SiO_2		Al_2O_3		TiO_2		FeO[a]		MnO		CaO		MgO		K_2O		Na_2O		P_2O_5	
		X[b]	1σ[c]	X	1σ	X	1σ	X	1σ	X	1σ	X	1σ	X	1σ	X	1σ	X	1σ	X	1σ
Grande Ronde Basalt	3	53.34	0.68	15.25	0.34	1.86	0.12	11.57	0.50	0.20	0.01	8.66	0.04	4.81	0.22	1.17	0.16	2.62	0.05	0.31	0.02
Wanapum Basalt																					
• French Springs Member																					
- Basalt of Ginkgo	3	50.66	1.02	14.30	0.13	3.07	0.04	14.43	0.36	0.23	0.02	8.17	0.22	4.32	0.10	1.29	0.05	2.72	0.30	0.61	0.01
- Basalt of Silver Falls	2	51.80	0.49	13.98	0.13	3.08	0.03	14.09	0.13	0.22	0.01	8.46	0.11	4.08	0.59	1.13	0.11	2.43	0.13	0.54	0.01
- Basalt of Sand Hollow	7	51.42	0.69	14.49	0.46	2.89	0.07	13.42	0.83	0.21	0.02	8.30	0.30	4.43	0.19	1.34	0.12	2.51	0.18	0.50	0.02
- Basalt of Sentinel Gap	9	51.36	0.66	14.62	0.53	3.05	0.10	13.56	0.71	0.21	0.02	8.23	0.46	4.22	0.17	1.32	0.17	2.68	0.29	0.55	0.03
• Roza Member[d]	13	50.60	0.35	14.35	0.37	3.01	0.11	12.44	0.54	0.23	0.01	8.65	0.20	4.59	0.31	1.17	0.13	2.43	0.20	0.54	0.03
• Priest Rapids Member																					
- Rosalia flow	4	50.39	0.61	14.68	1.10	3.65	0.19	13.83	0.52	0.22	0.02	8.34	0.99	4.15	0.23	0.85	0.30	2.82	0.36	0.69	0.03
- Lolo flow	7	50.04	0.73	14.62	0.34	3.17	0.06	13.64	0.67	0.22	0.01	8.77	0.53	4.89	0.30	1.07	0.14	2.72	0.31	0.67	0.02
Saddle Mountains Basalt																					
• Umatilla Member																					
- Umatilla flow	12	53.29	0.72	15.09	0.32	3.04	0.10	12.42	0.86	0.20	0.04	6.47	0.49	3.08	0.22	2.57	0.16	2.92	0.25	0.74	0.02
- Sillusi flow	6	54.06	0.28	15.29	0.19	2.65	0.03	12.27	0.46	0.20	0.01	6.04	0.28	2.78	0.13	2.86	0.25	2.89	0.28	0.86	0.04
• Esquatzel Member	8	51.65	1.82	14.90	0.54	3.23	0.16	13.04	1.10	0.20	0.02	8.22	1.47	3.78	0.12	1.73	0.31	2.63	0.24	0.43	0.04
• Pomona Member	29	51.57	0.63	15.76	0.34	1.69	0.08	9.97	1.24	0.18	0.02	10.44	0.54	6.54	0.39	0.48	0.14	2.56	0.34	0.24	0.02
• Elephant Mountain Member	7	50.30	0.49	14.41	0.27	3.58	0.06	14.40	0.65	0.21	0.01	8.41	0.18	4.29	0.25	1.15	0.14	2.45	0.19	0.50	0.02
• Ice Harbor Member[d]																					
- Basalt of Martindale	14	48.44	0.49	14.18	0.36	3.25	0.13	12.38	0.87	0.23	0.01	10.20	0.59	5.65	0.36	0.68	0.17	2.30	0.13	0.68	0.04

[a]FeO = FeO + 0.9 (Fe_2O_3).
[b]X = Mean.
[c]1σ = Standard Deviation.
[d] = Results taken from Reidel and Fecht (1981).

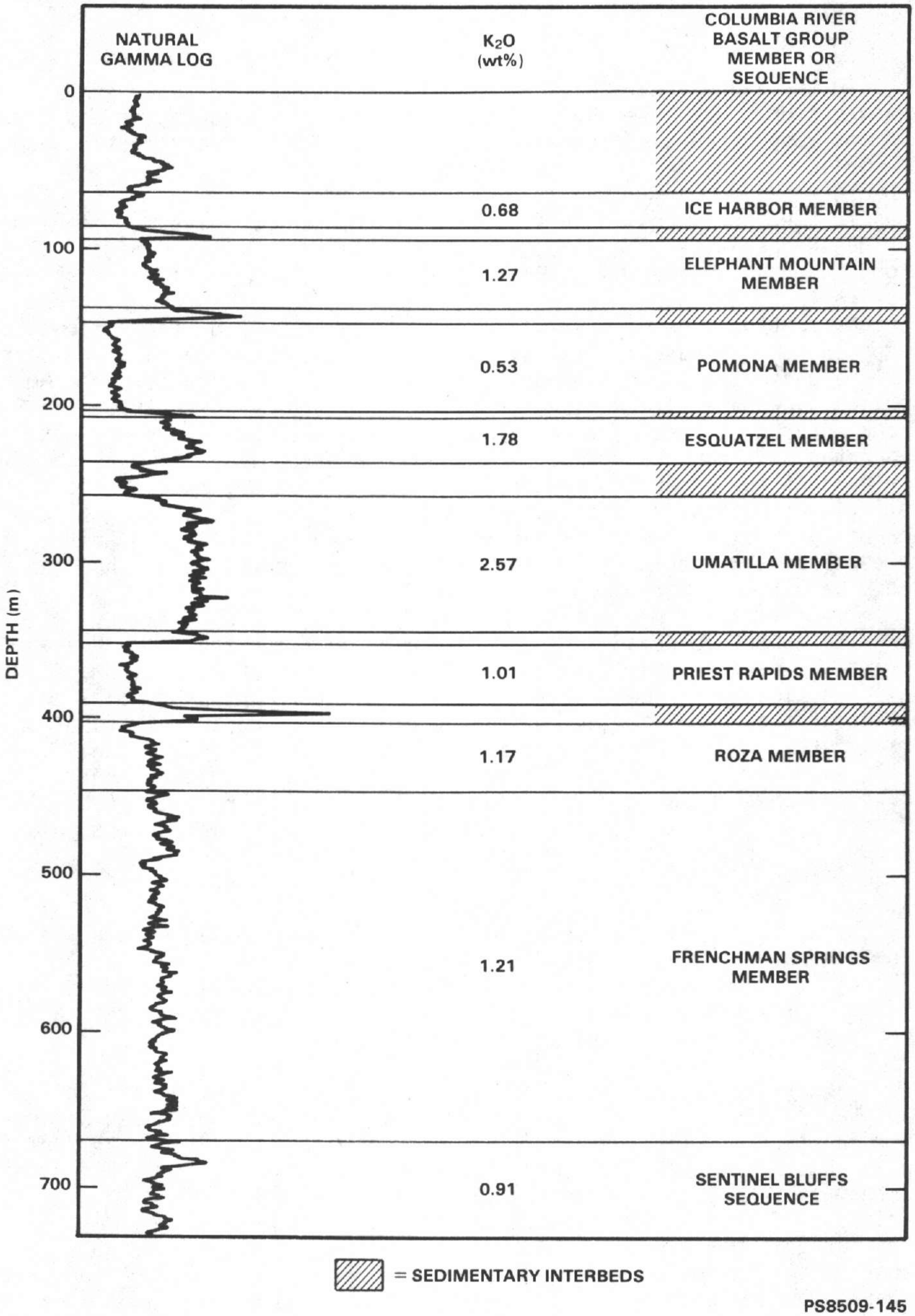


Figure 5. Natural Gamma Geophysical Log of Borehole DDH-3 Shown Alongside the Average Percent Concentration of K_2O for Columbia River Basalt Group Members.

2.2.1 Frenchman Springs Member

In the study area, the Frenchman Springs Member has been subdivided using criteria developed by Beeson et al. (1985). Major oxide and trace element compositions, paleomagnetics, and physical characteristics are used to divide this member into six stratigraphic units.

In the study area, only the upper stratigraphic units of the Frenchman Springs Member (i.e., basalts of Sand Hollow and Sentinel Gap) are exposed along the Horse Heaven Hills uplift. However, the Moon #1 and Horse Heaven Test wells on the Horse Heaven Plateau penetrated the entire Frenchman Springs section (see fig. B-10 and B-11). In these two wells, flows belonging to the basalts of Ginkgo, Silver Falls, Sand Hollow, and Sentinel Gap are present. Along the Horse Heaven Hills, the uppermost Frenchman Springs flows are either directly overlain by the Roza Member or the Squaw Creek interbed. These exposed upper Frenchman Springs flows are not separated by sedimentary interbeds, although an hyaloclastite is observed at the base of the uppermost Frenchman Springs flow along the Chandler anticline (NE1/4SW1/4 sec. 20, T. 9 N., R. 26 E.). In the Moon #1 and Horse Heaven Test wells, the Frenchman Springs Member is overlain by either the Priest Rapids Member or the Quincy interbed and underlain by the Grande Ronde Basalt.

The upper Frenchman Springs flows exposed along the Horse Heaven Hills uplift all have entablature-dominated jointing patterns with some flows having a flow top breccia up to 7 m thick. The flow top breccias contain basalt of a pahoehoe texture meshed with massive, angular clasts of basalt. Drill cuttings and borehole geophysical logs from the Moon #1 well indicate the presence of up to 13 m of flow top breccia in individual Sentinel Gap flows and up to 10 m in certain Sand Hollow flows. The hackly entablature flows of the Sentinel Gap and Sand Hollow form talus slopes of angular clasts that weather to a distinctive rust brown color. The basalt colonnade is very thin and is more gray in color relative to the entablature.

In hand sample, the Sentinel Gap and Sand Hollow flows have a black, fine-grained to glassy, and usually aphyric groundmass. An unknown black filling (possibly a mineraloid) is found locally in small circular vesicles in the entablature. Sparse tabular plagioclase phenocrysts up to a centimeter in length were found in these upper flows.

Data from the chemically analyzed Frenchman Springs Member fall within expected ranges of major oxide concentrations for the Frenchman Springs chemical type of Wright et al. (1973). Generally, the Frenchman Springs Member has distinctive P_2O_5 and TiO_2 concentrations that help differentiate it from other Columbia River Basalt Group flows (see table 2). Small variations in P_2O_5, TiO_2, and chromium concentrations, as well as stratigraphic position, help differentiate Frenchman Springs flows from each other. The Ginkgo flows have relatively higher P_2O_5 concentrations and lower chromium concentrations. The basalt of Sand Hollow has a lower P_2O_5 and TiO_2 concentration and a higher chromium concentration. Finally, the basalt of Sentinel Gap has an intermediate P_2O_5 value and a lower chromium value similar to the basalt of Silver Falls, but can be differentiated from the basalt of Silver Falls on the basis of the stratigraphic position.

2.2.2 Roza Member

Along the Horse Heaven Hills uplift, the Roza Member is composed of one or two flows, or flow lobes. The occurrence of the two flows appears to be more common in the western portion of the Horse Heaven Hills uplift. The Roza Member locally has a pillowed base, more commonly in the Byron Road area (center SW1/4 sec. 23, T. 8 N., R. 23 E.) where it is thickest (~5 m) and overlies a thin section of sediment that contains fragments of petrified wood. The Roza Member is overlain by either a thin sedimentary interbed or a flow of the Priest Rapids Member.

Outcrops of the Roza Member are commonly spheroidally weathered. The blocky basal colonnade of the Roza is locally platy jointed, with sheet fractures oriented perpendicular to the columns.

Fresh samples of the Roza Member have a medium-grained groundmass, are a dark gray color, and contain large (~1 to 2 cm), abundant, colorless to orange-yellow phenocrysts and glomerocrysts of plagioclase. The presence of these phenocrysts make the Roza Member an excellent stratigraphic marker in the field, although local occurrences have been found elsewhere where phenocrysts are absent (Myers 1973). The groundmass, where weathered, has the appearance of being coarse grained.

The major oxide composition of the Roza Member (see table 2) lies within the Frenchman Springs Member chemical type of Wright et al. (1973). The Roza Member cannot be distinguished from flows of the Frenchman Springs Member solely on the basis of its major oxide composition.

2.2.3 Priest Rapids Member

The Priest Rapids Member (Mackin 1961) is dated at ~14.5 m.y.B.P. In the Horse Heaven Hills, the Priest Rapids Member is overlain by the Mabton interbed and underlain by either the Quincy interbed or Roza Member. Within the study area, the Priest Rapids Member contains two distinct chemical types, an older Rosalia flow chemical type (Swanson et al. 1979c) and a younger Lolo flow chemical type (Wright et al. 1973). Although both chemical types are found within the study area, the flow of the Rosalia chemical type may be locally absent along the Horse Heaven Plateau as interpreted from borehole geophysical logs (see fig. B-10 and B-11). Multiple flow units of Rosalia composition were found along the Horse Heaven Hills uplift, but only a single Lolo flow was found. However, on the Horse Heaven Plateau, it is interpreted from borehole geophysical logs and major oxide chemistry (see fig. B-10 and B-11; table 2) that the Moon #1 and Horse Heaven test wells penetrated two flow units of the Lolo chemical type. Locally, a discontinuous sedimentary interbed of the Ellensburg Formation, the Byron interbed, is present between the Rosalia and Lolo flows.

Outcrops of the flows of the Priest Rapids Member along the Horse Heaven Hills uplift are usually characterized by spheroidal weathering. Less weathered outcrops reveal a hackly entablature overlying a well-developed basal colonnade. The basal colonnade is often characterized by platy jointing oriented subparallel to the dip of the flows.

Fresh hand samples of the Priest Rapids Member are medium-grained to glassy. However, a highly weathered groundmass appears coarse. The Lolo flow contains sparse plagioclase phenocrysts and glomerocrysts.

Both flows are chemically distinct from each other (see table 2). The Rosalia chemical type has higher TiO_2 and lower MgO concentrations than the Lolo chemical type.

2.3 SADDLE MOUNTAINS BASALT

Within the study area, the Saddle Mountains Basalt is represented by five members (see fig. 3). They are from oldest to youngest, the Umatilla, Esquatzel, Pomona, Elephant Mountain, and Ice Harbor Members. Members of the Saddle Mountains Basalt have diverse lithologies, major oxide concentrations, and paleomagnetic polarities that easily distinguish them from each other and from other Columbia River Basalt Group flows found within the study area. In addition, variations in K_2O concentrations between the flows of the Saddle Mountains Basalt members make natural gamma geophysical logs a useful tool in identifying these flows in the subsurface (see fig. 5).

2.3.1 Umatilla Member

In the study area, the Umatilla Member (Laval 1956) consists of the older Umatilla flow and the younger Sillusi flow (ARHCO 1976). The member directly overlies the Mabton interbed and underlies either the Cold Creek or Selah interbeds (see fig. 3).

Along the Horse Heaven Hills uplift, outcrops of the flows of the Umatilla Member are entablature-dominated. The hackly entablatures commonly weather to a reddish brown color and form talus composed of angular clasts. The basal portion of the flows are blocky jointed with thin, slabby to prismatic plates, and contain large almond-shaped vesicles near the lower contact. The basal portion is locally oxidized to a dark red. A highly distinctive, thick, rubbly flow top that is composed of scoriaceous and massive basalt clasts locally accompanies the flows of the Umatilla member (fig. 6). Outcrops of the Umatilla Member are similar in appearance to the flows of Sand Hollow and Sentinel Gap of the Frenchman Springs Member.

Fresh hand samples from the entablature of the Umatilla Member flows are black, fine-grained, aphyric, and fracture conchoidally. Small plagioclase crystals (<1 mm in length) are locally present along with widely spaced vesicles filled with a black to gray mineraloid. Towards the base of the flows, samples appear to be medium grained, bluish gray, and contain small plagioclase crystals $\sim$1 mm in length.

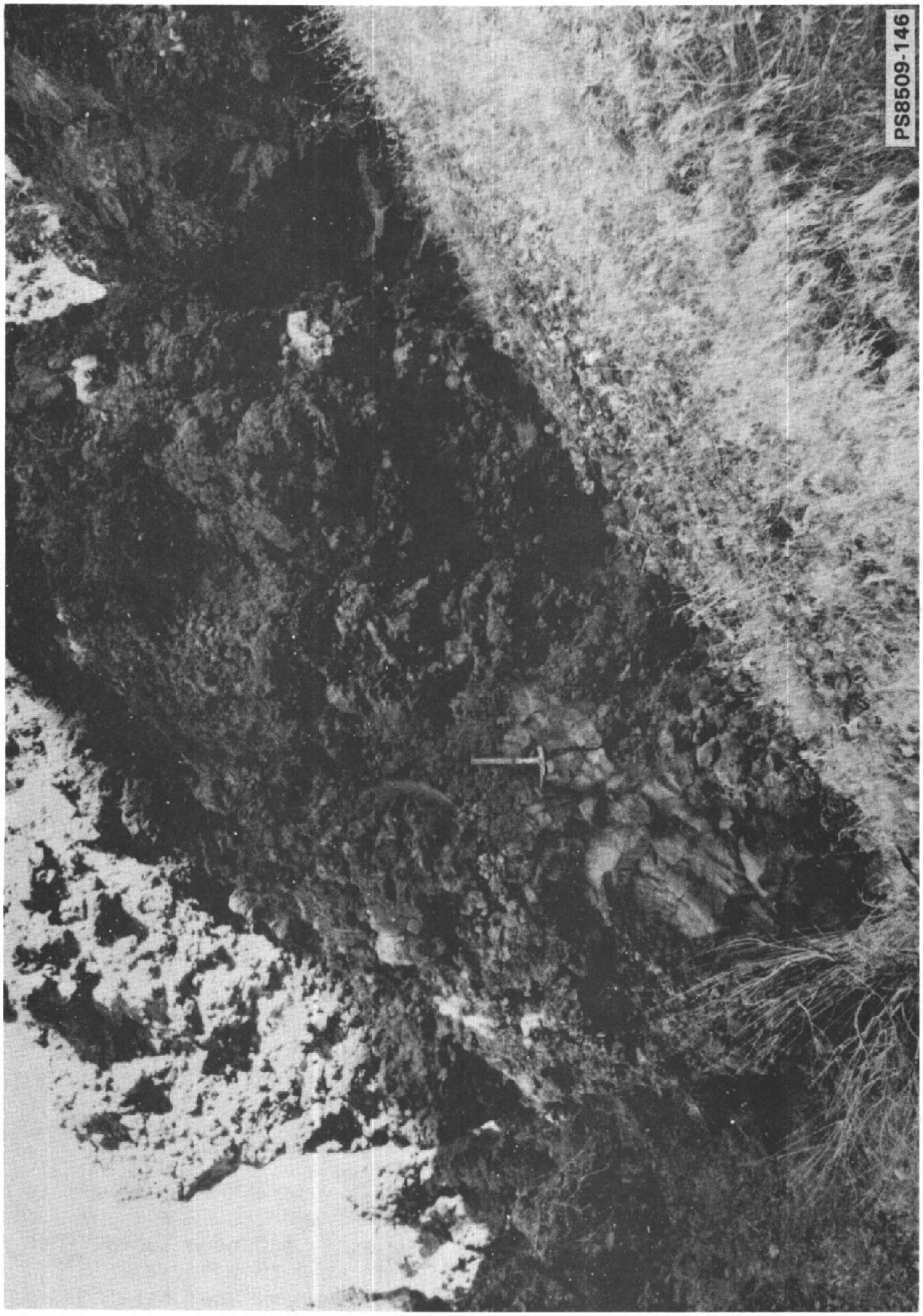


Figure 6. Flow-Top Breccia of the Umatilla Member (loc. NW1/4NE1/4 sec. 23, T. 9 N., R. 26 E.).

The major oxide composition of both flows of the Umatilla Member (see table 2) is quite distinctive from other Columbia River Basalt Group flows in the study area because it contains relatively higher P_2O_5, SiO_2, K_2O, and lower MgO, and both flows fall within the Umatilla chemical type of Wright et al. (1973). The Sillusi flow can be distinguished from the Umatilla flow by the relatively lower TiO_2 and MgO, and higher P_2O_5 concentrations (see table 2; Reidel and Fecht 1981). The high K_2O concentration of both flows provides an excellent signature in the natural gamma geophysical logs (fig. 5), aiding in the member's identification in boreholes.

2.3.2 Esquatzel Member

Within the study area, the Esquatzel Member consists of one flow that lies beneath the Pomona Member or Selah interbed and above the Cold Creek interbed of the Ellensburg Formation (see fig. 3).

Exposures of the Esquatzel Member are rare, but where exposed, the basalt colonnade displays platy jointing and vesicles oriented parallel to the dip of the flow. Hackly entablature overlies the columns and grades into an oxidized pahoehoe flow top. Esquatzel Member outcrops weather to a distinctive brown color.

Fresh hand samples of the Esquatzel Member gathered from either the colonnade or entablature are gray-black to black in color (darker in the entablature) and microphyric with sparse lath-shaped plagioclase phenocrysts found in the entablature (<3 mm in length). The groundmass of the entablature has a more glassy texture than the colonnade; it commonly fractures conchoidally and contains local diktytaxitic zones.

The major oxide composition of the Esquatzel Member (see table 2) lies within the Esquatzel chemical type defined by Swanson et al. (1979c). The flow is distinguished by its intermediate P_2O_5 and TiO_2. The K_2O concentration of the Esquatzel Member lies between that of the Pomona and Umatilla Members aiding in its identification in natural gamma geophysical logs (see fig. 5).

2.3.3 Pomona Member

The Pomona Member (Schmincke 1967c) is overlain by the Rattlesnake Ridge interbed and usually is underlain by the Selah interbed (see fig. 3), but also directly overlies the Umatilla Member where the Selah interbed, Esquatzel Member, and Cold Creek interbed are absent (e.g., Sunnyside-Grandview area).

The Pomona Member consists of one to three flow units. Two flows or flow lobes of the Pomona Member have been previously mapped and described in the Pasco Basin and eastern portion of the study area (Bond et al. 1978; Myers et al. 1979). Bond et al. (1978) named the upper flow unit the "Chandler flow" and proposed a source vent for it along the Badlands anticline (sec. 8, T. 9 N., R. 26 E.) based on the presence of pumice and pyroclastic material at this location. This interpretation was dismissed by Myers et al. (1979) because, based on its distribution, the "Chandler flow" would have flowed upslope. Further investigation of the Badlands "vent" area indicates it is a linear, low-amplitude anticline, and the pumiceous and pyroclastic material is more likely formed from steam-generated spiracles derived from the interaction of the Pomona lava and water. No evidence was found to support the existence of two separate Pomona flows within the study area.

Outcrops of the Pomona Member along the Horse Heaven Hills uplift display a distinctive jointing style. Overlying the thin basal colonnade are straight to curved, narrow prismatic columns (fig. 7). These narrow columns of the entablature are locally tiered and may be separated by vesicular zones. At Chandler Butte (SE1/4 sec. 21, T. 9 N., R. 26 E.) the Pomona Member is interpreted to form invasive dikes in the Selah interbed. These dikes are composed of curved and slender columns (such as the entablature) that are oriented horizontally and are interpreted to have formed perpendicular to the basalt-sediment contact. Locally emanating from the dikes are smaller, sinuous, chilled "dikelets" that merge and mix with the sediment forming peperites similar to those described by Schmincke (1967a). Talus derived from the Pomona entablature is very distinctive since it tends to be uniform in both angularity and size. Locally, a fused tuff of the Selah interbed directly underlies the Pomona Member. In poorly exposed areas, float from the bluish-gray and black fused tuff helps approximate the Pomona-Selah contact.

In hand sample, the groundmass of the Pomona Member is a distinctive grayish black and varies from medium to fine grained. The Pomona Member is phyric, containing small plagioclase phenocrysts which display equant slender tabular habits.

The chemical composition of the Pomona Member (see table 2) falls within the Pomona chemical type of Wright et al. (1973). The Pomona Member is marked by a lower P_2O_5 and TiO_2, and higher MgO and CaO content relative to other Columbia River Basalt Group flows in the study area. In addition, the Pomona Member's low, uniform K_2O content produces a distinctive signature on natural gamma geophysical logs (see fig. 5).

2.3.4 Elephant Mountain Member

The Elephant Mountain Member consists of two separate flows, the older Elephant Mountain flow of Waters (1955) and the younger Ward Gap flow of Schmincke (1967c). In the study area, the Elephant Mountain Member is commonly the uppermost Columbia River Basalt Group unit in field sections and is usually directly overlain by either Ellensburg Formation sediments, glaciofluvial deposits, or the Ice Harbor Member, and is directly underlain by the Rattlesnake Ridge interbed (see fig. 3).

Figure 7. Entablature of the Pomona Member (loc. SE1/4SW1/4 sec. 16, T. 9 N., R. 26 E.).

Weathered outcrops of the Elephant Mountain Member are commonly gray to reddish brown in color. Spheroidal weathering also occurs in the blocky basal colonnade, which produces large rounded remnant boulders. Locally, pipe vesicles are found at the base of the flows.

Fresh hand samples of the Elephant Mountain Member are black, fine grained, and locally diktytaxitic. It is readily apparent in direct sunlight that the rocks are abundantly microphyric. Larger-sized plagioclase phenocrysts are rare.

The two flows of the Elephant Mountain Member are readily distinguished from other Columbia River Basalt Group flows in the study area by their characteristically lower SiO_2, intermediate P_2O_5, and higher TiO_2 concentrations (see table 2). On the basis of these major oxide compositions, the two flows of the Elephant Mountain Member are indistinguishable from each other. Thus, they are recognized only by stratigraphic position and not delineated in the mapping. The Elephant Mountain Member has an intermediate K_2O concentration that is reflected in natural gamma geophysical log signatures (see fig. 5), and distinguishes it from the other Columbia River Basalt Group flows.

2.3.5 Ice Harbor Member

The Ice Harbor Member consists of three flows (Swanson et al. 1979c). These are (from oldest to youngest) the basalts of Basin City, Martindale, and Goose Island. No outcrops of the Ice Harbor are found along the Horse Heaven Hills uplift within the field mapping area, but other mapping in the vicinity of the uplift (Bond et al. 1978; Myers et al. 1979; Jones and Landon 1978; Gardner et al. 1981) and borehole data from this study indicate that only the Martindale flow is present within the study area (outside of the Horse Heaven Hills uplift). The Martindale flow directly overlies the Elephant Mountain Member or the Levey interbed.

The Martindale flow of the Ice Harbor Member can be distinguished from the Elephant Mountain Member on natural gamma geophysical logs as a direct reflection of their differing K_2O contents (see fig. 5).

2.4 ELLENSBURG FORMATION

The Ellensburg Formation (Russel 1893) consists of sediments interbedded with, and overlying, the Columbia River Basalt Group in the western and central Columbia Plateau (Rigby et al. 1979; Swanson et al. 1979c). Although the upper and lower boundaries of the Ellensburg Formation are not well defined, it is generally considered that the lower portion of the Ellensburg Formation includes sediments interbedded with and conformably underlying the Columbia River Basalt Group in the western part of the Columbia Plateau (Bentley et al. 1980a; Waitt 1979). The upper boundary in the Toppenish Basin is considered to be the sediment conformably overlying the Columbia River Basalt Group and unconformably underlying Pliocene and Quaternary rocks (Bentley et al. 1980a). In the Pasco Basin, it has been indicated the upper boundary of the Ellensburg Formation is overlain by the Ice Harbor Member (Myers et al. 1979) but has also been at the top of the late phase of the Snipes Mountain conglomerate (Fecht et al. 1985). Farooqui et al. (1981) designated coeval sediments above the Columbia River Basalt Group in Oregon as belonging to the Dalles Group and sediments interbedded with the Columbia River Basalt Group as belonging in the Ellensburg Formation. Since the base of the Columbia River Basalt Group is inaccessible in the study area, for the purposes of this study the Ellensburg Formation is defined as including all sedimentary rocks interbedded and conformably overlying the Columbia River Basalt Group (but does not preclude sediments underlying the Columbia River Basalt Group).

The Ellensburg Formation within the study area consists of one formal member, the Squaw Creek Member (Swanson et al. 1979c), and ten informal members: Quincy interbed, Byron interbed, Mabton interbed, Cold Creek interbed, Selah interbed, Rattlesnake Ridge interbed, Levey interbed, early and late phase of the Snipes Mountain conglomerate, and the McBee conglomerate (see fig. 3). The Vantage Member of the Ellensburg Formation was formalized by Swanson et al. (1979c) as well, but has not been found within the study area. The Ellensburg Formation interbeds are defined and identified on the basis of the identities of bounding Columbia River Basalt Group flows (Schmincke 1967c; ARHCO 1976; Myers et al. 1979; Swanson et al. 1979c) and not on the basis of their lithologic characteristics. However, both lithology as well as stratigraphic position are used to identify the Snipes Mountain conglomerate and McBee conglomerate. Borehole geophysical logs can be used to identify the sedimentary interbeds of the Ellensburg Formation which are intercalated with the Saddle Mountains Basalt since the Saddle Mountains Basalt flows are easily identified on the logs.

2.4.1 Squaw Creek Member

The Squaw Creek "Diatomite Bed" was assigned to lie beneath the Roza Member and designated as part of the Frenchman Springs Member by Grolier and Bingham (1966), but was later reassigned to the Ellensburg Formation as the Squaw Creek Member (Swanson et al. 1979c)

In the study area, the Squaw Creek Member is a discontinuous interbed which lies between the Roza Member and Frenchman Springs Member (see fig. 3), and is locally exposed west of Prosser along the Horse Heaven Hills uplift. Near Byron Road (center SW1/4 sec. 23, T. 8 N., R. 23 E.) the interbed is composed of tuffaceous silts containing fragments of petrified wood and is overlain by ~5 m of Roza Member pillow basalts.

2.4.2 Quincy Interbed

The Quincy interbed, as defined by ARHCO (1976), lies between the Priest Rapids Member and the Roza Member, but for the purpose of this study, includes sediment between the Priest Rapids Member and the next older basalt flow. Along the Horse Heaven Hills uplift, only one outcrop of the Quincy interbed was found (SW1/4 NW1/4 sec. 14, T. 8 N., R. 24 E.). At this location, it is composed of opalized material, petrified wood, and some tuffaceous sediment. The interbed here is less than several meters thick. In the Horse Heaven Test well (see fig. B-11) on the Horse Heaven Plateau (see fig. 4), no Roza Member and possibly no Rosalia chemical type flows of the Priest Rapids Member are present based on chemical analyses. Here, nearly 20 m of sediment is interpreted to lie between the Lolo flow of the Priest Rapids Member and the Frenchman Springs Member, and by definition is considered to be the Quincy interbed.

2.4.3 Byron Interbed

Along the Horse Heaven Hills uplift near Prosser, a discontinuous, thin interbed is found between the Rosalia and Lolo flows of the Priest Rapids Member. The interbed variably consists of a baked tuff, opalized material embedded with petrified wood, or tuffaceous sediment that contains fragments of petrified wood. This interbed has been noted elsewhere in the central Columbia Plateau (Reidel 1978; Taylor 1976; Jones and Landon 1978; Bentley et al. 1980a) and is here informally named the Byron interbed for a 0.5-m-thick section exposed along Byron Road (SE1/4SE1/4 sec. 23, T. 8 N., R. 23 E.) south of the old townsite of Byron.

2.4.4 Mabton Interbed

Sediment directly underlying the Umatilla Member and found along the Horse Heaven Hills south of Mabton, south-central Washington, was named the Mabton interbed by Laval (1956), was renamed the Mabton Member by Schmincke (1967c), and was later reduced to informal status by Swanson et al. (1979c). Within the study area, the Mabton interbed lies between the Umatilla Member and the Priest Rapids Member (see fig. 3). Near the upper contact with the Umatilla Member, the Mabton interbed is baked and is a distinctive brick-red color with alternating bluish-gray colored bands that parallel the contact. The baked zone is relatively erosion-resistant and contains a network of closely spaced columnar joints aligned perpendicular to the banding (fig. 8). The interbed, as a whole, usually forms erosional saddles along the north dip slopes of anticlines within the Horse Heaven Hills uplift.

The Mabton interbed is composed of tuffaceous clays, silts, and sands. Fluvially deposited sands and pebbly sands of the interbed are commonly found along the Horse Heaven Hills west of Prosser. These sands contain quartzite, feldspar, and mica, (identifications were made using hand lens) which were probably derived from outside the Columbia Plateau.

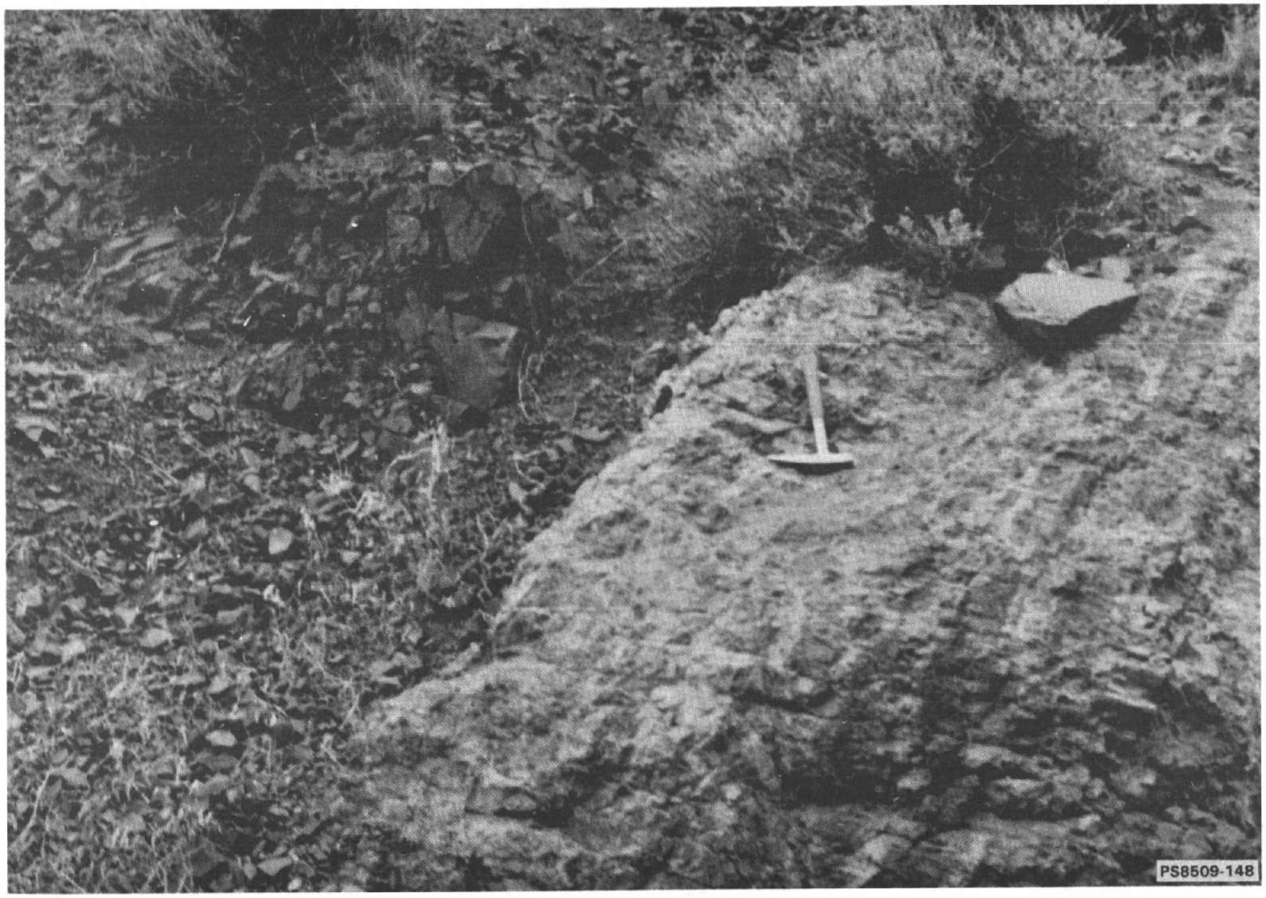


Figure 8. Near-Vertical Contact between the Umatilla Member and the Mabton Interbed (loc. SE1/4SW1/4 sec. 16, T. 9 N., R. 26 E.). The upper portion of the interbed has been baked.

2.4.5 Cold Creek Interbed

The Cold Creek interbed was informally named for sediments found in the Pasco Basin directly underlying the Esquatzel Member (ARHCO 1976; Myers et al. 1979). In the study area, the Cold Creek interbed lies between the Esquatzel Member and the Umatilla Member (see fig. 3).

The Cold Creek interbed is poorly exposed along the Horse Heaven Hills uplift, but where exposed, it is composed of unconsolidated silt. Natural gamma geophysical logs through the Cold Creek interbed (DNR 79-07 well, see fig. B-22; Shaw well, see fig. B-31; DDH-3 well, see fig. 5) suggest the interbed lacks a significant amount of potassium-rich sediments.

2.4.6 Selah Interbed

Mackin (1961) named the sediments found between the Pomona Member and Roza Member the "Selah Member" of the Ellensburg Formation. Schmincke (1967c) later redefined the "Selah Member" to be the sediments directly underlying the Pomona Member and overlying the next older basalt flow. This interbed was later informalized by Swanson et al. (1979c).

Following the definition of Schmincke (1967c), the Selah interbed within the study area lies between the Esquatzel and Pomona Members (fig. 3), or between the Umatilla and Pomona Members where the Esquatzel flow is absent.

The Selah interbed consists of sands, silts, tuffs, and conglomerates. A blue-black to gray, banded, fused vitric tuff (Schmincke 1967b), up to several centimeters thick, is often found at the contact between the Selah interbed and the Pomona Member. Float from the fused tuff layer can often be found on hillsides aiding in locating the upper boundary of the Selah interbed. A fluvial facies is recognized within the Selah interbed which consists of a generally poorly indurated conglomerate (fig. 9). The sand matrix is quartzose and mica rich. The majority of clasts within the conglomerate are Columbia River basalt (see table 3), but the conglomerate also contains a significant percentage of plutonic and metamorphic clasts (∿40%). As the clast size increases, the Columbia River Basalt Group comprises a higher percentage of the clasts, and as the plutonic and metamorphic rocks (derived from outside the plateau) increase in abundance, clast size diminishes (see table 3). The size change, along with the composition of the clasts and sand, reflects distant provenance of the exotics and local derivation of the basalt. The conglomerate is rarely cemented by an iron-bearing mineral. At Chandler Butte (SE1/4 sec. 21, T. 9 N., R. 26 E.) the conglomerate is found adjacent to invasive Pomona dikes and exposures of hyaloclastite. The hyaloclastite is interpreted to have formed from the interaction of the fluid Pomona lava with the water-saturated Selah interbed. Fecht et al. (1985) interpret the Selah conglomerate as representing the westward extension of the ancestral Clearwater-Salmon River (ancestral Snake River of Swanson and Wright 1976; see section 3.0). The exposures at Chandler Butte suggest that a paleoriver

Figure 9. Conglomerate within the Selah Interbed (loc. NE1/4SW1/4 sec. 29, T. 9 N., R. 27 E.).

Table 3. Pebble Counts of Gravels from Various Ellensburg Formation Outcrops.

Sedimentary unit	Location			Count (intermediate axis size)	CRBG (%)	Quartzite (%)	Other[a] (%)
	Township	Range	Section				
McBee Conglomerate	9 N	26 E	SE SE 23	100	100.0	0.0	0.0
Snipes Mountain Conglomerate[b]	8 N	24 E	SE SE 9	50 or 100	16.0	10.0	74.0
Rattlesnake Ridge Interbed	8 N	24 E	SW NE 18	194	18.0	15.0	67.0
				42 (6-25 cm)	78.6	0.0	21.4
Selah Interbed	9 N	26 E	SW SE 21	164 (3-6 cm)	72.6	6.1	21.3
				139 (1-3 cm)	48.2	15.8	36.0
Selah Interbed	9 N	25 E	SE NE 25	218	60.6	11.9	27.5

NOTE: CRBG = Columbia River Basalt Group.
[a]Generally consists of metamorphic and plutonic lithologies.
[b]Recalculated from Schmincke (1964). Correlated with the late phase of the Snipes Mountain conglomerate of Fecht et al. 1985.

was present here just prior to the incursion of the Pomona Member. Both the fused tuff and conglomerate within the study area were deposited during the Esquatzel-Pomona interval (see section 3.0).

A signature "kick" in the natural gamma log is found at the top of the Selah interbed section in several of the boreholes (see fig. B-2 through B-31). Observations from this study support Brown's (1978) idea that this signature "kick" represents the vitric tuff found regionally at the upper contact of the interbed (Schmincke 1967b).

2.4.7 Rattlesnake Ridge Interbed

Thick sediments separating the Pomona and Elephant Mountain Members, or the upper vitric tuff of the Selah "Member", were named the Rattlesnake Ridge Member by Schmincke (1967c), but the interbed was later informalized by Swanson et al. (1979c).

Outcrops of the Rattlesnake Ridge interbed are rare along the northern flanks of the Horse Heaven Hills uplift, because the steeply dipping interbed acts as a slip plane facilitating slumping. Exposures are more commonly found along the ridge crests of the Horse Heaven Hills and along cliffs created by the down-cutting of the Yakima River. Where exposed, the interbed is light tan, light gray, or off-white in color.

The Rattlesnake Ridge interbed consists of laminated silts and clays, cross-bedded, ripple-marked, or massively bedded sandstone, or massive tuffs. The sandstones are locally micaceous and mixed with other heavy minerals of exotic derivation (from outside the Columbia Plateau). Along Ward Gap Road, a 2-m-thick conglomerate (see fig. 10; NW1/4NE1/4 sec. 17, T. 8 N., R. 24 E.), containing nearly 15% quartzitic pebbles and cobbles (see table 3), conformably overlies the flow top of the Pomona Member and is itself overlain by a thicker section of laminated siltstone. Based on the gravel lithologies (see table 3), stratigraphic position, and geographic location, the conglomerate is here interpreted to have been deposited by the ancestral Columbia River whose channel is found farther to the north (Schmincke 1964, 1967a, 1967c; see section 3.0). Absence of a major component of Columbia River Basalt Group clasts in the conglomerate indicates that the ancestral Columbia River was not influenced by the ancestral Clearwater-Salmon River at this time at this location (or to the north of this location).

2.4.8 Levey Interbed

The Levey interbed consists of those sediments between the Ice Harbor and Elephant Mountain Members (ARHCO 1976; fig. 3). The Levey interbed is not found along the Horse Heaven Hills uplift in the study area, but is found in two of the geophysically logged boreholes (DC-15, DDH-3). The Levey interbed gives a high natural gamma response in these two boreholes, and has been described as being composed of tuffaceous silt or siltstone (Bond et al. 1978; Myers et al. 1979).

Figure 10. Conglomerate within the Rattlesnake Ridge Interbed (loc. NW1/4NW1/4 sec. 17, T. 8 N., R. 24 E.).

2.4.9 Snipes Mountain Conglomerate

The Snipes Mountain conglomerate was informally introduced by Schmincke (1967c) as an areally extensive conglomerate deposit that directly overlies the Elephant Mountain Member in south-central Washington. The Snipes Mountain conglomerate is characterized by an abundance of quartzite and other metamorphic rocks. Schmincke (1967c) attributed the source of the conglomerate to a sheet deposit of the ancestral Columbia River. Fecht et al. (1985) divide the Snipes Mountain conglomerate into an early and late phase (see fig. 3) based on lithology and distribution. The early phase was deposited between the emplacement of the Elephant Mountain Member and the Ice Harbor Member (between 8.5 and 10.5 m.y.B.P.) and is coeval with the deposition of the Levey interbed. The late phase of the Snipes Mountain conglomerate was deposited after the emplacement of the Ice Harbor Member and is thought to be coeval with the basal unit of the Ringold Formation of the Pasco Basin (Fecht et al. 1985). Both phases contain deposits from the ancestral Columbia River, but from slightly different time intervals and in different geographic locations, reflecting a diversion of the ancestral Columbia River (see section 3.0).

Outcrops of both the early and late phases of the Snipes Mountain conglomerate are identified in the study area based on clast lithology and stratigraphic position, but are tentatively differentiated solely on the geographic distribution of the conglomerates in accordance with the distribution specified by Fecht et al. (1985). The early phase of the Snipes Mountain conglomerate is not found along the portion of the Horse Heaven Hills uplift that was in the field mapping area, but is found along the Horse Heaven Hills uplift to the immediate west (Schmincke 1964, 1967a, 1967c; Swanson et al. 1979b; Bentley et al. 1980a) and within the lower Yakima Valley in the vicinity of Sunnyside, Washington (Campbell 1977; Rigby et al. 1979). Two outcrops of the late phase of the Snipes Mountain conglomerate are tentatively identified along the Horse Heaven Hills uplift. One occurrence is found along Richards Road (SE1/4SE1/4 sec. 9, T. 8 N., R. 24 E.). Here, Snipes Mountain conglomerate is found conformably overlying the steeply dipping Elephant Mountain Member along the northern flank of the Drake anticline. The conglomerate occurs in lenses surrounded by silts and sands. The outcrop was first identified by Schmincke (1964) who described the lithology of the clasts (see table 3). The other occurrence is found along the cliffs at the Gibbon railroad siding (center NE1/4 sec. 26, T. 9 N., R. 25 E.). Here, the flat-lying Elephant Mountain Member is overlain by a thin conglomerate (<30 cm thick). No pebble counts were conducted on this exposure, but the conglomerate appears to contain a high percentage of plutonic and metamorphic clasts. This conglomerate is overlain by ~1 m of siltstone. This exposure was assigned to the Levey interbed by Bond et al. (1978).

2.4.10 McBee Conglomerate

Another conglomerate, informally named the McBee conglomerate in this study, was found in two locations along the crest of the Horse Heaven Hills within the northwest trend. Alongside McBee Grade (SE1/4SE1/4 sec. 23, T. 9 N., R. 26 E.), the conglomerate is exposed in a gravel pit (fig. 11) where it appears to overlie the Pomona Member. Laval (1956) described these gravels at this location to be foreset-bedded with a northwest dip, although this foreset bedding is not apparent today. Near Webber Canyon (SE1/4SE1/4 sec. 32, T. 9 N., R. 22 E.), gravels of the McBee conglomerate appear to overlie the Elephant Mountain Member. The clasts within the conglomerate at both locations consist mostly of rounded to subrounded Columbia River Basalt Group and are considered here to be locally derived (from within the Columbia Plateau). Further, a majority of the Columbia River Basalt Group clasts appear to be Pomona basalt. The exact age of the deposit is unknown, but the McBee conglomerate is tentatively thought to be coeval with the late phase of the Snipes Mountain conglomerate based on its distribution (see section 3.0).

2.4.11 Undifferentiated Ellensburg Formation Sediments

Rarely, sediments outcrop along the Horse Heaven Hills uplift that conformably overlie the Elephant Mountain flow and consist of bedded and laminated silts and clays (e.g., along the northern flank of the Prosser anticline, SW1/4 sec. 13, T. 8 N., R. 23 E.), or tuffaceous silts (e.g., along the southern limb of the Chandler anticline, NW1/4NW1/4 sec. 30, T. 9 N., R. 26 E.). The exact age of these sediments is unknown (except that they are post-Elephant Mountain in age), but because of their conformable relationship to the Elephant Mountain Member and their lithologies, they are included in the Ellensburg Formation.

Figure 11. The McBee Conglomerate (loc. SE1/4SE1/4 sec. 23, T. 9 N., R. 26 E.).

3.0 STRUCTURE

This section describes the structure of the portion of the Horse Heaven Hills uplift which encompasses the intersection of the northwest and northeast structural trends of the uplift. Because of their proximity and intrinsic relationship with the Horse Heaven Hills uplift, the structure of portions of the lower Yakima Valley, Horse Heaven Plateau, Badger Coulee, and Hog Ranch-Naneum Ridge anticline are also described.

3.1 STRUCTURE OF THE IMMEDIATE AREA

Lying between the Rattlesnake-Wallula structural alignment (RAW) and the Toppenish Basin, and between the Rattlesnake Hills uplift and the Horse Heaven Hills uplift (fig. 12) is a broad east-west-trending syncline called here the lower Yakima Valley syncline. The syncline broadens and abruptly plunges westward towards the Toppenish Basin west of Sunnyside. The lower Yakima Valley syncline is structurally higher than, and separates the Toppenish and Pasco Basins as indicated by top-of-basalt elevations from this and other studies (for the Toppenish Basin - Robbins et al. 1975; Bentley et al. 1980a; Biggane 1982; for the Pasco Basin - Myers 1981). Low-relief, generally east-west-and northwest-trending anticlines and monoclines are superimposed upon the broad syncline (see fig. 12).

Trending approximately north-northwest across the Yakima folds (fig. 12) is a broad structural arch which generally separates the Yakima River and Columbia River drainages. The fold system has been referred to in whole or in part as the Table Mountain anticline (Barrash et al. 1983), the Naneum Ridge anticline (Campbell 1984), the Naneum High (a coincident subsurface high, Campbell 1984), the Hog Ranch Axis (Mackin 1961; Bentley 1977; Waitt 1979), the Hog Ranch anticline (Bentley 1977), and the Hog Ranch-Naneum Ridge anticline (Reidel 1984; used in this study). The Hog Ranch-Naneum Ridge anticline has been traced north into the Wenatchee Mountains (Swanson et al. 1979b, Tabor et al. 1982) where basement structure is involved with the uplift (Campbell 1984; Tabor et al. 1982). The southern extension of this structure (fig. 12) has been shown to extend as far as the Rattlesnake Hills on maps (Mackin 1961; Bentley 1977) but has also been shown to extend to the immediate south of Rattlesnake Hills into the lower Yakima Valley syncline (Bentley 1977; Waitt 1979; Barrash et al. 1983; Campbell 1984). Data from this study suggest that the fold may exist as a buried structure in the lower Yakima Valley.

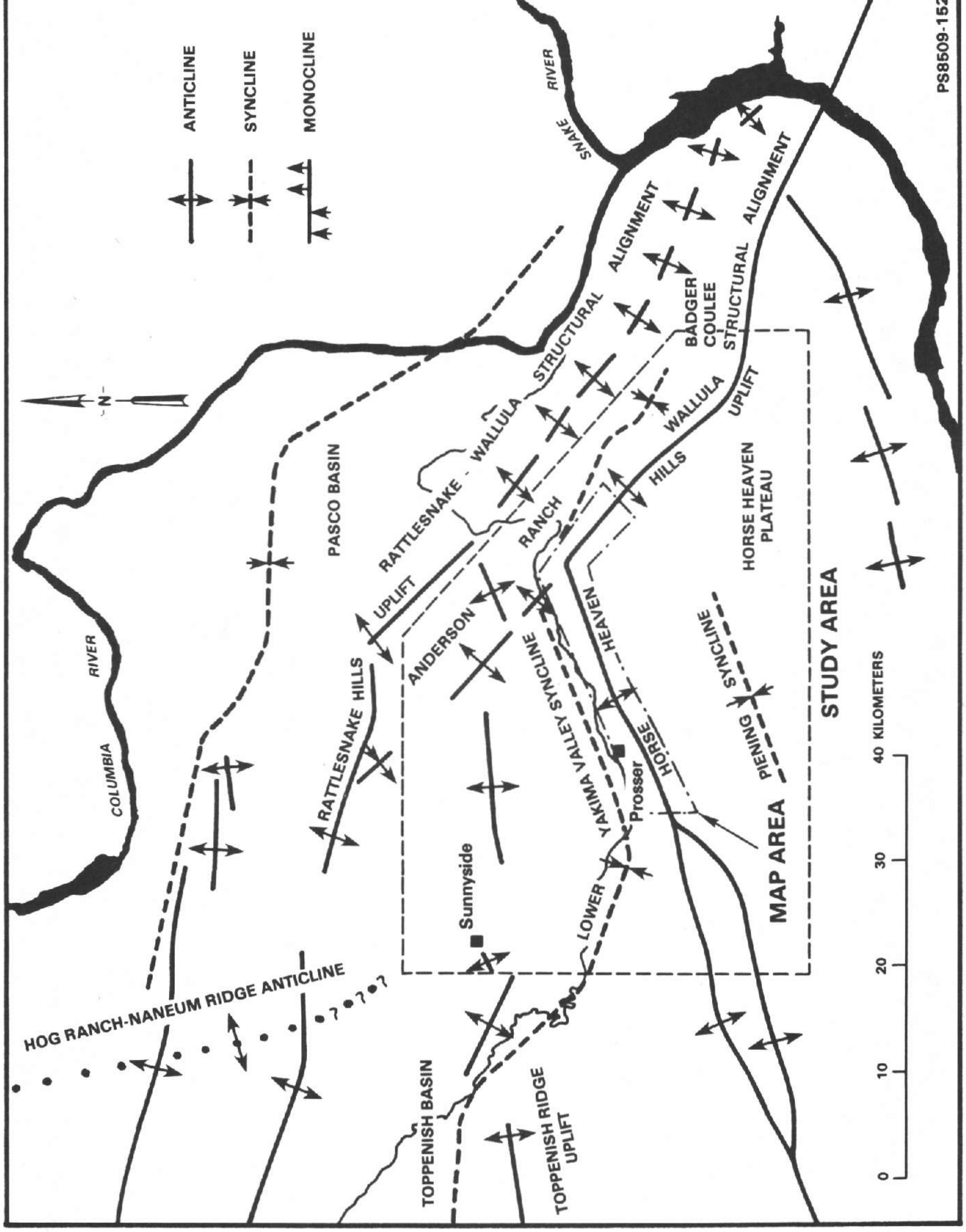


Figure 12. Generalized Map Showing Structures in and Adjacent to the Study Area.

The portion of the Horse Heaven Plateau that lies within the study area is composed of gentle dips from the south flanks of folds along the northwest and northeast trends of the Horse Heaven Hills uplift. A low-relief syncline, here named the Piening syncline (see fig. 12), can be defined on the structure contour map (fig. 13). The southwestern extent of the syncline is unknown, but may continue to the southwest of the study area.

Badger Coulee (see fig. 12) is a narrow valley which lies between the RAW and the northwest trend of the Horse Heaven Hills anticline. Brown (1979) mapped the valley as a syncline based on borehole data.

3.2 HORSE HEAVEN HILLS UPLIFT

The two structural trends of the Horse Heaven Hills uplift (fig. 16, N50°-55°W and N65°-70°E) are only generally shown in the structure contour map (fig. 13), but reflect a superimposed en echelon fold pattern along the two trends (fig. 14). The folds within the northeast trend are oriented in a left-stepping sense to the trend while the folds along the northwest trend are aligned or oriented in a slight right-stepping sense to this trend (see fig. 14). The asymmetry of the uplift is well displayed in the structure contour map showing the northward vergence of the folds in both trends.

Based on geometric distinctions between folds, the Horse Heaven Hills uplift within the study area has been subdivided into six segments (fig. 15). The names Byron, Gibbon, and Chandler have been applied to segments in the northeast trend, and Webber and Kiona to segments in the northwest trend. Another segment, called the Junction segment, covers the intersection of the two trends. Two types of cross sections have been constructed to display the fold and fault geometry along the Horse Heaven Hills uplift: descriptive cross sections which display structure as observed in the field (see appendix C, fig. C-1 through C-6), and interpretive geologic cross sections (see fig. 18, 20, 22, 24, 26, and 27).

3.2.1 Byron Segment

The Horse Heaven Hills uplift within the Byron segment consists of two parallel folds, the Prosser anticline and the Drake anticline (see fig. 14, 16).

The Prosser anticline is an erosional remnant of a double-hinged, asymmetric fold (north vergence) with a N70°-80°E trending axial trace. East of Prosser, the anticline locally plunges to the northeast, at its northeast end.

The northern limb of the Prosser anticline is offset over the southern limb of the Drake anticline along the Prosser fault, a high-angle reverse or thrust fault (fig. 17 and 18). In another location (NW1/4 sec. 12, T. 8 N., R. 24 E.), the northern hinge of the Prosser anticline is cut by a normal fault (see cross section C-C' in fig. 18). Within the "interhinge limb"--that portion of the fold that lies between the northern and southern hinge of a double-hinged fold--a minor thrust fault with only a few meters

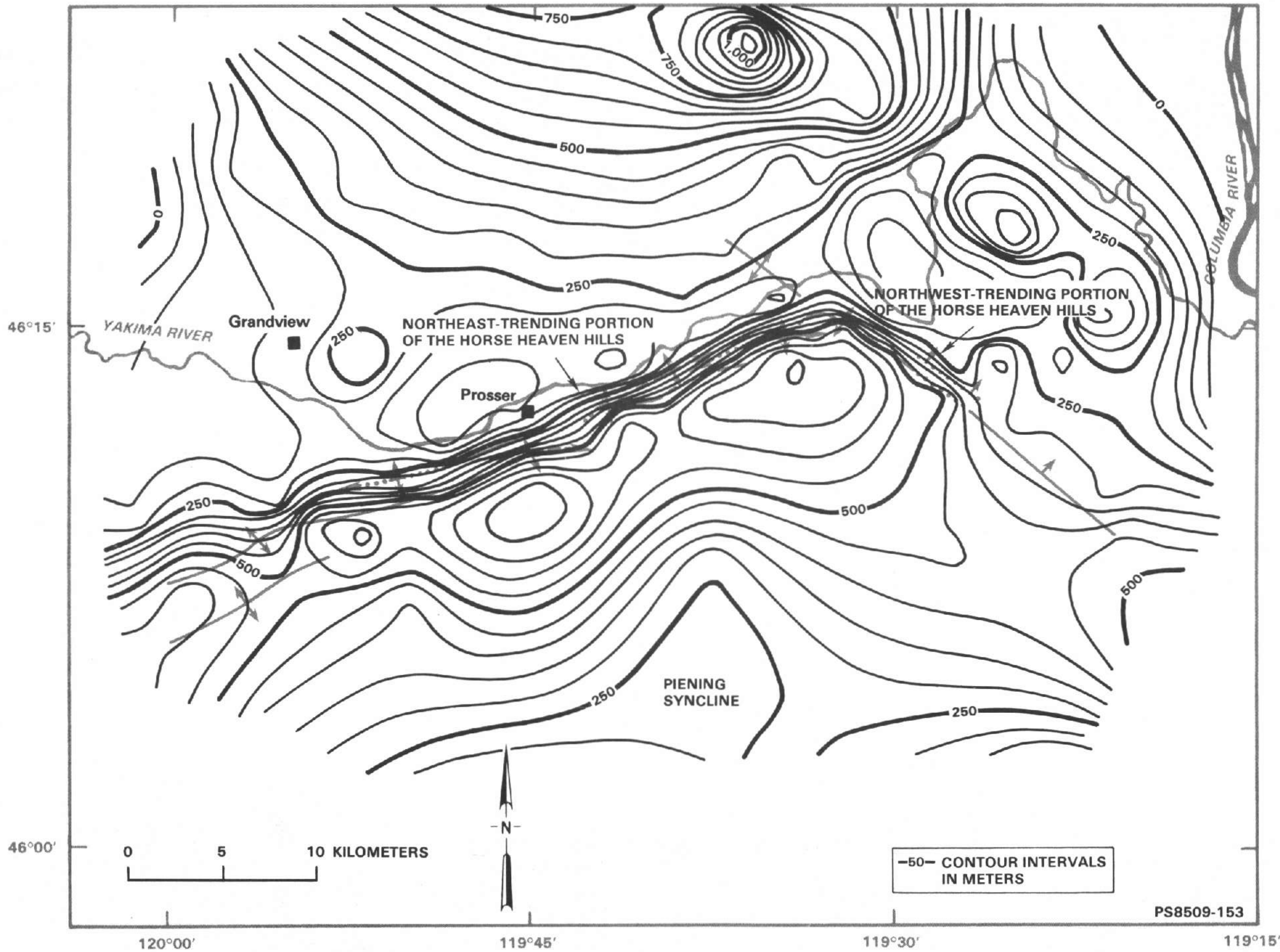


Figure 13. Structure Contour Map on Top of the Pomona Member within the Study Area and Immediate Vicinity.

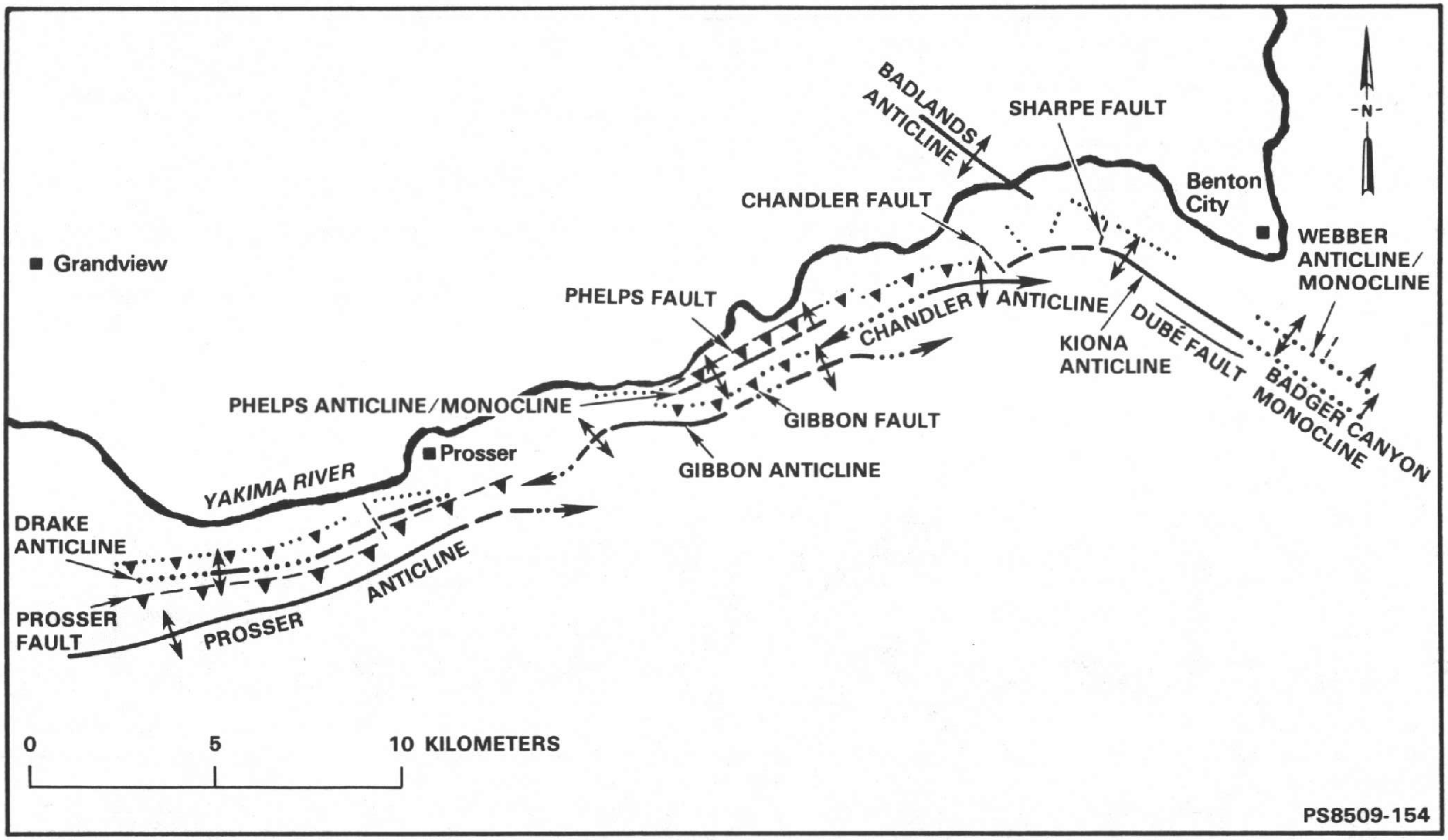


Figure 14. Generalized Structure Map of the Horse Heaven Hills Uplift within the Study Area.

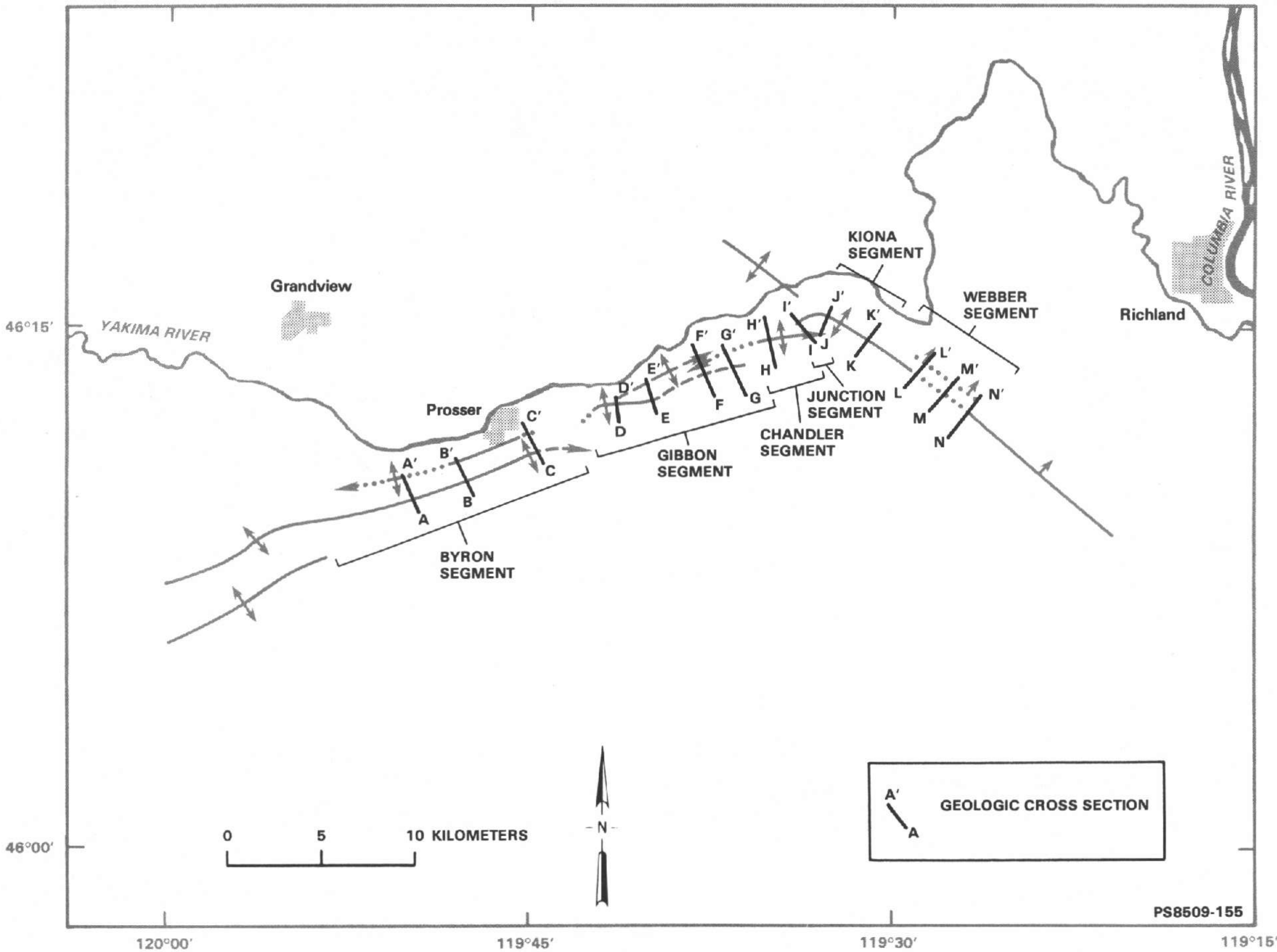


Figure 15. Map Showing Locations of Segments of the Horse Heaven Hills Uplift and Geologic Cross Sections within the Study Area.

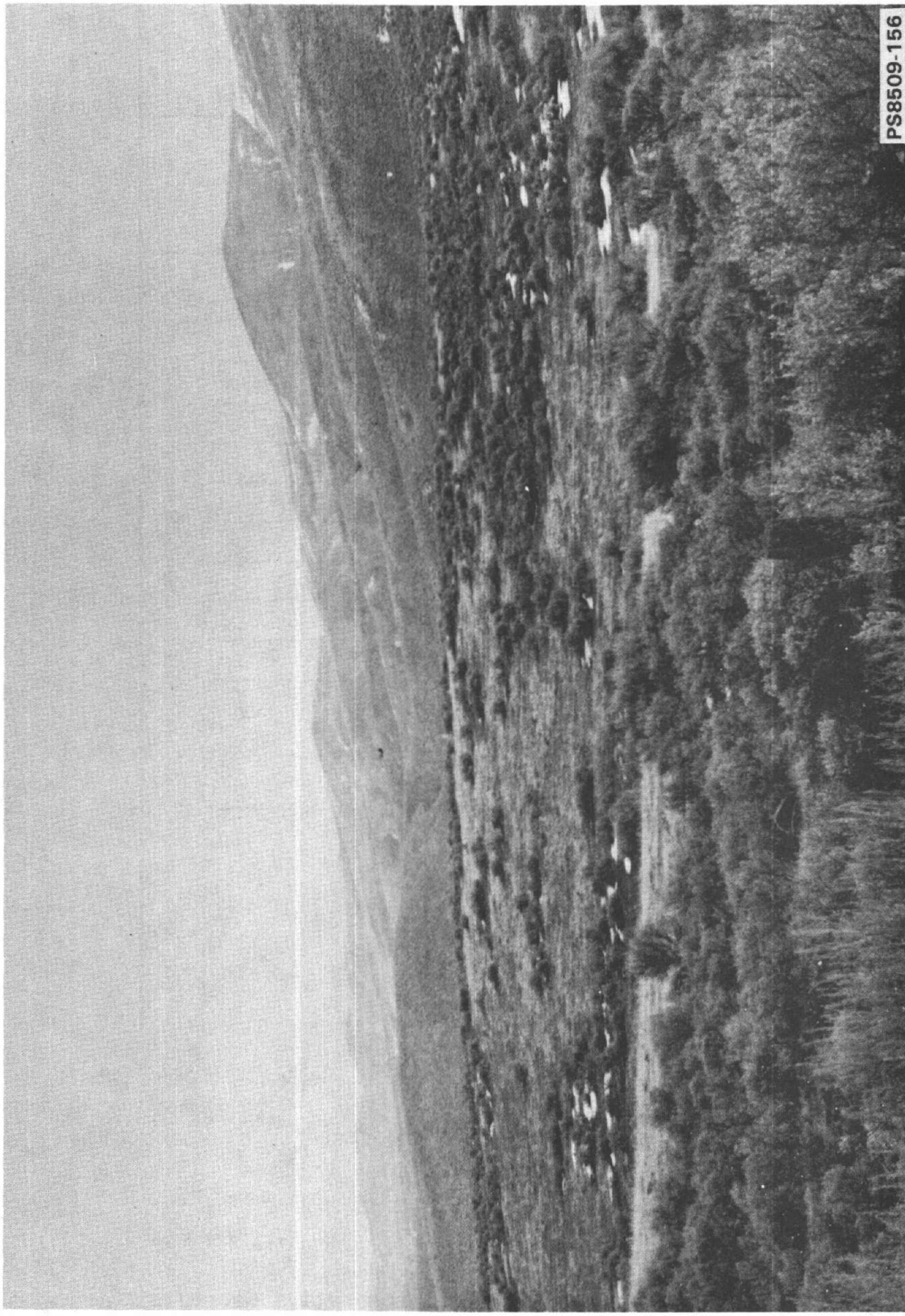


Figure 16. The Horse Heaven Hills Uplift within the Byron Segment.

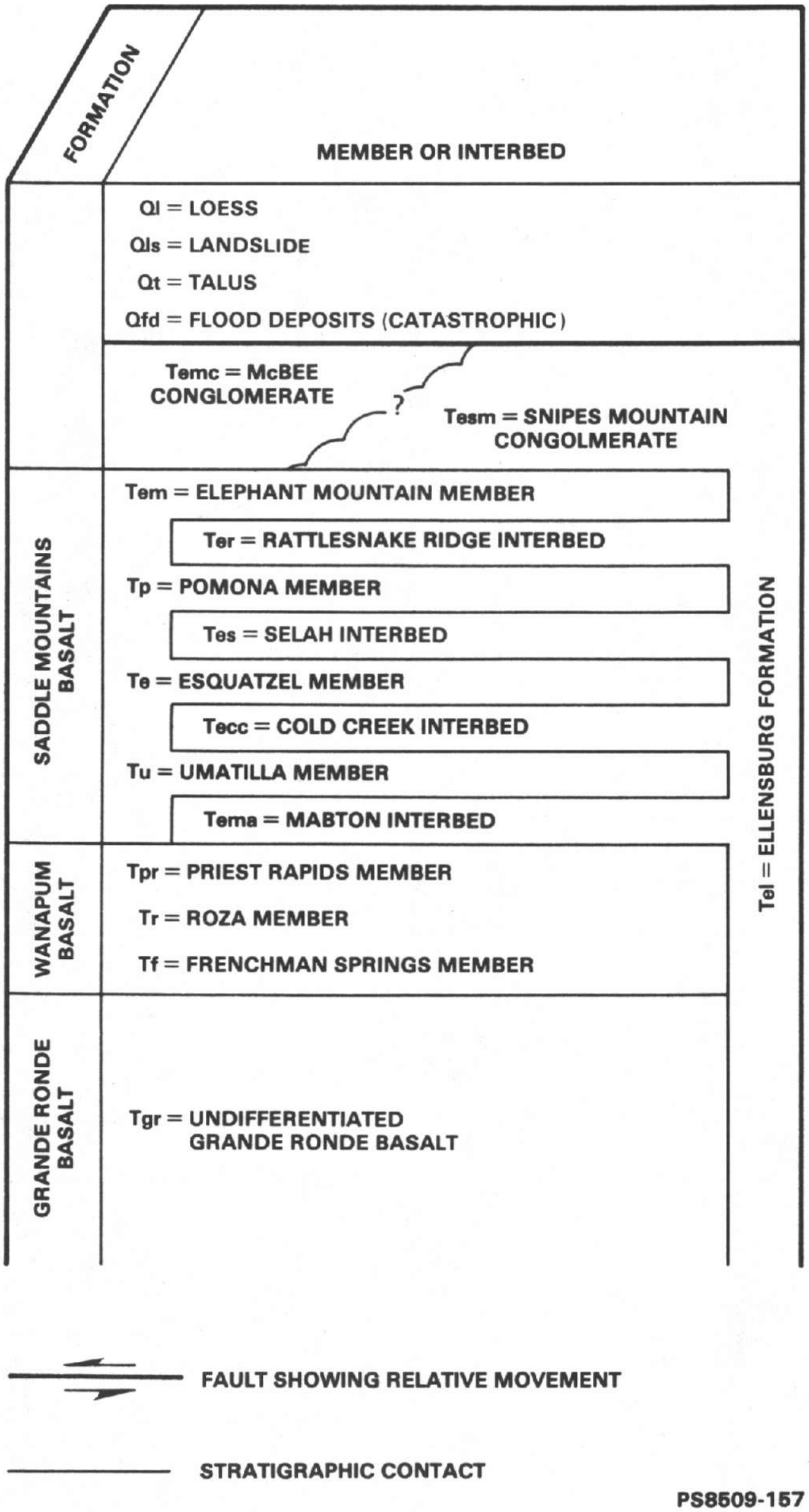


Figure 17. Legend for the Interpretive Geologic Cross Sections.

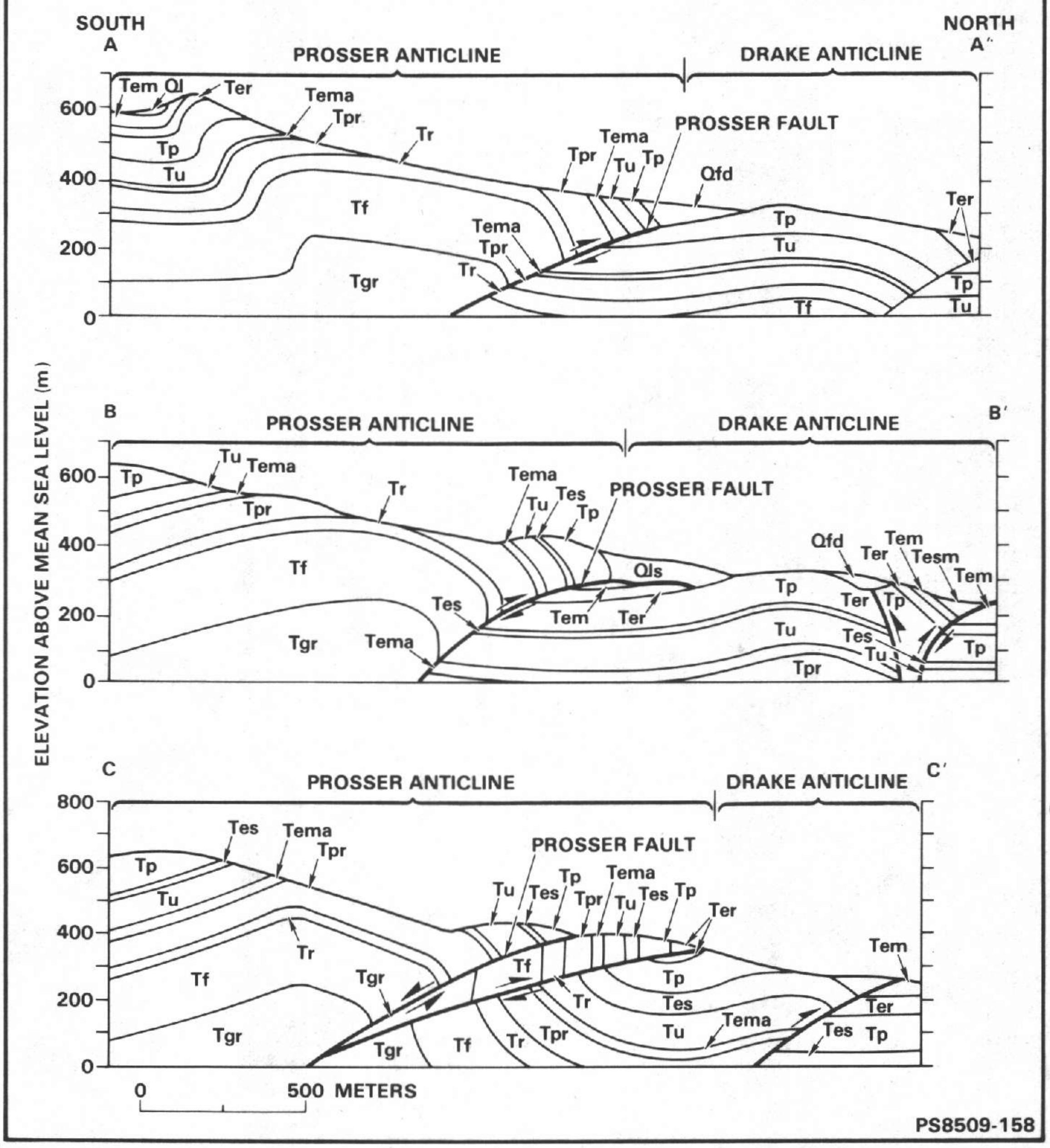


Figure 18. Interpretive Geologic Cross Sections through the Horse Heaven Hills Uplift within the Byron Segment (see fig. 17 for legend and fig. C-1 for corresponding descriptive cross sections).

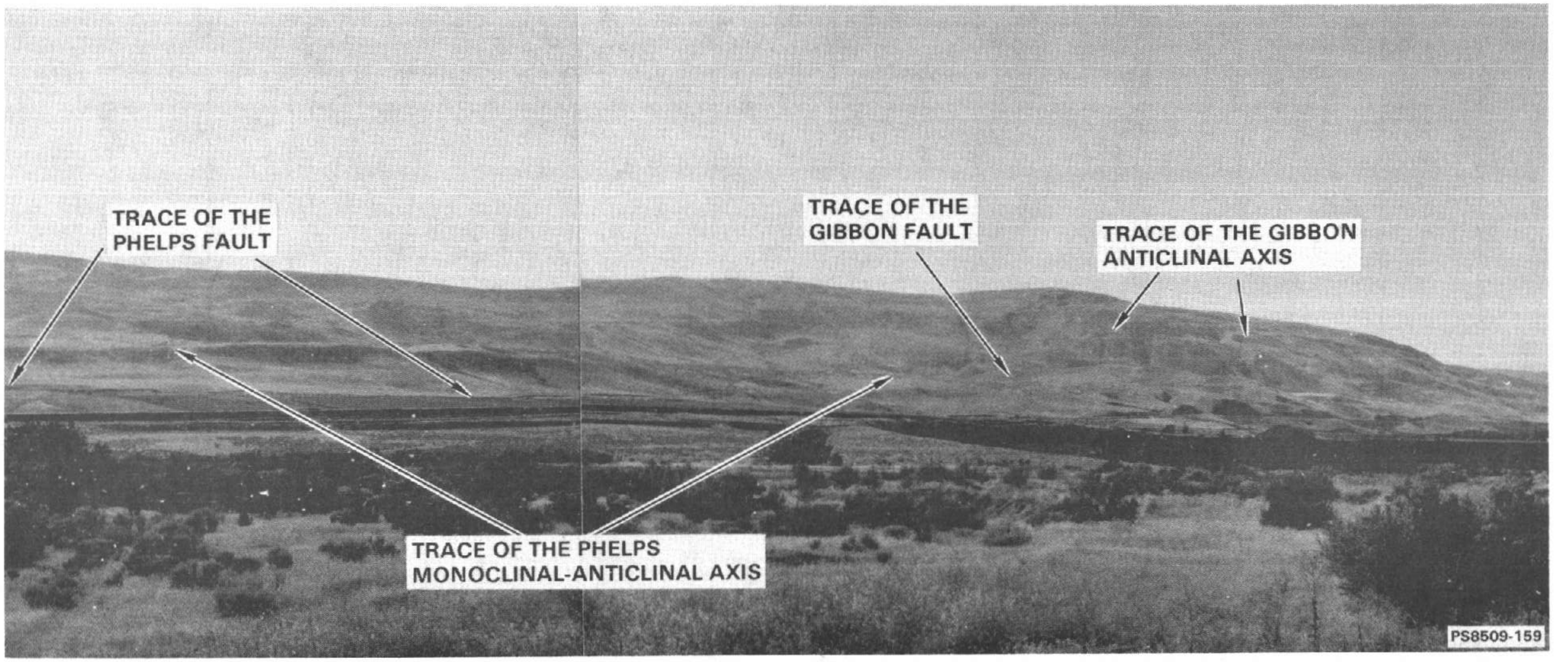


Figure 19. The Horse Heaven Hills Uplift within the Western Portion of the Gibbon Segment.

displacement repeats the upper portion of the Frenchman Springs section (NW1/4SW1/4 sec. 7, T. 8 N., R. 25 E.). Layer-parallel faulting, indicated by the presence of slickenside striae and fault breccia, are found along stratigraphic contacts of steeply dipping strata such as observed along the Umatilla-Selah contact of the southern limb at Ward Gap (NW1/4SE1/4 sec. 20, T. 8 N., R. 24 E.).

The Drake anticline (see fig. 18) is a subtle, low-relief, asymmetric (north vergence), double-hinged fold that parallels the Prosser anticline. Strikes of strata are dichotomous, with the southern limb locally oriented ~70° counterclockwise from the axis of the fold while the northern limb parallels the axis (related to movement along the Prosser fault or local plunging of the anticline??). The Drake anticline either dies out or is buried beneath surficial sediment both east of Prosser and west of Byron road.

At one location (NE1/4NE1/4 sec. 16, T. 8 N., R. 24 E.) a high-angle reverse fault can be traced through the northern hinge of the Drake anticline (see cross section B-B' in fig. 18). In another location (NW1/4SW1/4 sec. 11, T. 8 N., R. 24 E.) a tear fault with right-lateral offset strikes perpendicular to the axis of the Drake anticline (see fig. 14). The attitude of layering and the presence of tectonically shattered basalt along the northern front of the Drake anticline suggest that a thrust or high-angle reverse fault may offset the northern limb of the anticline to the north.

3.2.2 Gibbon Segment

The Horse Heaven Hills uplift within the Gibbon segment consists of two subparallel folds, the Gibbon anticline and the Phelps anticline-monocline (fig. 14, 19).

The Gibbon anticline is an eroded, asymmetric fold (north vergence) which may be locally double hinged. The trace of the anticlinal axis generally trends N.70°E., but locally deviates from this trend. The crestal area of the Gibbon anticline is marked by a local structural dip in the center of the segment that is interpreted to coincide with a less deformed portion of the Gibbon anticline. To the east, the anticline dies out onto the south flank of the Chandler anticline. The western end of the anticline plunges beneath landslide debris to the south of Prosser obscuring its structural relationship with the Gibbon anticline. However, based on the last traceable portions of the Gibbon and Prosser anticlines, the Gibbon anticline appears to be en echelon with the Prosser anticline.

A thrust or high-angle fault (the Gibbon fault, fig. 20) is interpreted to lie below the northern limb of the Gibbon anticline and is locally manifested by tectonically shattered basalt along the northern limb of the anticline. At one location (NE1/4SW1/4 sec. 33, T. 9 N., R. 25 E.) the hinge zone is cut by a thrust fault (see cross section D-D' in fig. 20). At another location (see cross section G-G' in fig. 20), a high-angle fault has been mapped by Bond et al. (1978) along and parallel to the crest of the Gibbon anticline at its extreme northeastern end. No tear faults across the

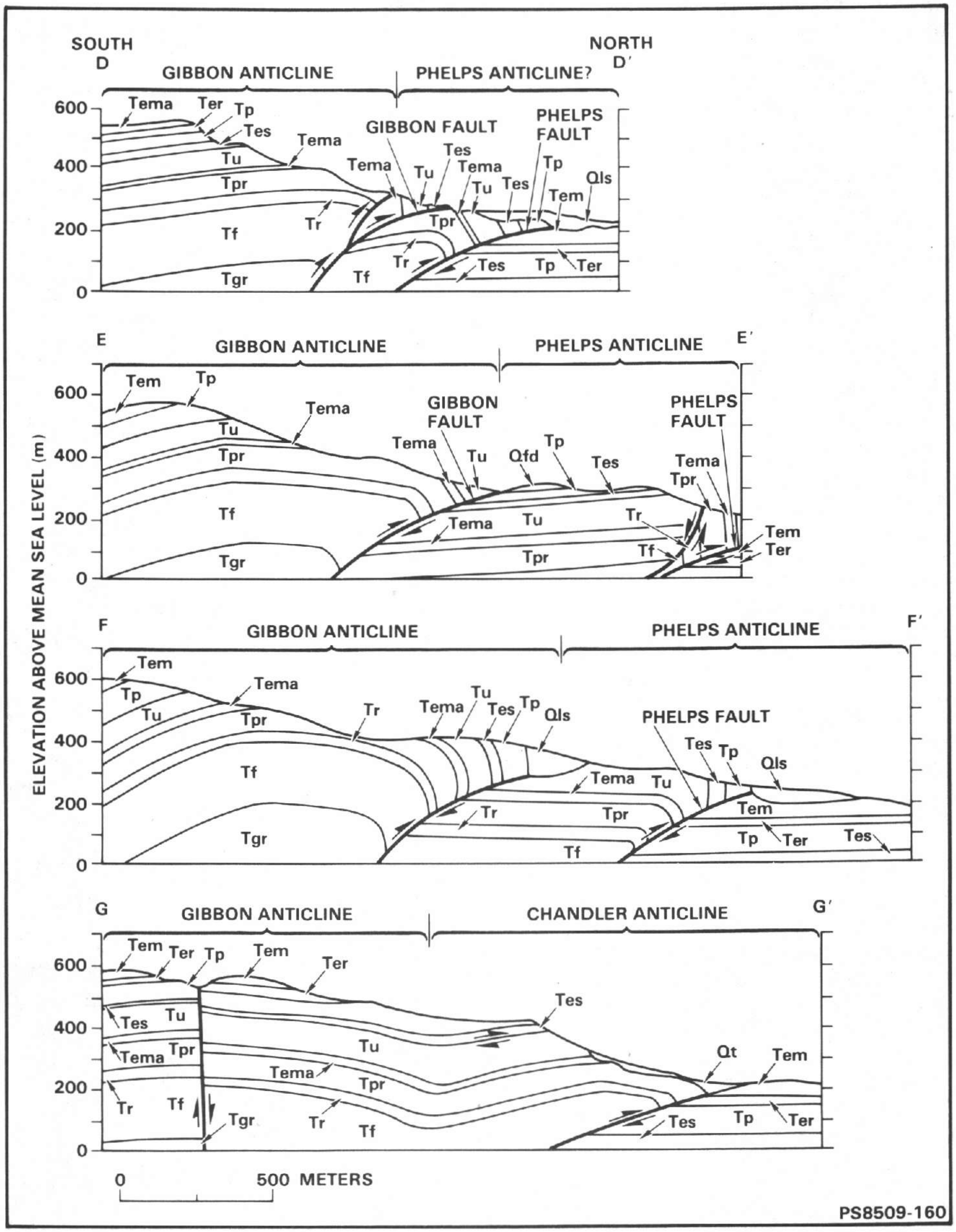


Figure 20. Interpretive Geologic Cross Sections through the Horse Heaven Hills Uplift within the Gibbon Segment (see fig. 17 for legend and fig. C-2 for corresponding descriptive geologic cross sections).

uplift were observed directly, but such faults may be present between the areas represented by the cross sections F-F' and G-G' (see fig. 20) due to the difference in degree of fold development between these two areas.

To the immediate north of the Gibbon anticline is a subparallel fold which is an anticline at the west end but changes to a monocline at its east end. Thus the fold is named the Phelps anticline and Phelps monocline, respectively. The Phelps anticline is an erosional remnant of a low-relief, asymmetrical anticline (north vergence; see cross sections D-D', E-E', F-F' in fig. 20). Both the monocline and anticline have near-vertical northern limbs and a hinge zone which is reflected in a subtle topographic bench along their length (see fig. 19) The western extension of the fold is lost in complex faulting and landslide debris while the eastern end of the fold either dies out or merges with the Chandler anticline.

The hinge zone of the Phelps anticline and monocline has locally been obliterated by a fault that offsets the southern limb over the northern limb. A thrust or reverse fault, the Phelps fault (see fig. 20), is thought to offset the steep northern limb to the north as well. These two faults have produced a zone of fault breccia, which, along with the presence of thick sedimentary interbeds on the steeply dipping northern limb, facilitates local slumping. A fault mapped along the Gibbon railroad siding by Bond et al. (1978) is interpreted as offsetting the Pomona Member and Selah interbed over the Elephant Mountain Member. Reexamination of this area leads this writer to interpret the Pomona Member and Selah interbed as composing a local landslide block that originated from along the northern limb of the Phelps monocline and was emplaced overlying the Elephant Mountain Member.

3.2.3 <u>Chandler Segment</u>

The Horse Heaven Hills uplift within the Chandler segment consists of one fold, the Chandler anticline (see fig. 14 and 21).

The Chandler anticline is an eroded, asymmetric (north vergence), subtly double-hinged fold, that trends N 70° E for most of its length but changes to ~N 85° W at its eastern end. To the east, the anticline plunges in the southern limb of the Kiona anticline (see fig. 14) and to the west the anticline dies out, possibly onto the back of the Phelps monocline.

The Bauder fault (fig. 22) is a reverse fault that is inferred to offset the northern limb of the anticline to the north, based on the proximity and attitudes of strata observed between the Chandler well and the northern limb of the anticline. Layer-parallel faults are found along the near-vertical northern limb of the anticline in a hyaloclastite at the base of the Roza Member (NW1/4SE1/4 sec. 20, T. 9 N., R. 26 E.) and within a flow top of the upper Frenchman Springs flow (NW1/4SE1/4 sec. 20, T. 9 N. R. 26 E.). Another layer-parallel fault is observed within the Umatilla Member along the southern limb and is characterized by a 5-m-thick zone of tectonic breccia surrounding more coherent basalt blocks in an anastomosing pattern (see cross section G-G' in fig. 20; SE1/4NE1/4 sec. 25, T. 9 N., R. 25 E.).

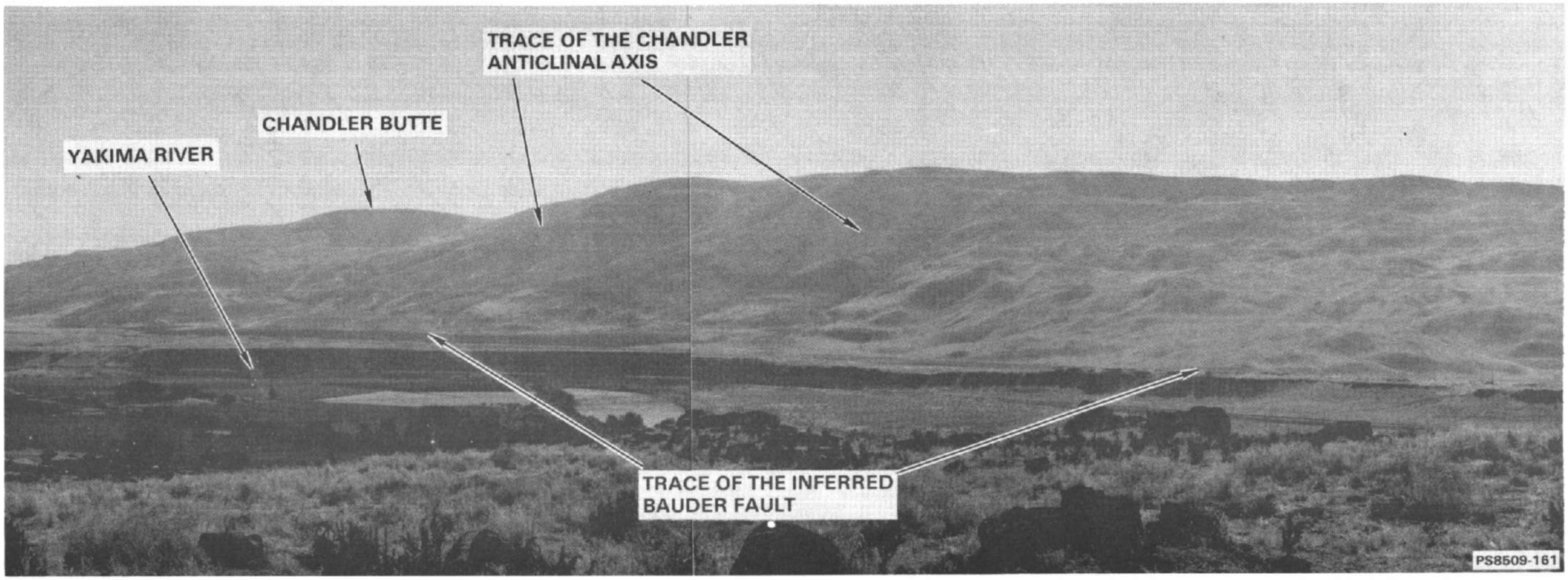


Figure 21. The Horse Heaven Hills Uplift within the Eastern Portion of the Chandler Segment.

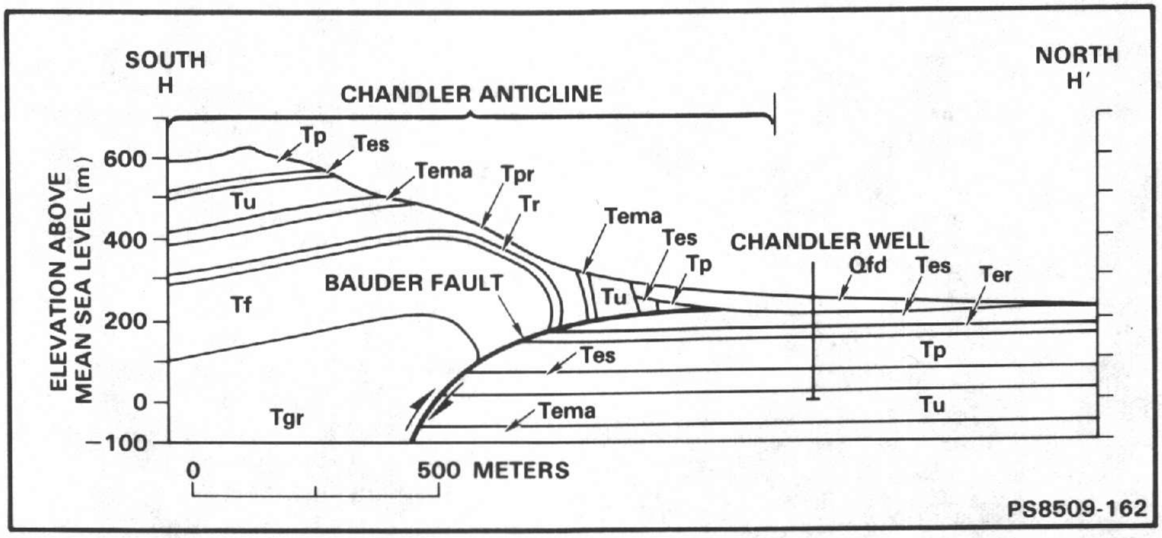


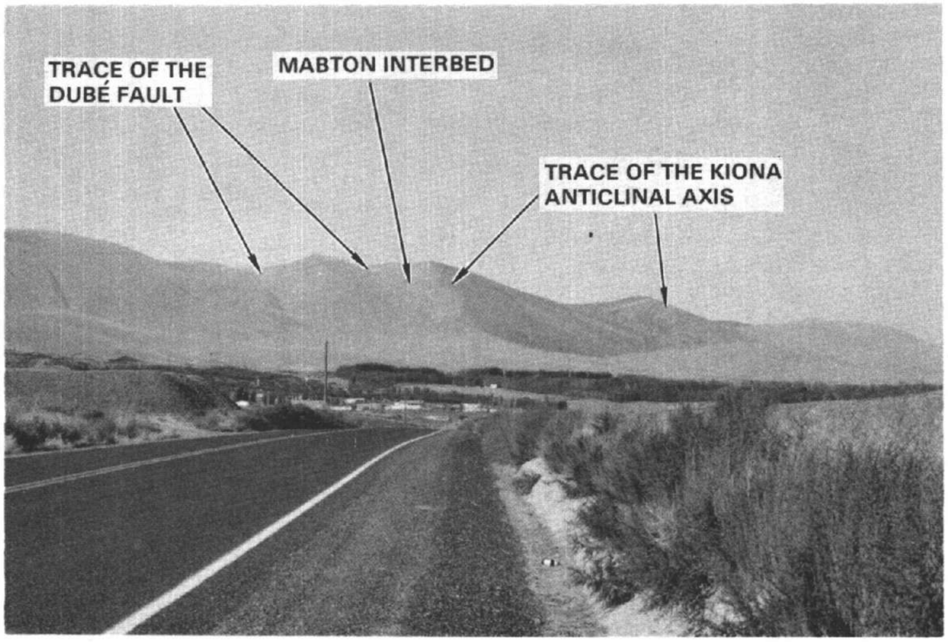
Figure 22. Interpretive Geologic Cross Section through the Horse Heaven Hills Uplift within the Chandler Segment (see fig. 17 for legend and fig. C-3 for corresponding descriptive geologic cross section).

3.2.4 Webber Segment

The Webber segment (see fig. 15) contains two parallel folds (see fig. 14), one, constituting the topographic ridge crest of the Horse Heaven Hills, and the other, a lower-relief anticline found to the immediate northeast (fig. 23). Both folds change geometry from monoclines at the southeast end of the segment to anticlines at the northwest end of the segment.

The fold which composes the topographic ridge crest of the Horse Heaven Hills uplift at the southeastern end of the segment is the Badger Canyon monocline of Myers et al. (1979) and the Kiona anticline at the northwestern end of the segment. The Badger Canyon monocline and Kiona anticline have northeast vergence. The Kiona anticline is interpreted to be a double-hinged, asymmetric anticline with a southwestern hinge exposed near the ridge crest but the northeastern hinge obscured by surficial deposits.

A high-angle reverse fault, the Dubé fault (see fig. 14), which parallels the ridge crest, cuts the southeastern hinge of the Kiona anticline (see cross section L-L' in fig. 24) juxtaposing the Priest Rapids Member of the southwestern hinge against the Elephant Mountain Member of the southwestern limb. Offset decreases along the trace of the fault to the northwest as indicated by the progressive juxtaposition of younger stratigraphic units (Priest Rapids Member, Umatilla Member, Pomona Member). Although no fault was observed at the base of the northern limb of the Badger Canyon monocline, one may be present along the base of the Kiona anticline.



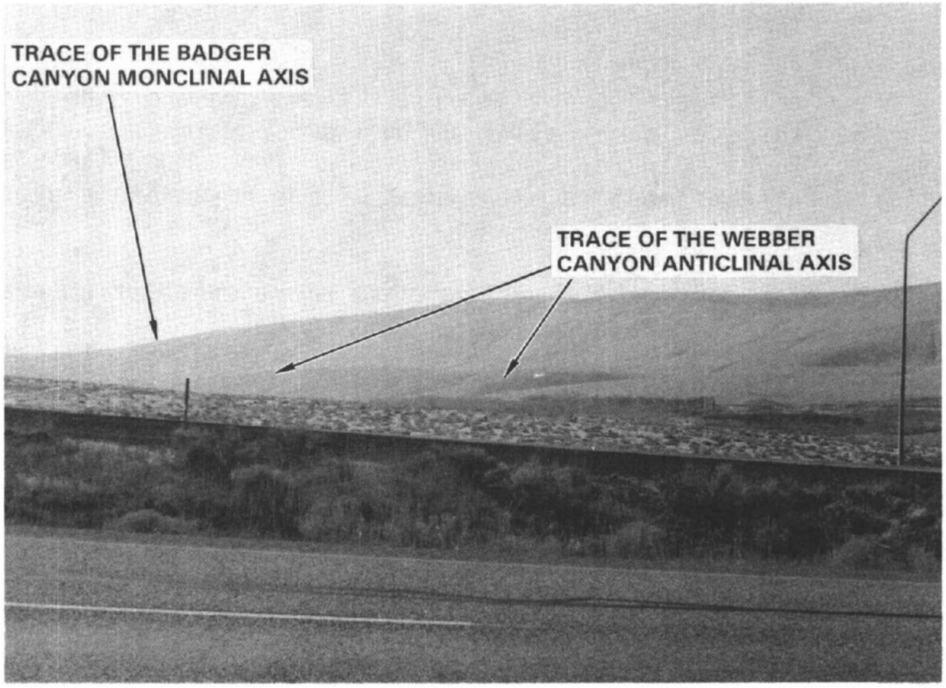


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Figure 23. The Horse Heaven Hills Uplift within the Northwestern Portion (top) and Southeastern Portion (bottom) of the Webber Segment.

The subtle, low-relief fold which parallels the Badger monocline-Kiona anticline is referred to here as the Webber monocline at its southeastern end and the Webber anticline at its northwestern end (see fig. 14). Both folds have northeast vergence. The Webber monocline extends southeast past Webber Canyon and out of the study area. The northwest extension of the Webber anticline is lost ~4 km northwest of Webber Canyon but is thought to continue buried beneath surficial deposits as indicated by a subtle topographic bench in the topography.

A tear fault is interpreted to cut the Webber anticline (SE1/4SW1/4 sec. 29, T. 9 N., R. 27 E.) based on a marked change in the attitude of layering in two adjacent gullies which cut across the anticline. The more-northern gully exposes a vertically dipping sequence composed of the Pomona Member, Selah interbed, and Umatilla Member (southwest to northeast) penetrated by numerous faults generally oriented subparallel to the layering. The more southern gully exposes gently dipping layering as shown in cross section N-N' in figure 24.

Overall there is a progressive southeast to northwest increase in deformation (increase in strain) within the Webber segment. Both folds tighten considerably from southeast to northwest; buckling occurs in the transition from monoclines to anticlines; and the elevation of the crest of the fold increases from the Badger Canyon monocline to the Kiona anticline.

3.2.5 Kiona Segment

The portion of the northwest-trending Horse Heaven Hills uplift that lies within the Kiona segment consists of a single fold, the Kiona anticline (see fig. 14, 25).

The cross-sectional geometry of the Kiona anticline displays a distinct change between the northwest and southeast ends of the fold. The Kiona anticline within the northwest portion of the segment is an eroded, faulted, broad, double-hinged fold, while the fold in the southeastern portion of the segment is an eroded, tightly folded, asymmetric anticline. Both folds have northeast vergence. The anticlinal axis trends N 60°W, but at the northwest end of the segment the northern limb appears to plunge northwest near Interstate 82, while the crestal portion of the anticline appears to be continuous with the Kiona anticline in the Junction segment.

The two geometrically distinct portions of the Kiona anticline are separated by the northeast-trending Sharpe fault which cuts across the northeastern limb of the anticline (see fig. 14). In the northwest portion of the Kiona segment the northern hinge of the Kiona anticline contains several high-angle reverse and thrust faults (see cross section J-J' in fig. 26). Fault breccia was also encountered within the core of the anticline in the southeast portion of the segment (in the Frenchman Springs Member, SW1/4NE1/4 sec. 23, T. 9 N., R. 26 E.), but it is unclear whether the breccia represents local thrust faulting within the core of the fold or whether it is caused by layer-parallel faulting. However, a thrust fault is tentatively proposed here based on the tightness of the fold (see cross section K-K' in fig. 26). A reverse fault is inferred at the northern base of the fold as well.

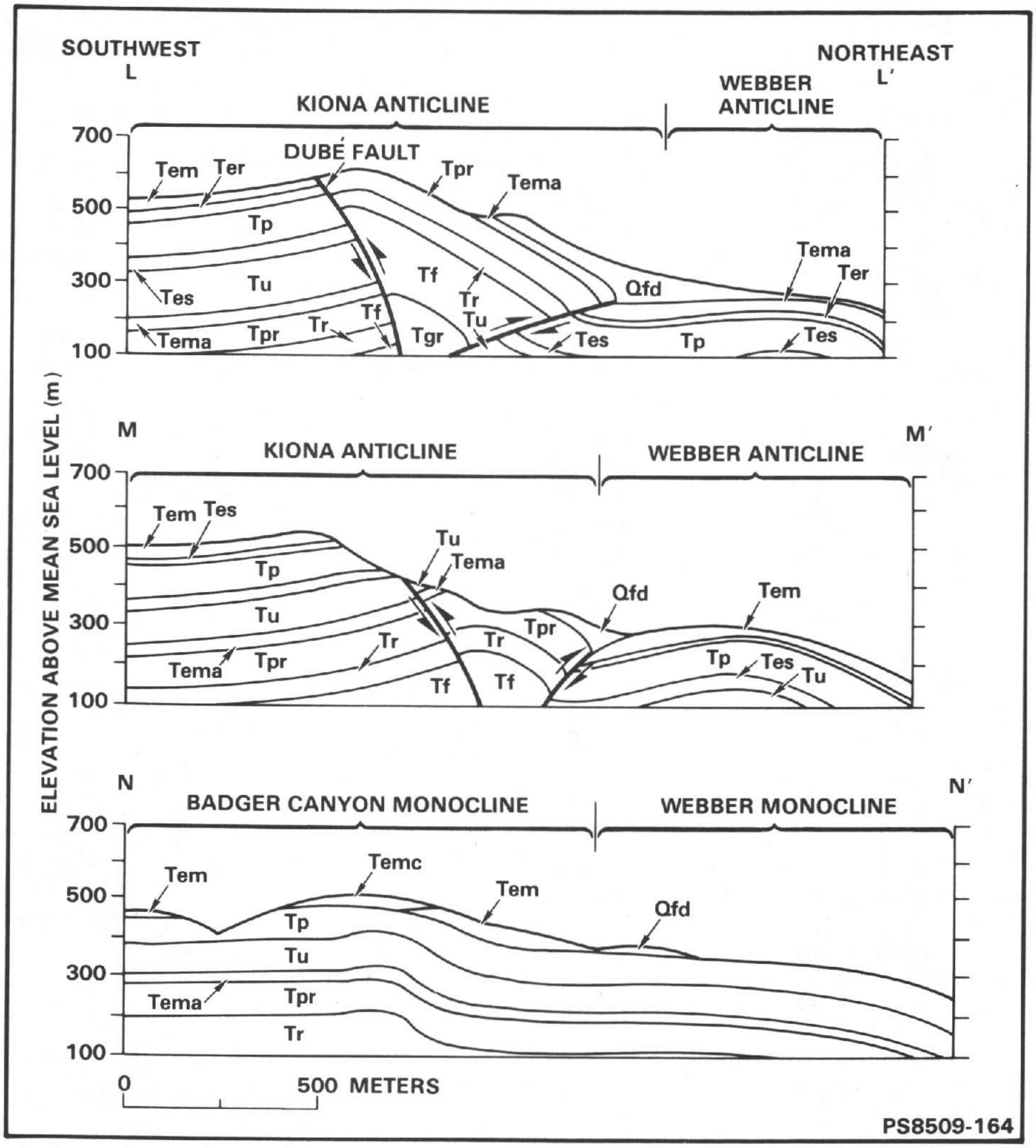

Figure 24. Interpretive Geologic Cross Sections through the Horse Heaven Hills Uplift within the Webber Segment (see fig. 17 for legend and fig. C-4 for corresponding descriptive geologic cross section).

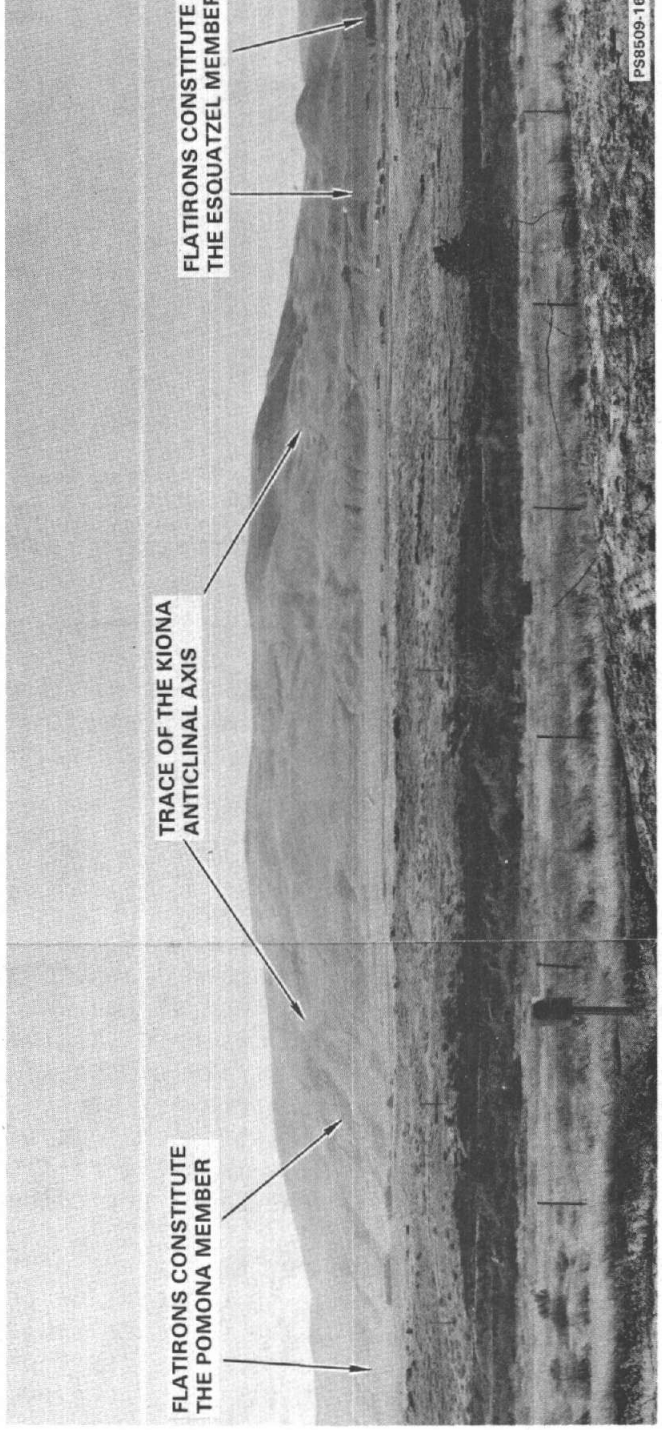

Figure 25. The Horse Heaven Hills Uplift within the Kiona Segment.

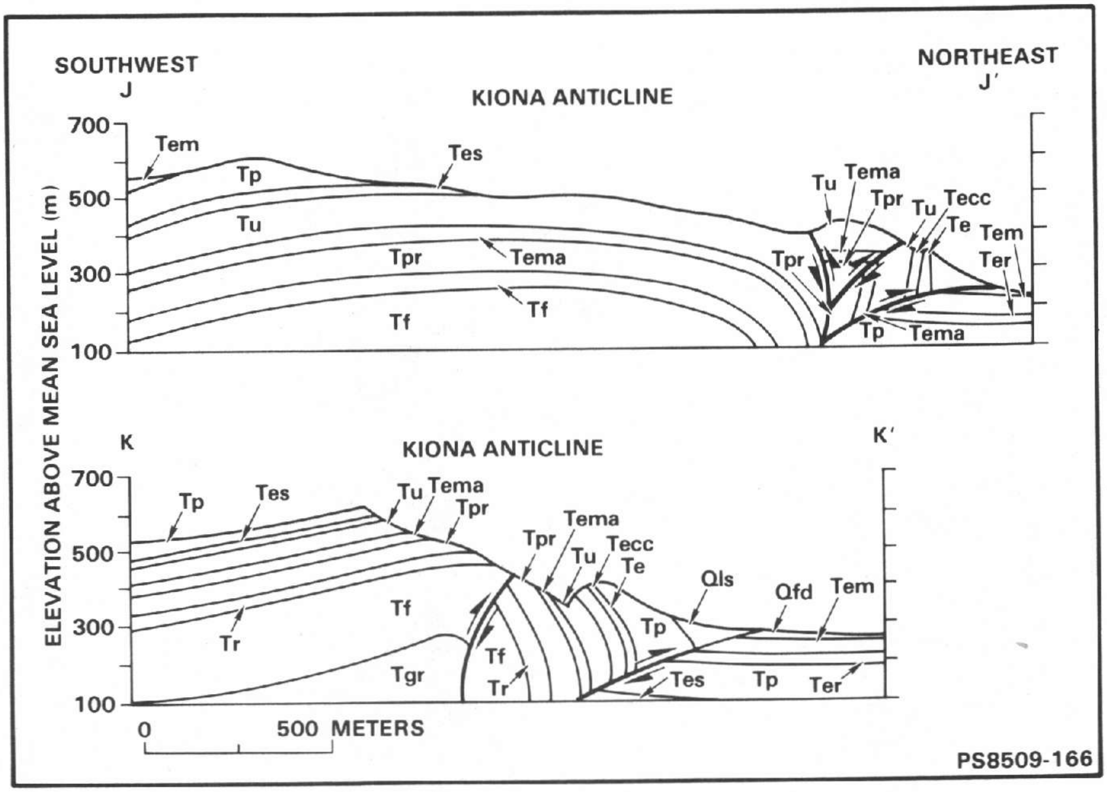

Figure 26. Interpretive Geologic Cross Sections through the Horse Heaven Hills Uplift within the Kiona Segment (see fig. 17 for legend and fig. C-5 for corresponding descriptive geologic cross sections).

3.2.6 Junction Segment

The Junction segment consists of the mergence of the northwestern end of the Kiona anticline and the northeastern end of the Chandler anticline (see fig. 14). The Chandler anticline plunges onto the southern limb of the Kiona anticline within this segment. The strike of the Kiona anticline in the Kiona segment markedly changes from a northwest strike to a nearly east-west strike. A representation of the cross-sectional geometry of the Horse Heaven Hills uplift is shown in figure 27. This figure also shows the broad asymmetric (north vergence) geometry of the Kiona anticline.

Several tear faults cut across the northern flank of the Kiona anticline coincident with a marked change in geometry or trend of the anticline. One left-lateral tear fault, the Chandler fault (see fig. 14), was inferred by Bond et al. (1978) as crossing the crest of the ridge here (the Chandler anticline). Mapping for this study, however, indicates that this fault is probably limited to the northern flank.

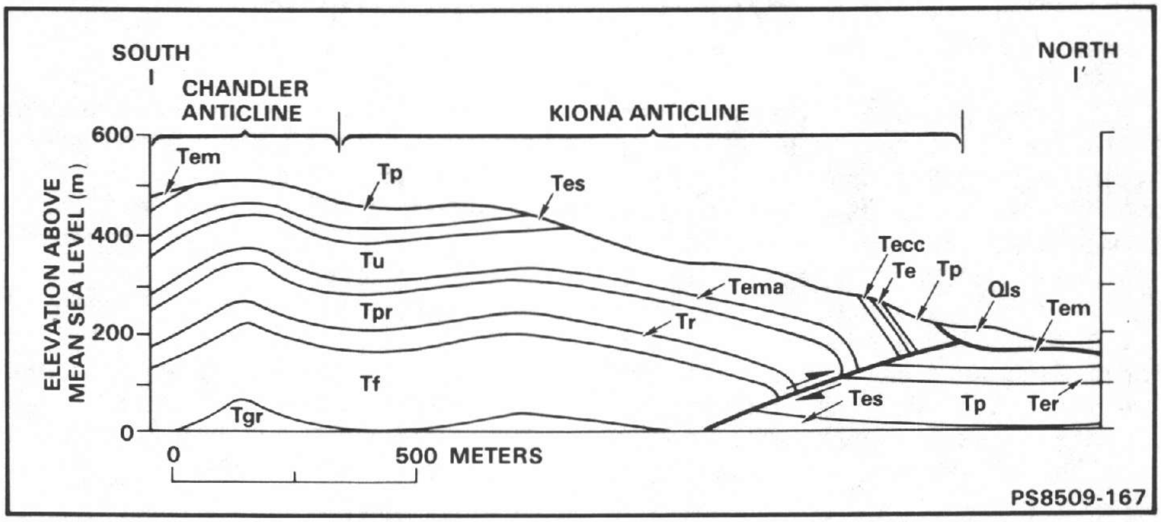

Figure 27. Interpretive Geologic Cross Section through the Horse Heaven Hills Uplift within the Junction Segment (see fig. 17 for legend and fig. C-6 for corresponding descriptive geologic cross section).

One explanation for the change in trend of the Kiona anticline is that the east-west striking portion of the Kiona anticline may represent the broad northwest plunging end of the Kiona anticline. Another explanation may be that the oddly oriented fold resulted from the interaction of stresses caused by uplift along the northwest and northeast trends.

It remains unclear as to how the Badlands anticline (see fig. 14) relates structurally with the Kiona anticline. It is aligned with and is proximal to the northwest-trending portion of the Kiona anticline, but its possible connection with the Kiona anticline is obscured by landslide debris.

4.0 TIMING AND LOCATION OF DEFORMATION

Several proposals in the literature indicate when and in what sequence the Yakima folds developed. Some proposals also suggest the period when folding occurred along the Horse Heaven Hills uplift (table F-1) in relation to other Yakima folds. One suggestion is that most of the uplift along the Yakima folds developed after 10.5 m.y.B.P. - during late Miocene time and Pliocene time (Barrash et al. 1983; Bentley 1977; Brown 1970; Kienle et al. 1978; Swanson et al. 1979b). Other studies (Reidel 1984) propose that deformation along the Yakima folds has been continuous since at least middle Miocene time. It is also suggested that the Yakima folds originated time sequentially, from south to north, across the Columbia Plateau (Laubscher 1981). Another suggestion is that growth is currently occurring along the Yakima Folds (Campbell and Bentley 1981; Reidel 1984).

It is the purpose of this section to ascertain the timing of uplift at the mergence of the northwest and northeast trends of the Horse Heaven Hills uplift. This is accomplished principally by using isopach maps of individual Columbia River Basalt Group members and Ellensburg interbeds, along with paleodrainage maps of the ancestral Columbia River system to define developing folds at specific times or time intervals. Because of the absence of a sedimentary record for a portion of the late Miocene and the Pliocene, the timing and location of growth along the Horse Heaven Hills uplift during this time can only be inferred from observations of the present structure. The results will help reconstruct the evolution of the Horse Heaven Hills uplift as well as provide a detailed example of the timing of uplift along a set of intersecting northwest-and northeast-trending Yakima folds. In addition, the timing of development of the Horse Heaven Hills uplift can then be compared to the timing and development of other Yakima folds. The timing and location of deformation found within portions of the lower Yakima Valley syncline and the Horse Heaven Plateau are also evaluated as a consequence of their intrinsic structural relationship with the Horse Heaven Hills uplift.

4.1 ISOPACH STUDY

Distribution patterns and thickness trends of Columbia River Basalt Group flows and sedimentary deposits of the Ellensburg Formation have been recently outlined for the Pasco Basin and some of the bordering Yakima Folds (Long and Landon 1981; Myers et al. 1979; Price 1982; Reidel 1984; Reidel and Fecht 1981, 1982; Reidel et al. 1980, 1983a,b). Variations in thicknesses of these stratigraphic units are thought to be controlled by the interplay of the following four factors (Reidel et al. 1980; Reidel and Fecht 1981): the volume of each basalt flow; the constructional topography created by previous basalt flow margins; the effect of uplift and subsidence; and the influence of regional paleoslopes. Reidel and Fecht (1981) argue that the lateral extent and thicknesses of the basalt flows in the Pasco Basin are controlled primarily by uplift and subsidence and secondarily by flow volume, constructional topography, and/or regional paleoslopes.

Flows of the Columbia River Basalt Group generally entered the study area from the east (Schmincke 1964, 1967a) repeatedly inundating the paleotopography. These basalt flows were fluid and traversed the Columbia Plateau within a few weeks (Shaw and Swanson 1970), forming a cast of the paleotopography at instances of time. Thickness variations of the interbeds of the Ellensburg Formation in the study area also record the presence of paleotopography but over longer intervals of time. Isopach maps of individual members of the Wanapum and Saddle Mountains Basalts and individual interbeds of the Ellensburg Formation are constructed for this study (see fig. 28 through 38) to delineate paleostructures present in the study area. The isopach maps constructed for Wanapum Basalt members have a lesser definition due to the presence of fewer measurable exposures along the Horse Heaven Hills uplift and the difficulty in identifying individual members from borehole data (see appendix B).

From the isopach maps, several structures appeared recurrently in the paleotopography: the northwest and northeast trends of the Horse Heaven Hills uplift; the lower Yakima Valley syncline; the Piening syncline; and the southern extension of the Hog Ranch-Naneum Ridge anticline.

Uplift along folds of both trends of the Horse Heaven Hills (the Prosser, Gibbon, Chandler, and Kiona anticlines and the Badger Canyon monocline) was occurring simultaneously since at least Roza time (see fig. 28 through 38). However, the portions of the Badger Canyon monocline and the Kiona anticline that lie within the Webber segment were not present through at least Pomona time. Topographic relief along the Horse Heaven Hills uplift was extremely low during the emplacement of the Wanapum Basalt and deposition of the Mabton interbed (see fig. 28 through 30) but was better expressed during Saddle Mountains time (see fig. 30 through 38) due to the longer time intervals separating basalt flow incursions. A local structural low separated the Chandler and Kiona anticlines during at least Pomona time (see fig. 34). Another structural low also existed along the western portion of the Chandler anticline since at least Umatilla time. Its location is now marked by the overlap of the the Gibbon and Chandler anticlines. Yet another structural low has existed between the Prosser and Gibbon anticlines since at least Priest Rapids time. Growth along the Drake anticline, the Phelps anticline-monocline, and the Webber anticline-monocline cannot be evaluated from the isopach maps because no strategic section thicknesses could be measured along these low-relief folds.

The present structural relief observed along the Horse Heaven Hills uplift developed after Elephant Mountain time. But because of a gap in the late Miocene and Pliocene stratigraphic record in the study area, it is not known whether the uplift developed in a relatively uniform process as suggested for Columbia River Basalt Group time (in this study) or whether growth occurred more intermittently. Presently, however, relief along both trends is very similar.

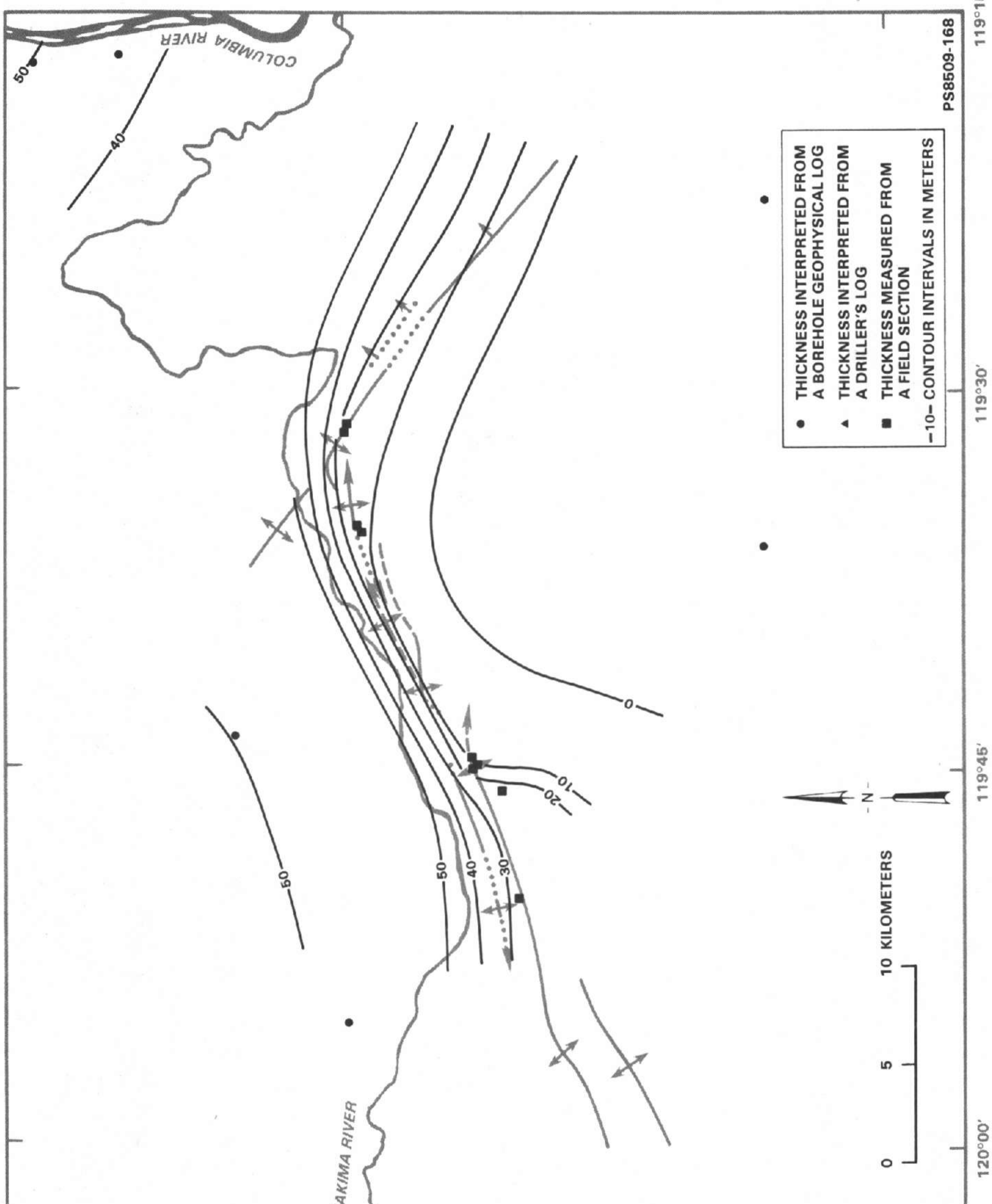

Figure 28. Isopach Map of the Roza Member within the Study Area.

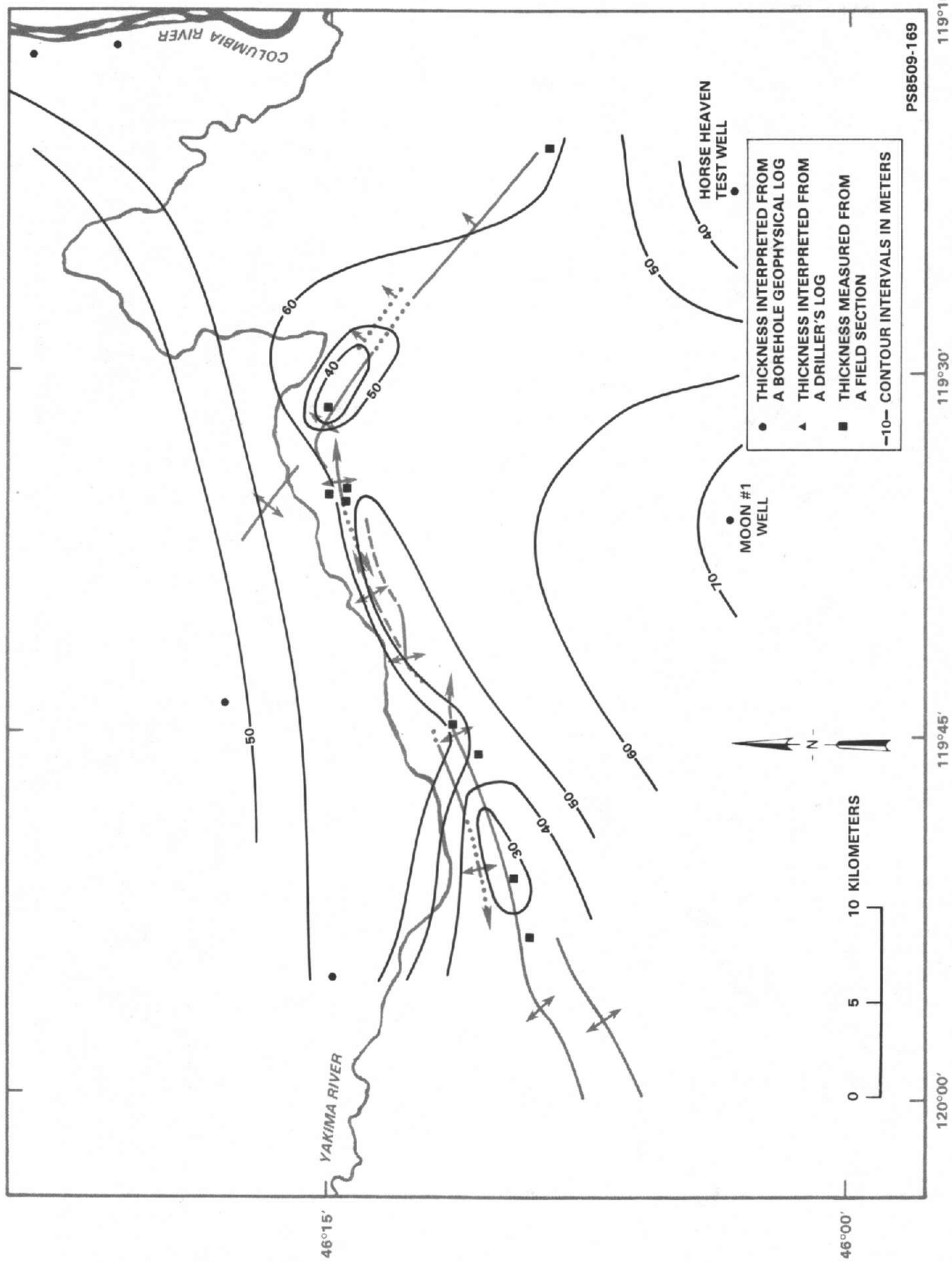

Figure 29. Isopach Map of the Priest Rapids Member within the Study Area.

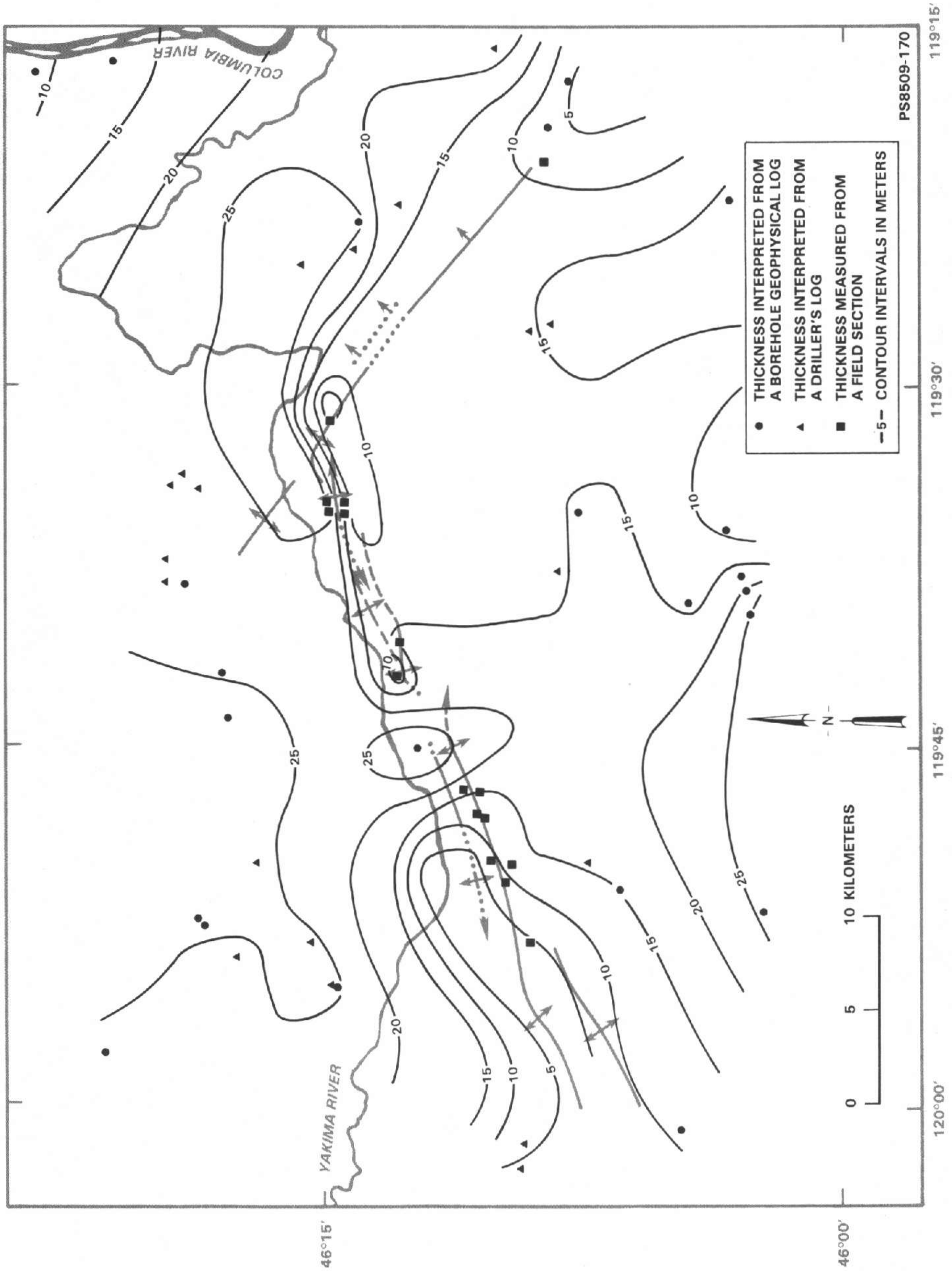

Figure 30. Isopach Map of the Mabton Interbed within the Study Area.

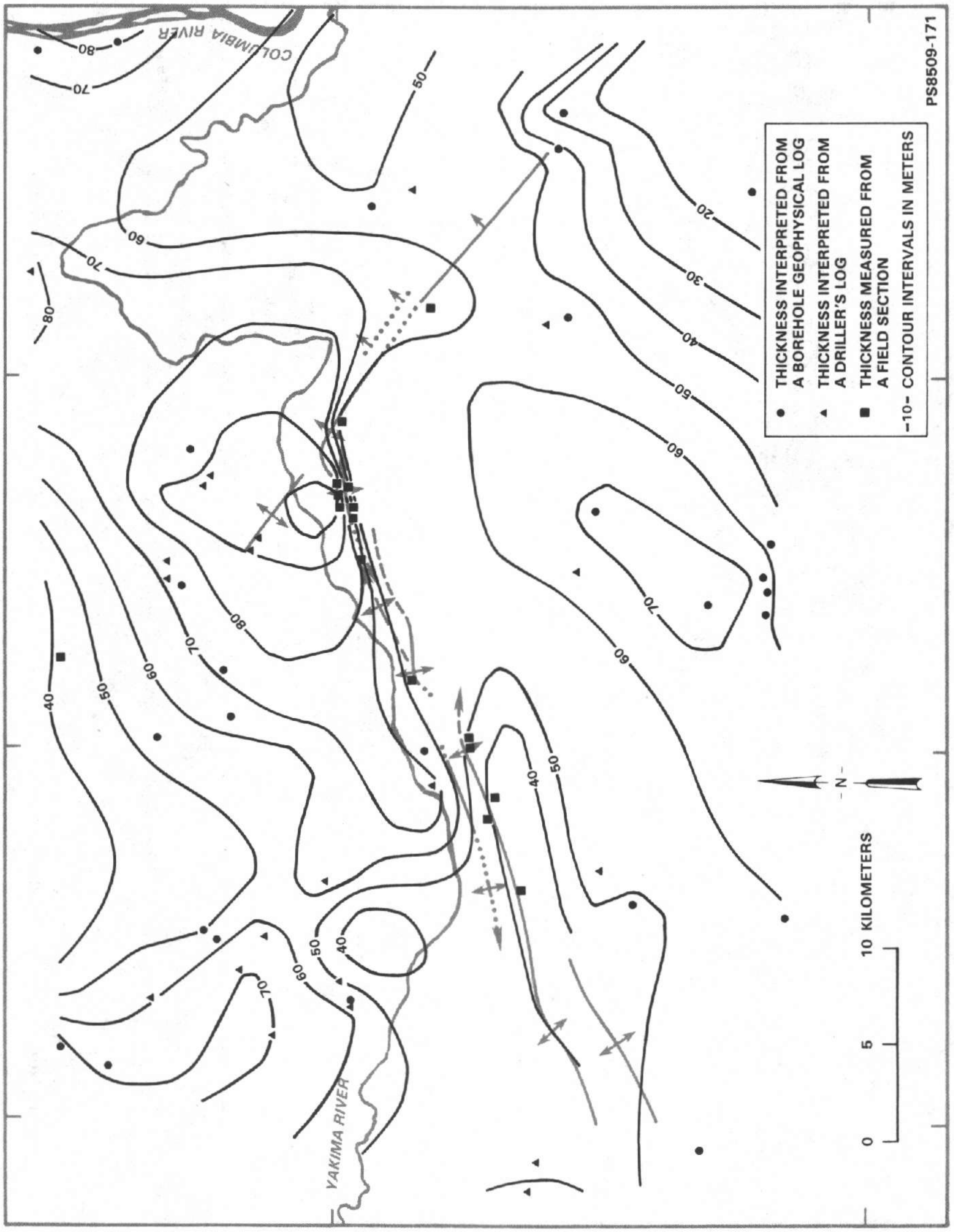

Figure 31. Isopach Map of the Umatilla Member within the Study Area.

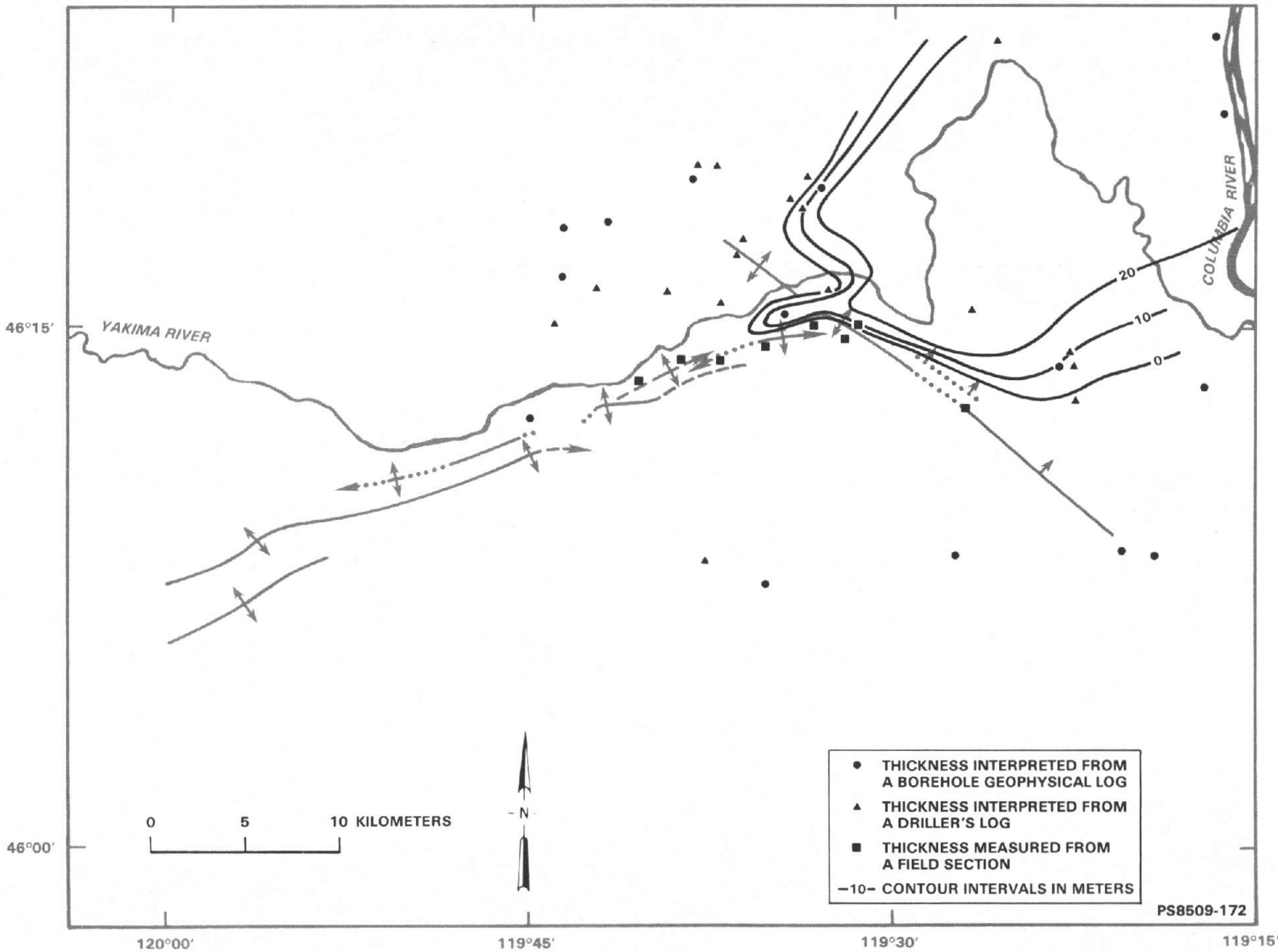

Figure 32. Isopach Map of the Esquatzel Member within the Study Area.

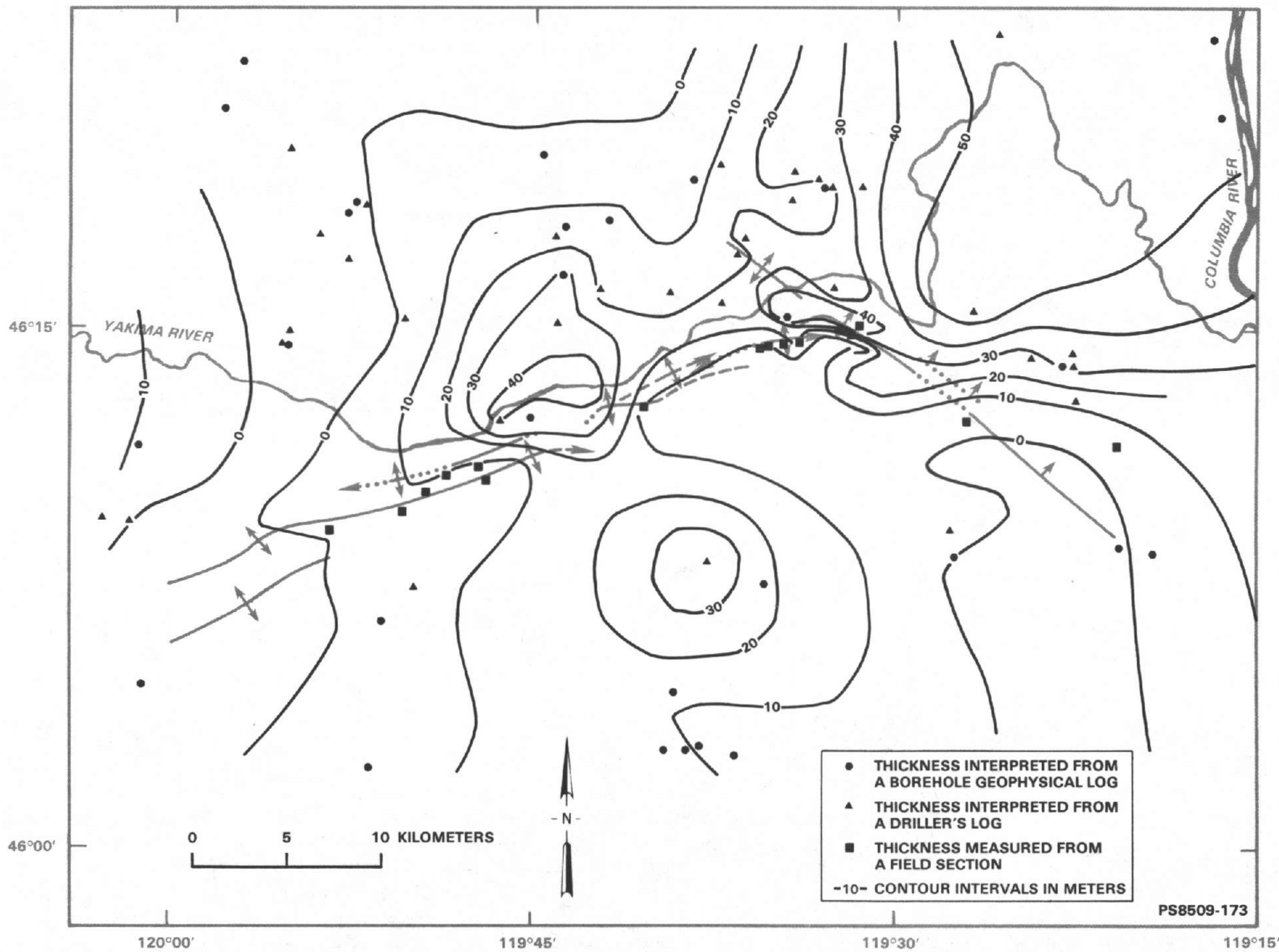

Figure 33. Isopach Map of the Cold Creek Interbed, Esquatzel Member, and Selah Interbed within the Study Area.

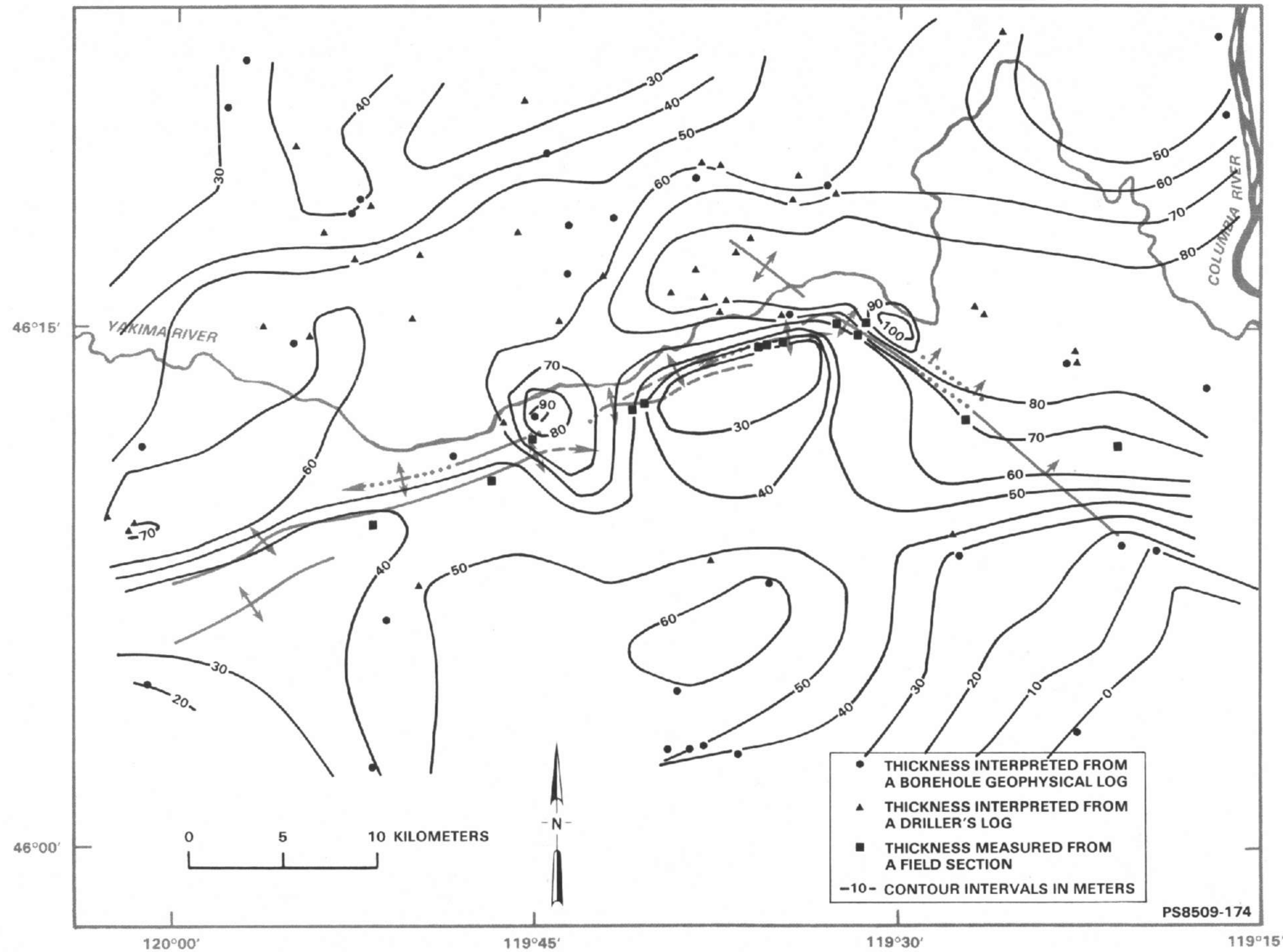

Figure 34. Isopach Map of the Pomona Member within the Study Area.

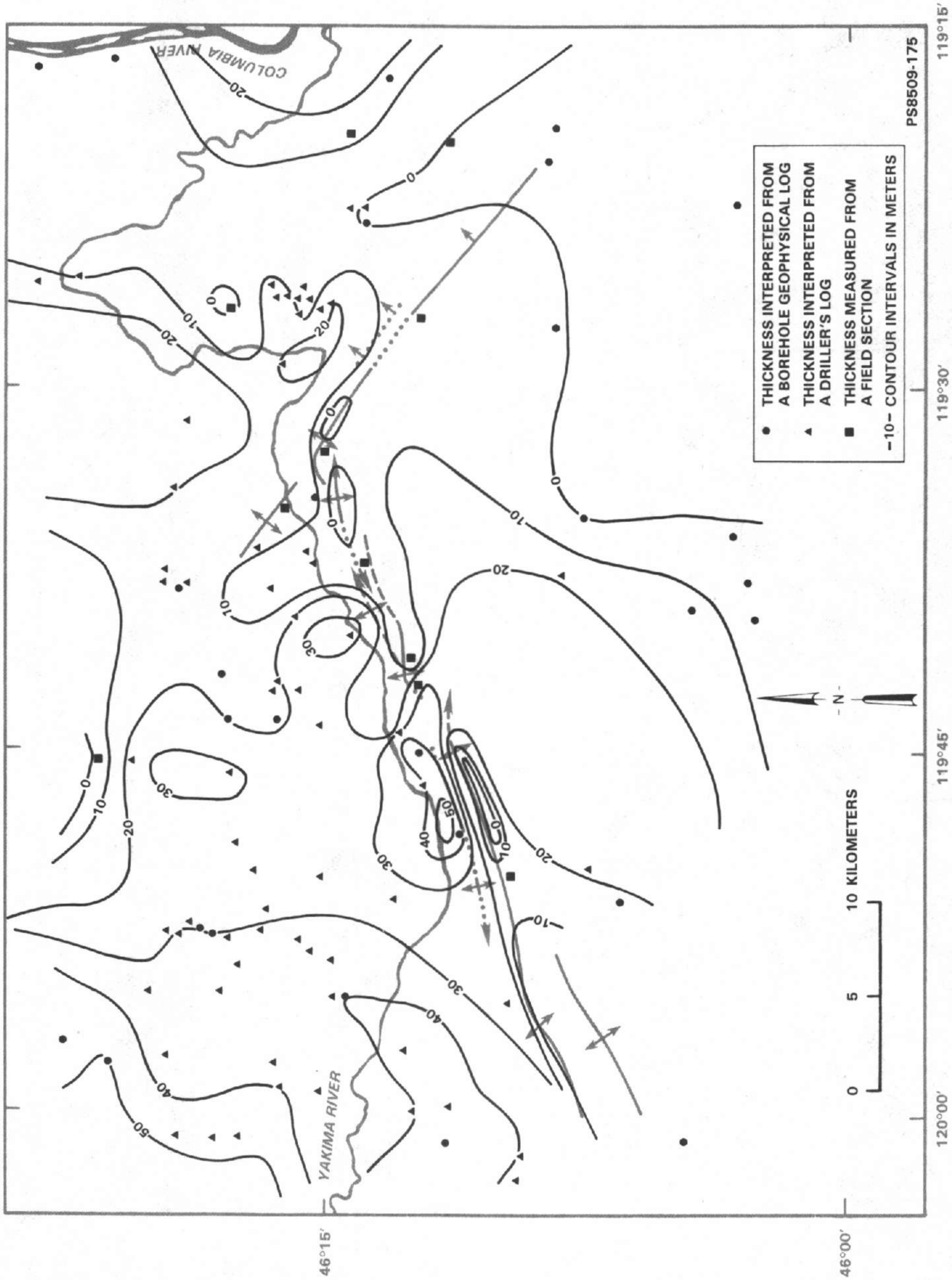

Figure 35. Isopach Map of the Rattlesnake Ridge Interbed within the Study Area.

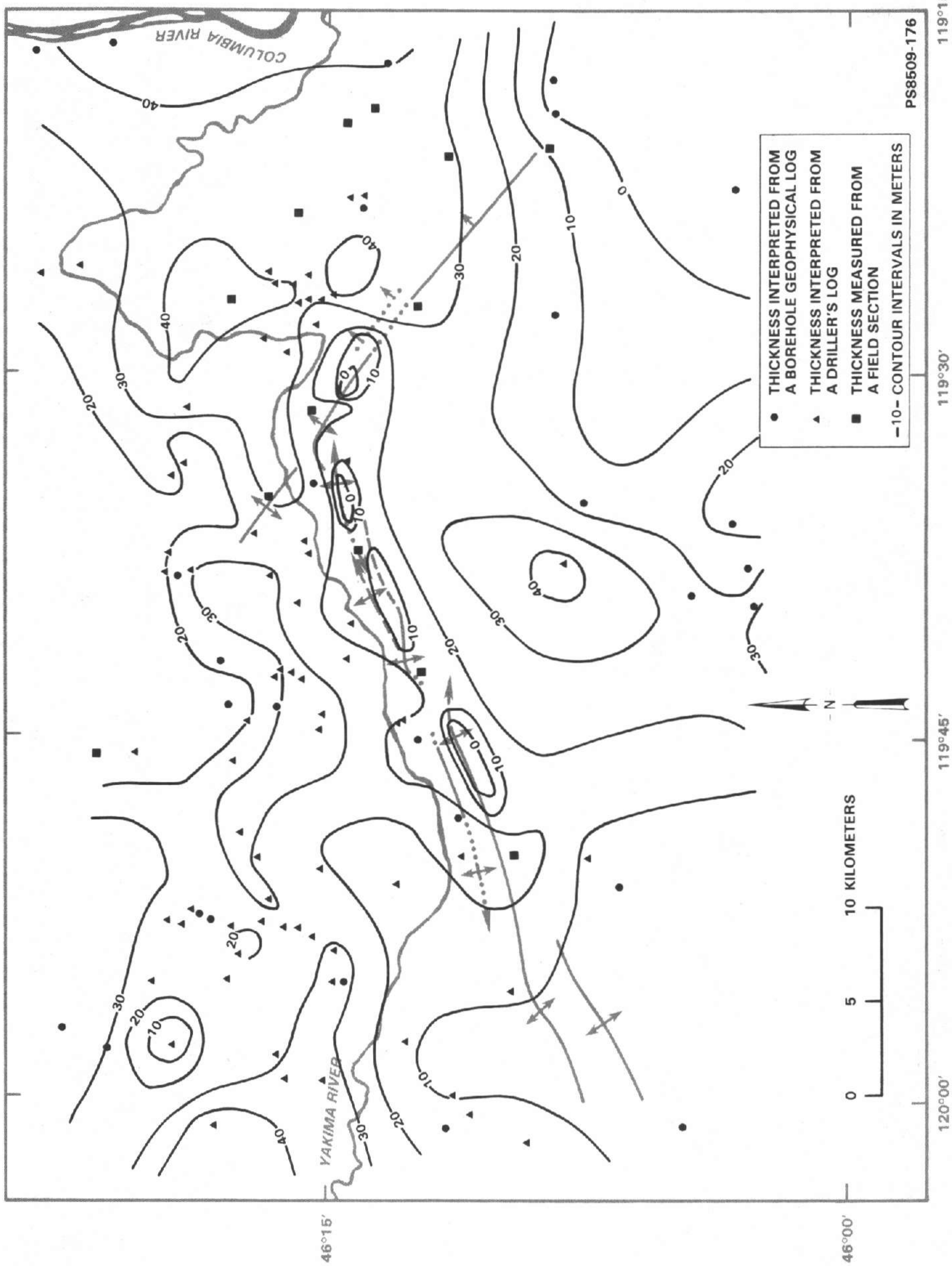

Figure 36. Isopach Map of the Elephant Mountain Member within the Study Area.

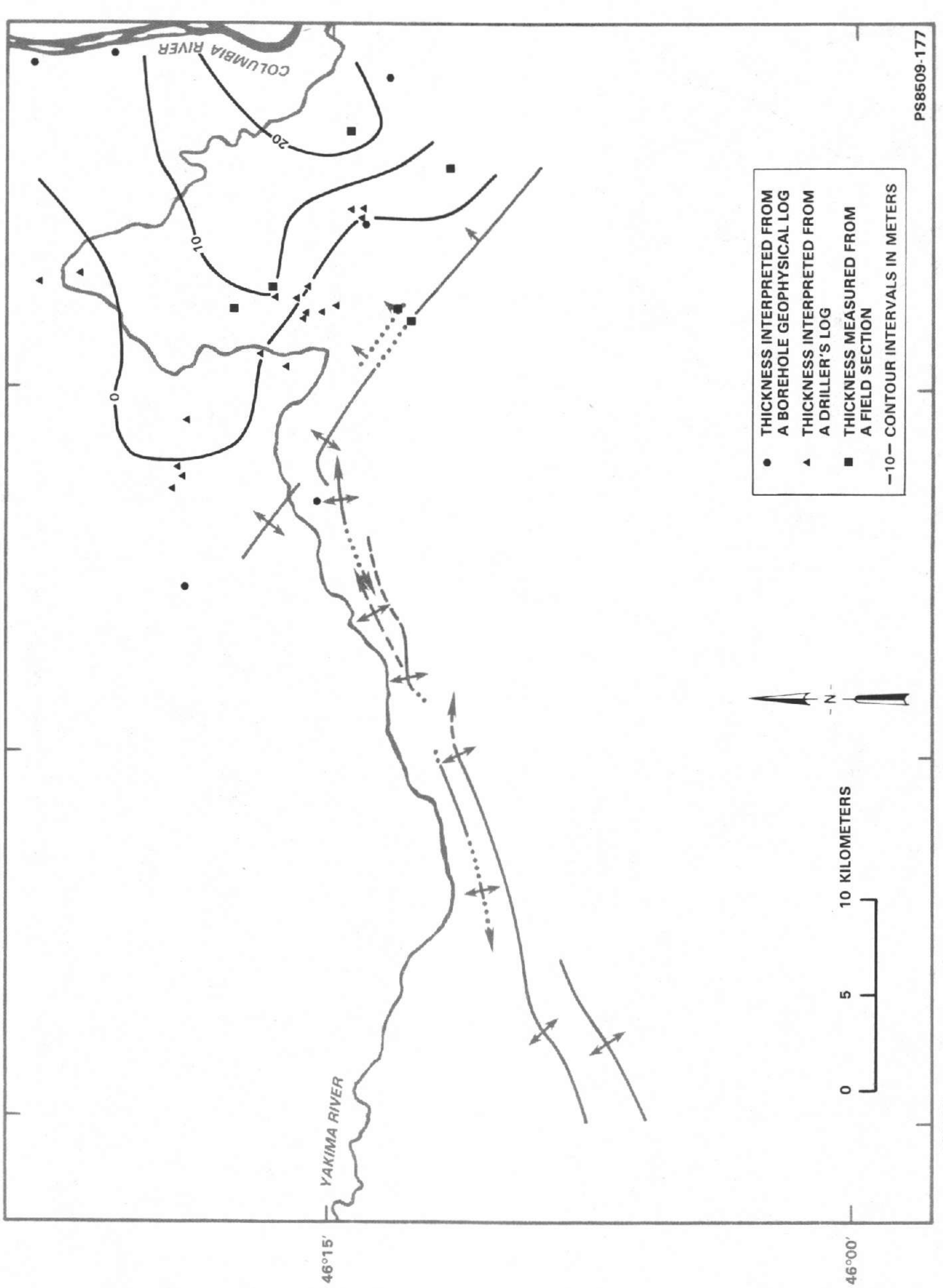

Figure 37. Isopach Map of the Levey Interbed within the Study Area.

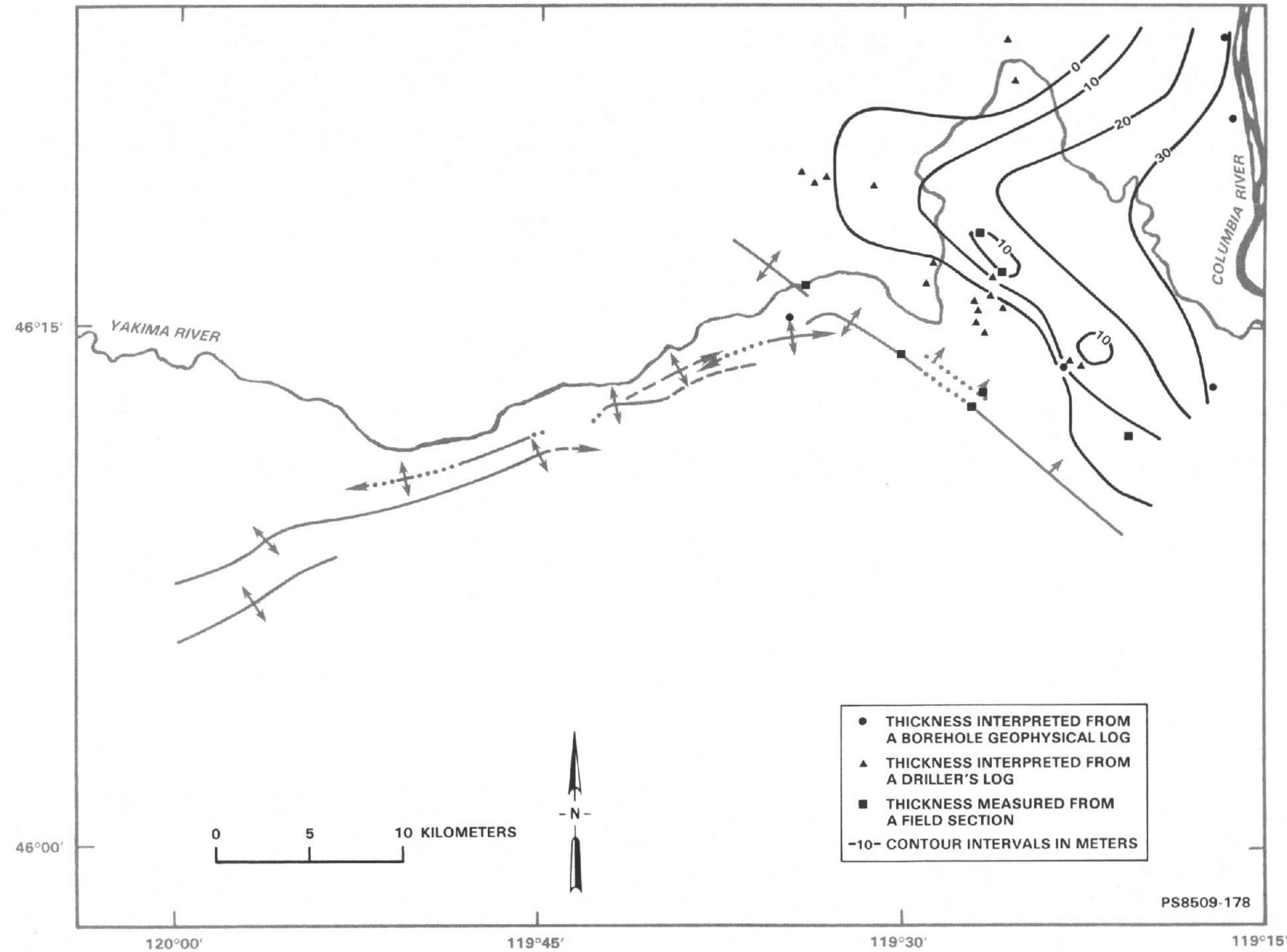

Figure 38. Isopach Map of the Ice Harbor Member within the Study Area.

Recurrent thickening trends in the isopachs indicate the development of the lower Yakima Valley syncline since at least Roza time. However, the syncline is not well-defined until Saddle Mountains time (see fig. 31-38). The syncline generally is aligned parallel with the northeast trend of the Horse Heaven Hills uplift, with the trace of its axis located near the present-day Yakima River. The eastern end of the syncline is interpreted to have been connected with the Pasco Basin, probably south of the emerging Rattlesnake Mountain (Reidel and Fecht 1981). However, the data are too sparse to indicate whether during this time other folds along the Rattlesnake-Wallula structural alignment were present to separate the Pasco Basin and the lower Yakima Valley syncline.

From the isopach maps of the Umatilla, Esquatzel, and Pomona Members, and the combined sections of the Cold Creek interbed, Esquatzel Member, and Selah interbed (see fig. 31-34), it is apparent that the western extension of the lower Yakima Valley syncline was interrupted by a local eastward-dipping slope located a few miles west of Prosser in the Grandview-Sunnyside area. This slope probably represents the presence of the southern extension of the north-northwest-trending Hog Ranch-Naneum Ridge anticline. However, there is some question as to whether the limited westward extent of the Esquatzel Member (fig. 32) was caused by the presence of the Hog Ranch-Naneum Ridge anticline or by folds developing along the RAW. The low volume of the Esquatzel Member cannot be the sole cause of the limited westward progression of the flow, since the member reached as far west as 120° west longitude in the next valley to the north via an ancestral river canyon (Myers et al. 1979). Further definition of the Hog Ranch-Naneum Ridge anticline can be attained for Pomona time by combining section measurements from Biggane's (1982) study with those of this study. The east slope of the the Hog Ranch-Naneum Ridge anticline is less clearly defined in isopach maps of both the Rattlesnake Ridge interbed and Elephant Mountain Member (see fig. 35-36), but the west slope of the anticline is delineated by a marked increase in thickness of the Rattlesnake Ridge interbed and Elephant Mountain Member. The distribution of the Ice Harbor Member suggests that the west slope of Hog Ranch-Naneum Ridge anticline was still present during its incursion, preventing the Martindale flow from entering the lower Yakima Valley; however this could have been influenced by the presence of folds along the RAW. It is unclear why the eastern margin of the Hog Ranch-Naneum Ridge anticline loses its definition after Pomona time. It is possible that the slope developed eastward forming a broad slope through the lower Yakima Valley or that the growth along the Hog Ranch-Naneum anticline slowed such that it was a less prominent topographic feature across the lower Yakima Valley and, eventually, became buried.

It is apparent from this study that two components of uplift have occurred since Ice Harbor time within the lower Yakima Valley. The first was the uplift of the lower Yakima Valley syncline relative to the Toppenish and Pasco Basins (or subsidence occurred in the two basins relative to the lower Yakima Valley syncline), as indicated by the elevation of the top of the basalt (usually the Elephant Mountain Member) in these three areas: lower Yakima Valley (this study), Toppenish Basin (Robbins et al. 1975; Biggane 1982), and Pasco Basin (Myers 1981). The second component that occurred is that the lower Yakima Valley syncline was tilted westward into its present position. This is indicated on the structure contour map of the Pomona Member (see fig. 13) and by the progressively-eastward downcutting through the basalt by the Yakima River. This westward-plunge is in an opposite direction to that present during portions of the middle- and late-Miocene time. The cause of this tilting can be hypothesized to be a result of continued subsidence of the Toppenish basin and/or uplift along the RAW. The role of the Hog Ranch-Naneum Ridge anticline in the development of the syncline is not understood, but could be intricately involved.

A local trough appears recurrently in the isopach maps covering the Horse Heaven Plateau that is coincident with the Piening syncline. The Piening syncline is not well-defined in the isopach maps until the emplacement of the Umatilla Member (see fig. 31, 33 through 36). However, this is probably partially due to less data available for Wanapum time. The syncline may be elongated in a northeast direction, but the extent of the syncline along its length in either direction is unknown. From patterns observed in certain isopach maps (see fig. 31, 33 through 35), it is possible that the Piening syncline was continuous with the Badger Coulee area (recall the late development of portions of the Kiona anticline and Badger monocline within the Webber segment). The Piening syncline may have also been continuous with the lower Yakima Valley syncline via a structural low in the Horse Heaven Hills uplift just south of Prosser (see fig. 33 and 34). Of special interest is the alignment of the Piening syncline with the zone of thickening in the lower Yakima Valley syncline in the Prosser area (see fig. 31, 33-35). This alignment may be coincidental; however there may also be a relationship between this alignment and the Hog Ranch-Naneum Ridge anticline trending through both of these areas. The Piening syncline may actually represent a local basin, formed against the southern extension of the Hog Ranch-Naneum Ridge anticline.

The north-dipping slope composing the southern limb of the Piening syncline can be roughly delineated from Priest Rapids time through Elephant Mountain time from the isopach maps. The slope may be indicative of uplift to the south and may be related to development of the Paterson Ridge uplift or the southeastern extension of the Horse Heaven Hills uplift.

The thinning of the Priest Rapids Member southward between the Moon #1 well and Horse Heaven test well (see fig. 29) provides the first evidence of deformation on the Horse Heaven Plateau. These two boreholes are the only boreholes on the Horse Heaven Plateau in which section thicknesses were interpreted for members of the Wanapum Basalt. The thickness of the Frenchman Springs Member does not change between these two boreholes, and the Roza Member is not present in either of the boreholes. In addition, the Rosalia flow of the Priest Rapids Member is not present in the Horse Heaven Test well, but is present in the Moon #1 well and is less than a few meters thick. It is interpreted that both the Rosalia flow and the Roza Member were prevented from entering the Horse Heaven Plateau by the presence of the northwest trend of the Horse Heaven Hills uplift southeast of Webber Canyon, but the constructional topography which they created in the Badger Coulee area allowed the Lolo flow to enter the Horse Heaven Plateau after their emplacement.

4.2 PALEODRAINAGE

At least three major ancestral rivers are interpreted to have deposited clastic sediments into the central Columbia Plateau during the Miocene and Pliocene: the Columbia, Clearwater-Salmon (ancestral Snake River of Swanson and Wright 1976) and the Yakima River (Warren 1941a,b; Waters 1955; Laval 1956; Mackin 1961; Schmincke 1964, 1967a, Tallman et al. 1981; Fecht et al. 1985). Conglomerates deposited by two of these ancestral rivers, the Columbia and the Clearwater-Salmon Rivers, are found within the study area in the Selah and Rattlesnake Ridge interbeds and in the early- and late-phase Snipes Mountain conglomerate. By tracing outcrops of these conglomerates through the study area (and using data adjacent to the study area), paleodrainage patterns are constructed (fig. 40 through 43) for specific time intervals (i.e., the time between the emplacement of two basalt flows) which can then be used to infer the presence and location of regional paleoslopes, local structure, and basalt flow margins. In this study, the paleodrainage patterns, in conjunction with the isopach data, are primarily used to delineate areas of structural uplift or subsidence that affected the courses of the ancestral rivers.

Before discussing the structural implications of the paleodrainage patterns, it is necessary to briefly construct the general paleodrainage patterns in the vicinity of the study area from just prior to Esquatzel time through the time of deposition of the late phase of the Snipes Mountain conglomerate.

Preceding Esquatzel time, the ancestral Clearwater-Salmon River was flowing westward across the northern Pasco Basin (see item a in fig. 39). The river exited to the west of the Pasco Basin via a channel located north of Rattlesnake Hills on Yakima Ridge (Goff and Myers 1978). When the Esquatzel flow entered the Pasco Basin, the ancestral Clearwater-Salmon River was displaced to the southern edge of the flow and directed into the lower Yakima Valley syncline (see item a in fig. 39). The river then flowed westward, possibly flowing into the Toppenish Basin where it met the ancestral Columbia River. Upon the emplacement of the Pomona Member, the ancestral Clearwater-Salmon River was forced out of the lower Yakima Valley, while the ancestral Columbia River established a course south across the Yakima Valley (see item b in fig. 39). The ancestral Columbia River did not progress laterally to the east past the present-day location of Grandview, but deposited gravels in a great swath to the west (Schmincke 1964, 1967a). It is speculated that at this same time the ancestral Clearwater-Salmon River was diverted to along the southern flow margin of the Pomona flow. This idea is based on the observation that there is a lack of Clearwater-Salmon River lithologies in the Rattlesnake Ridge conglomerate and only clasts characteristic of the ancestral Columbia River are present (see section 2.0). Thus, the two rivers did not meet in, or to the north of, the Yakima Valley. During the Elephant Mountain-Ice Harbor interval, the ancestral Columbia River reestablished itself in approximately the same course as during the Pomona-Elephant Mountain interval. Again, the ancestral Columbia River did not laterally progress to the east past the present-day Grandview area (see item c in fig. 39), but deposited gravels

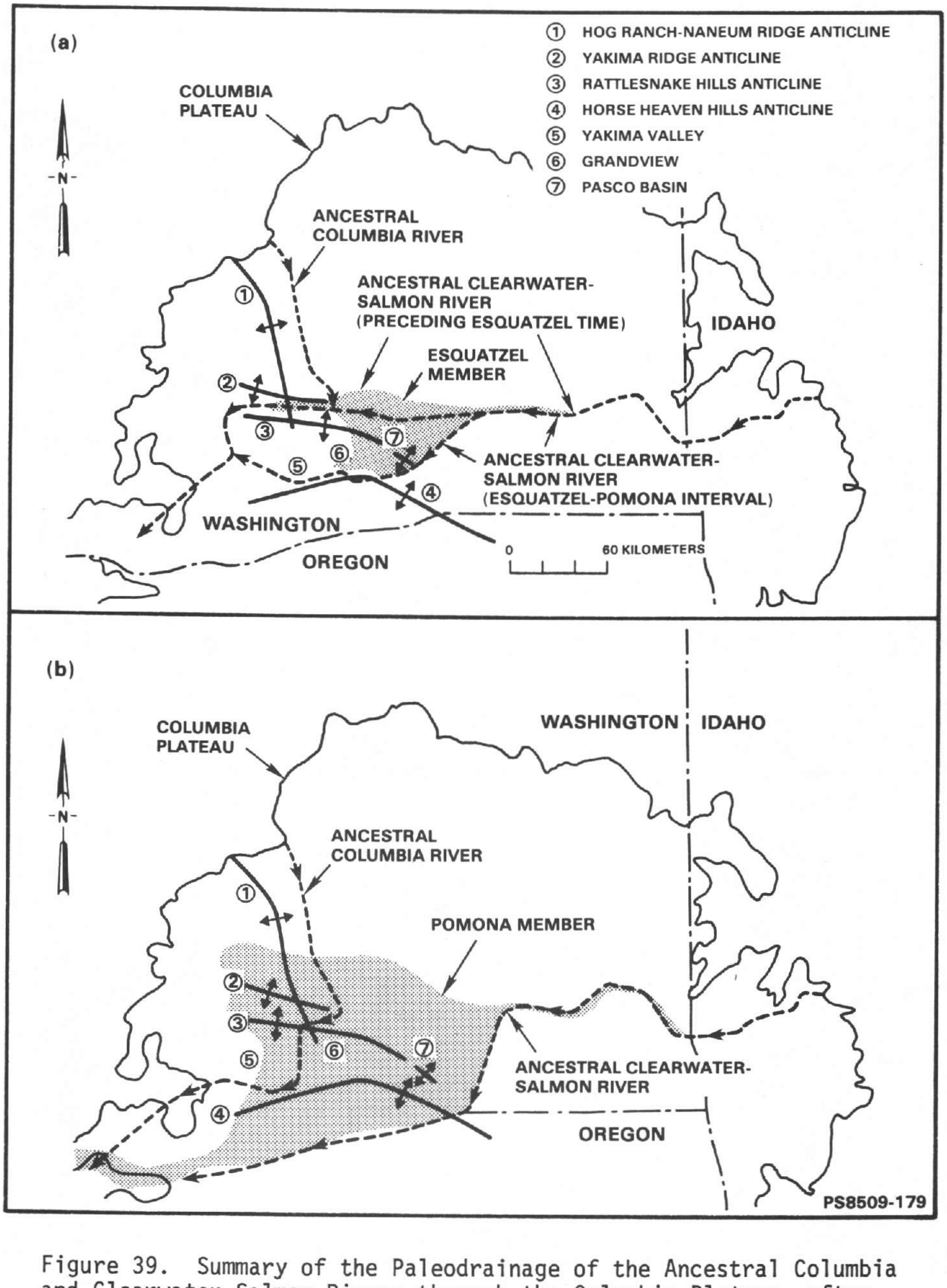

Figure 39. Summary of the Paleodrainage of the Ancestral Columbia and Clearwater-Salmon Rivers through the Columbia Plateau, after Fecht et al. (1985), Preceding Esquatzel Time to the Late Phase of the Snipes Mountain Conglomerate Time. (sheet 1 of 2)

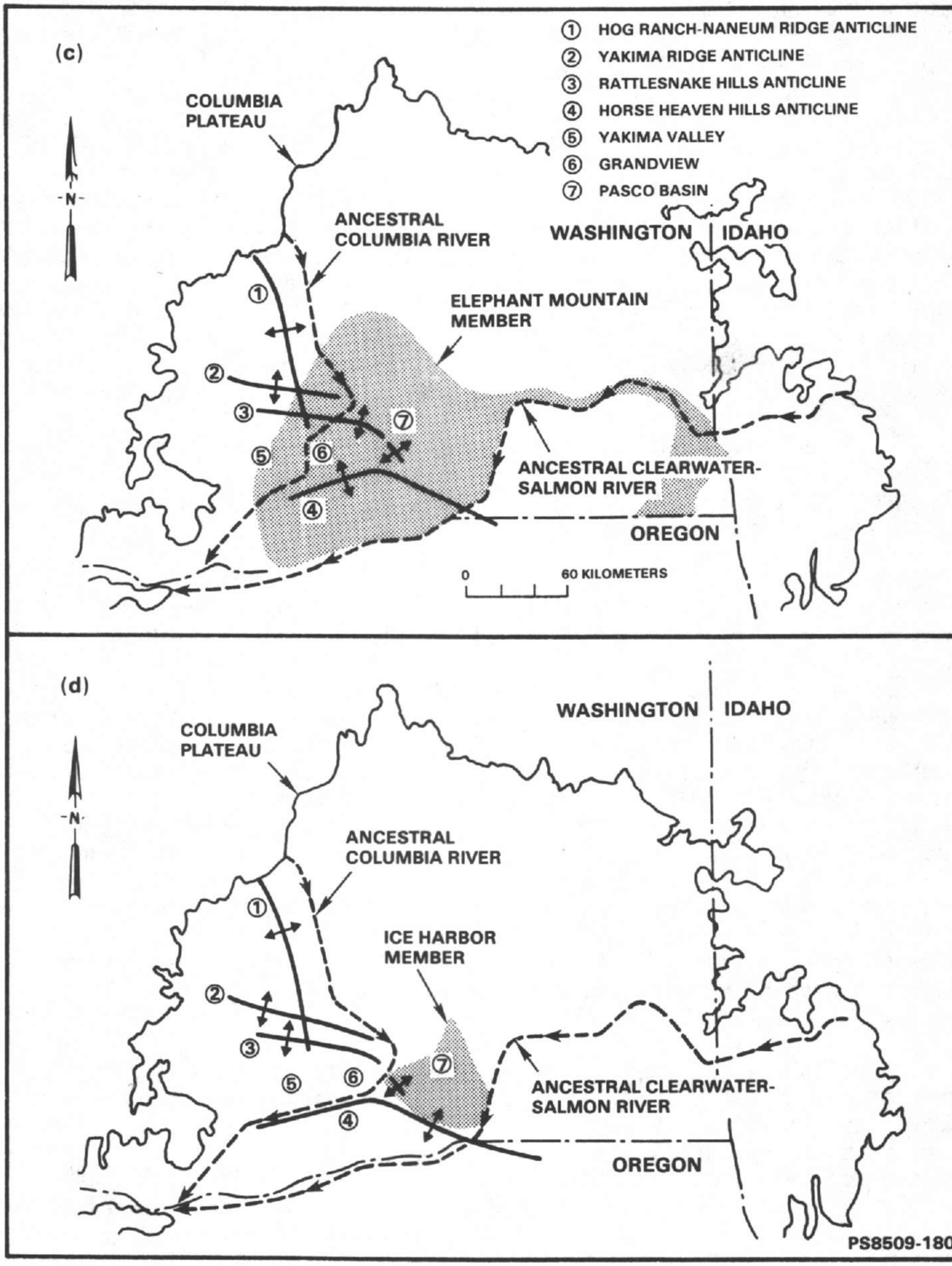

Figure 39. Summary of the Paleodrainage of the Ancestral Columbia and Clearwater-Salmon Rivers through the Columbia Plateau, after Fecht et al. (1985), Preceding Esquatzel Time to the Late Phase of the Snipes Mountain Conglomerate Time. (sheet 2 of 2)

over a wide area to the west. Sometime between Elephant Mountain and Ice Harbor time, the ancestral Columbia River was diverted into the Pasco Basin north of the lower Yakima Valley.

Some suggested causes of the diversion of the ancestral Columbia River are the combined uplift and subsidence of the Hog Ranch-Naneum Ridge anticline and Pasco Basin, respectively (Goff and Myers 1978; Fecht et al. 1985), the rise of the Horse Heaven Hills (Warren 1941b), the emanation of volcaniclastic fans from the Cascades (Waters 1955), and the rise of Umtanum Ridge (Schmincke 1964). Regardless, the ancestral Columbia River upon entering the Pasco Basin was diverted back into the lower Yakima Valley along the northern flow edge of the Ice Harbor Member and along the rising Horse Heaven Hills uplift (see item d in fig. 39) for a short period of time, before finally establishing itself within the Pasco Basin (Fecht et al. 1985).

It is not known when the ancestral Yakima River established itself in the lower Yakima Valley, but it is speculated by Fecht et al. (1985) that this occurred at nearly the same time the ancestral Columbia River reestablished itself into the Pasco Basin.

Three major structures delineated within the study area using the paleodrainage patterns are the Horse Heaven Hills uplift, the lower Yakima Valley syncline, and the Hog Ranch-Naneum Ridge anticline.

The northeast-trending portion of the Horse Heaven Hills uplift was a topographic barrier that controlled both the ancestral Clearwater-Salmon and ancestral Columbia Rivers within the lower Yakima Valley syncline during the Esquatzel-Pomona time interval and during deposition of the late phase of the Snipes Mountain conglomerate, respectively (see fig. 40 and 43). The ancestral Clearwater-Salmon River was controlled by the northern edge of the Horse Heaven Hills uplift over an area that is presently occupied by the Phelps anticline-monocline and the Drake anticline (see fig. 40), indicating either the absence or the low relief of these folds during this time. The uplift also diverted the ancestral Columbia River westward from its southward course across the lower Yakima Valley during both the Pomona-Elephant Mountain interval and the Elephant Mountain-Ice Harbor interval (see fig. 41 and 42).

The northwest trend of the Horse Heaven Hills uplift affected the course of the ancestral Clearwater-Salmon River during the Esquatzel-Pomona interval and an intraplateau tributary stream (to the ancestral Columbia River) of post Ice Harbor time (see fig. 40 and 43). A fold coincident with a portion of the Kiona anticline (within the Kiona segment), in coordination with the Esquatzel flow, diverted the ancestral Clearwater-Salmon River into a local structural low in the uplift around its southwestern flank (see fig. 40). The tributary stream of the ancestral Columbia River was probably pinched between the western flow edge of the Ice Harbor Member and the northwest trend of the uplift (see fig. 43). The location of the conglomerate deposited by this stream (along the crest of the Kiona anticline and Badger Canyon monocline) suggests that they were located along undeveloped portions of the uplift.

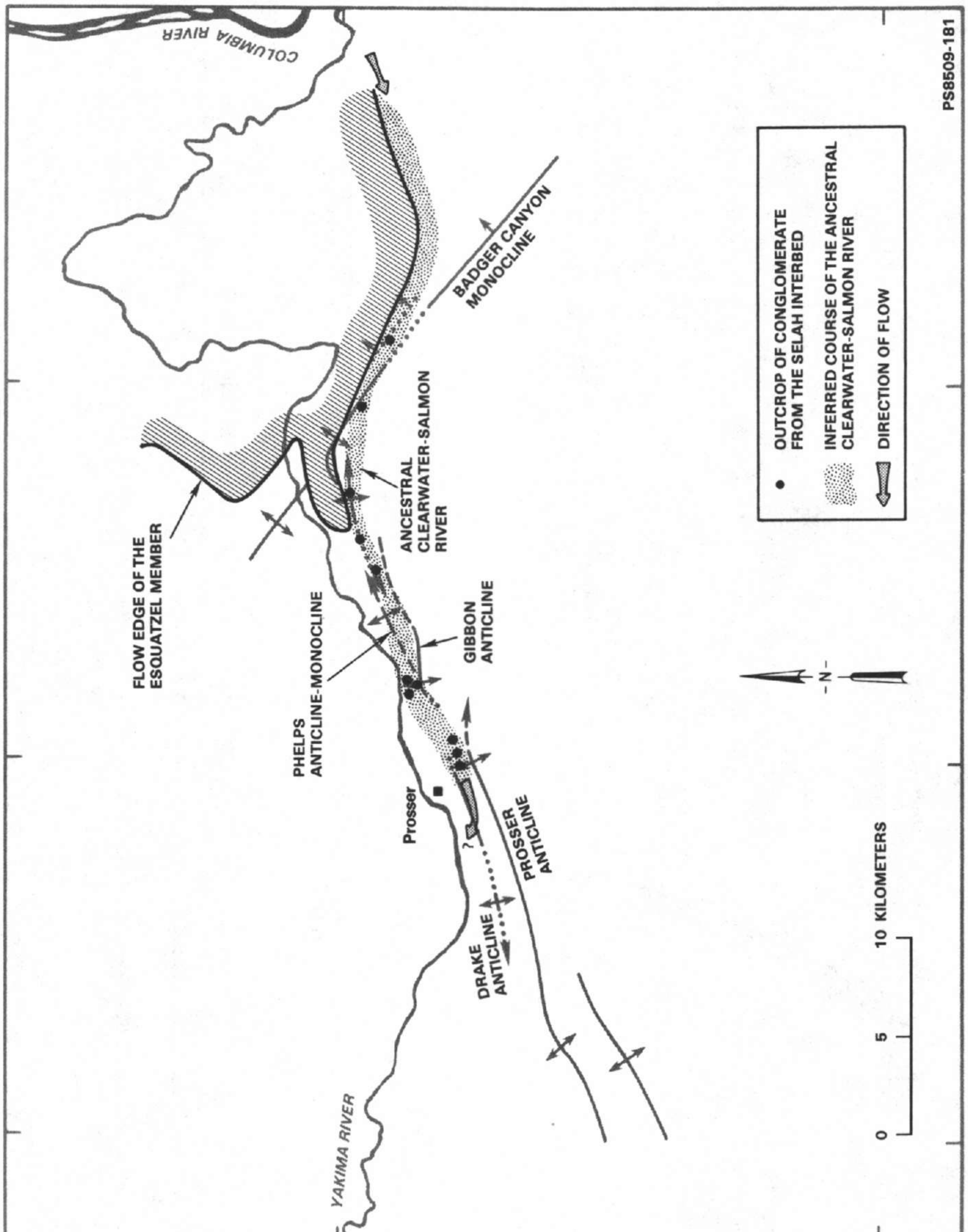

Figure 40. Inferred Course of the Ancestral Clearwater-Salmon River through the Study Area during the Esquatzel-Pomona Time Interval.

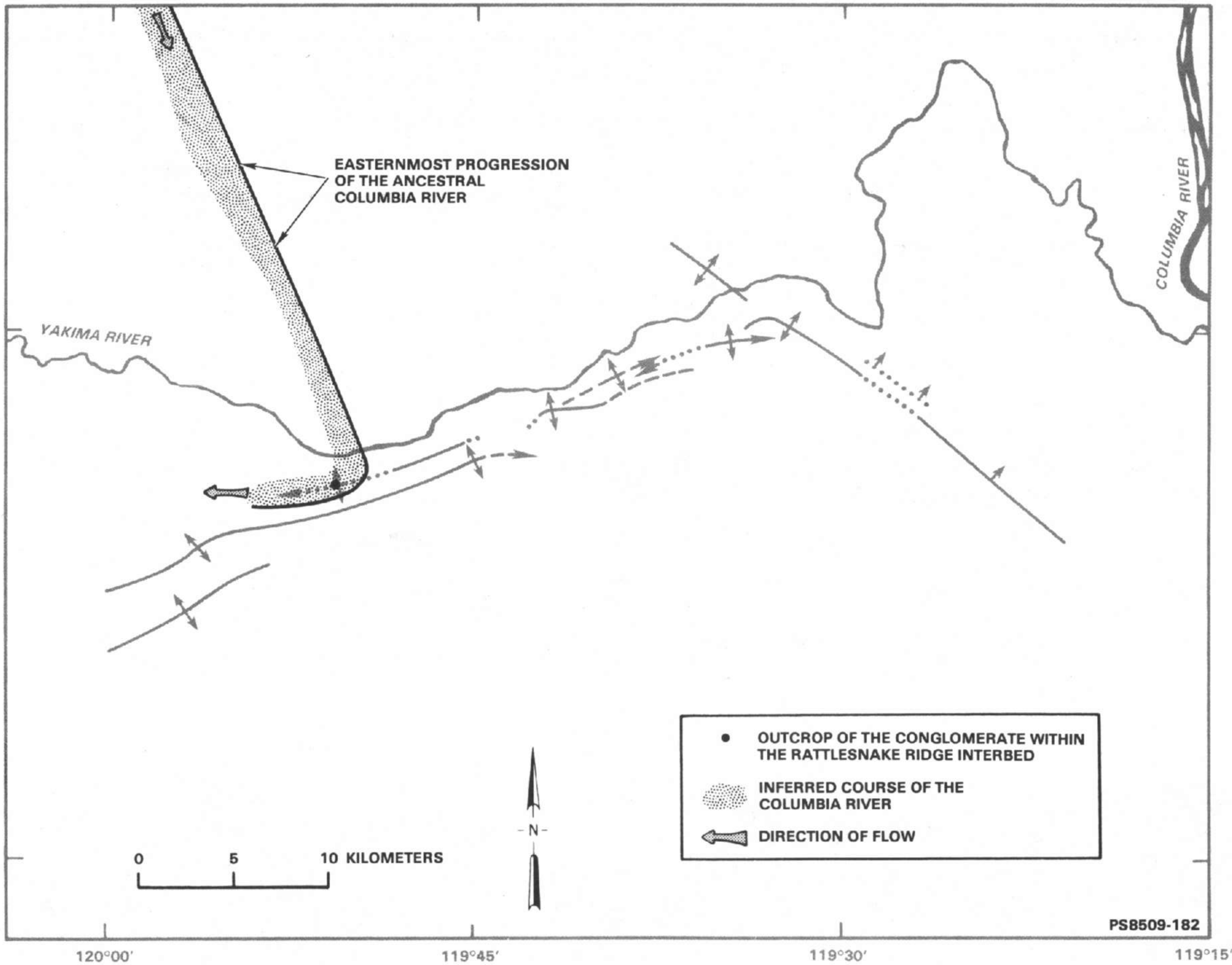

Figure 41. Inferred Course of the Ancestral Columbia River through the Study Area during the Pomona-Elephant Mountain Time Interval.

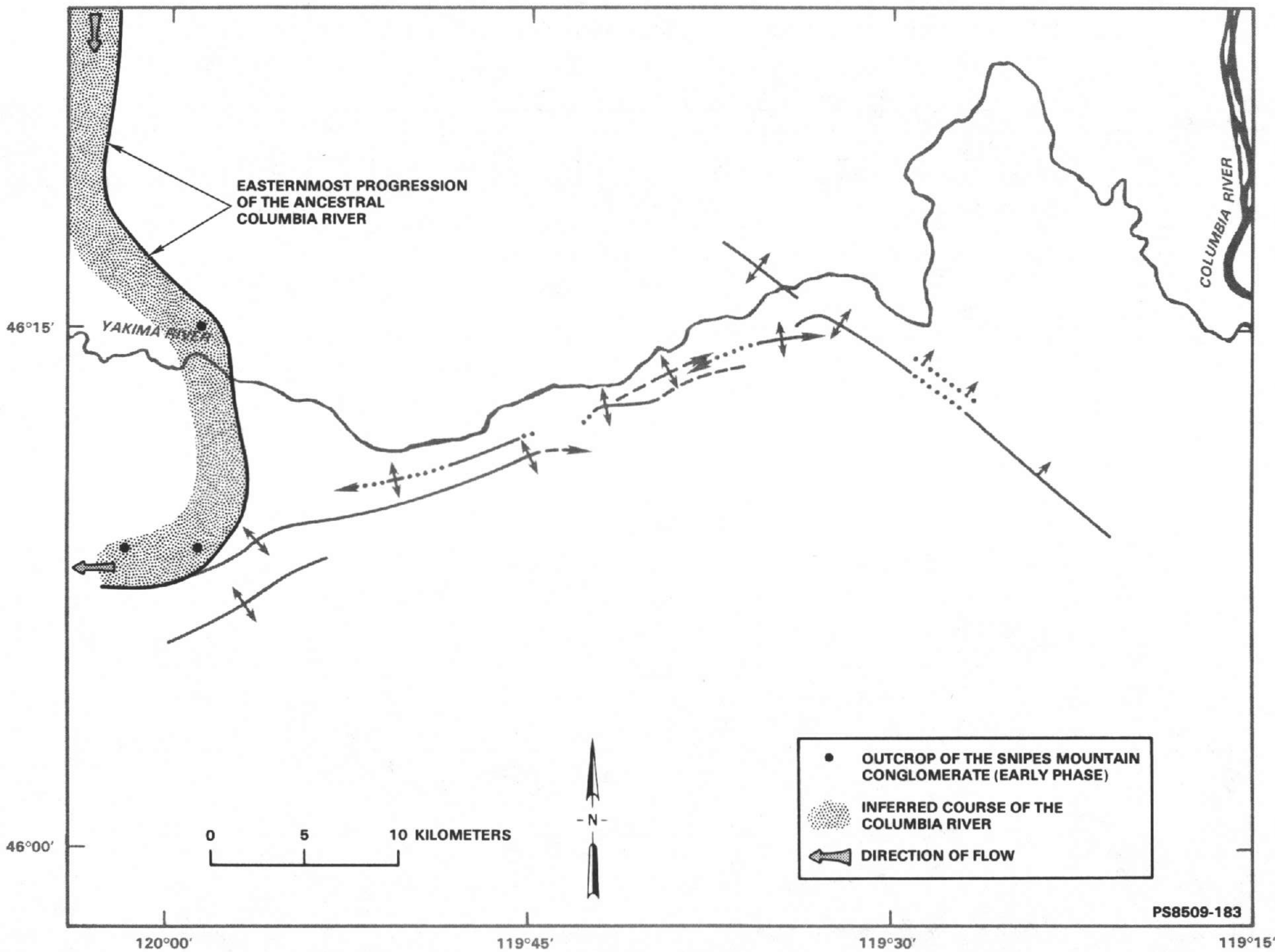

Figure 42. Inferred Eastern Lateral Extent of the Ancestral Columbia River through the Study Area during the Elephant Mountain-Ice Harbor Time Interval.

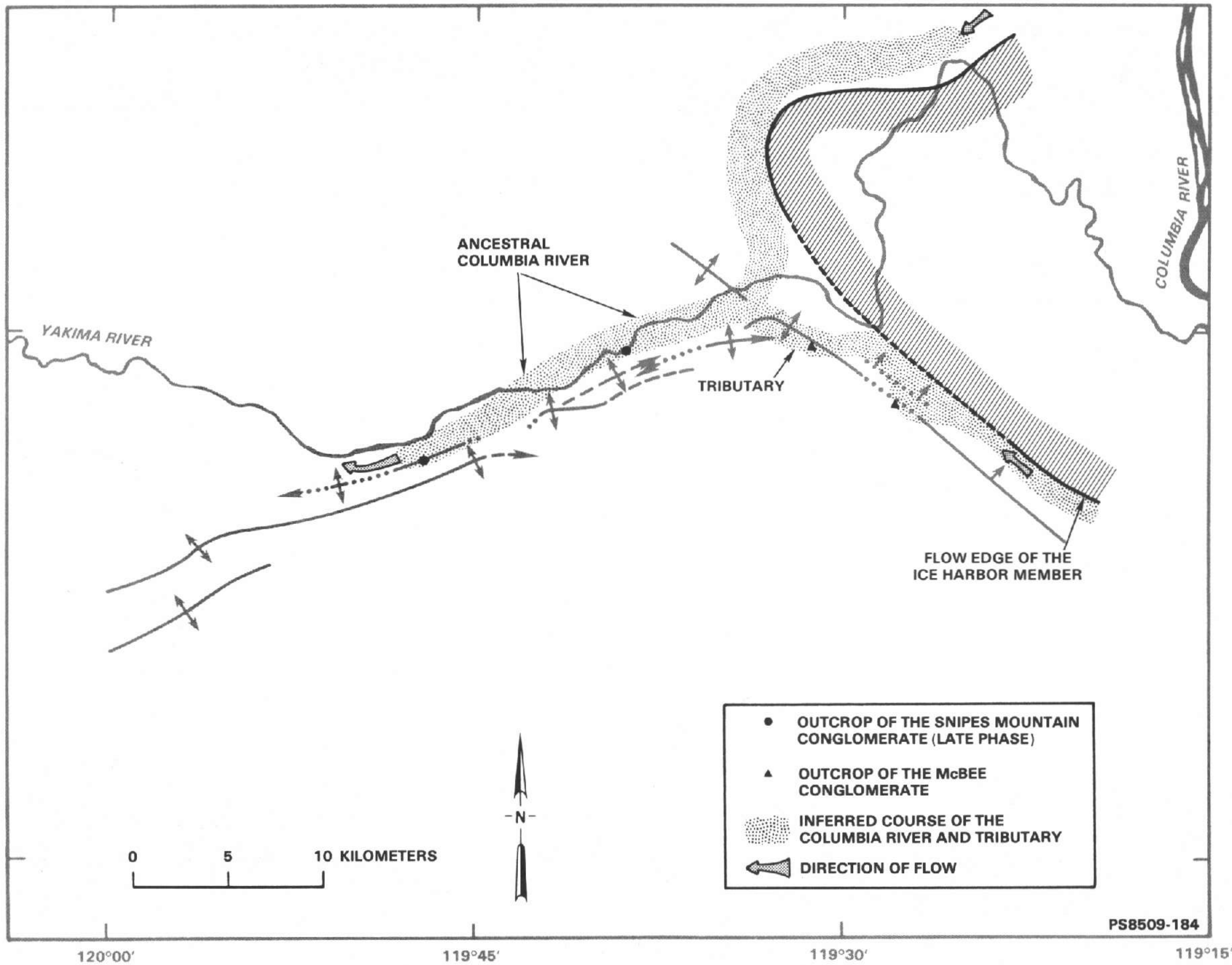

Figure 43. Inferred Course of the Ancestral Columbia River and Tributary Stream through the Study Area following the Emplacement of the Ice Harbor Member.

Two structural lows within the Horse Heaven Hills uplift during the Esquatzel-Pomona interval are delineated from the paleodrainage pattern of the ancestral Clearwater-Salmon River (see fig. 40). One was a former structural low found locally along the northwest trend of the uplift approximately where the folds in the Webber segment are now located. The other local structural low separated the northwest and northeast trends of the uplift (now occupied by Chandler Butte). These former structural lows are now located at the ridge crests of the Horse Heaven Hills uplift.

The southern extension of the Hog Ranch-Naneum Ridge anticline in the lower Yakima Valley was a controlling factor for the course of both the ancestral Clearwater-Salmon River and the ancestral Columbia River. The trace of the ancestral Clearwater-Salmon River (Esquatzel-Pomona interval) deposits are not found west of Prosser (see fig. 40); this anticline coincides with a marked decrease in thickness of the Selah interbed. One explanation is that the river may have encountered the Hog Ranch-Naneum Ridge anticline and eventually cut across the anticline, entering the Toppenish Basin via a channel. An alternative to this hypothesis is that the river was diverted south across the Horse Heaven Hills uplift near Prosser, but this idea is dismissed because of the absence of any fluvial deposits or eroded channels along the crest of the uplift. Evidence is also found for the presence of the Hog Ranch-Naneum Ridge anticline during the Pomona-Elephant Mountain and Elephant Mountain-Ice Harbor intervals. During both intervals, the ancestral Columbia River was flowing south across the lower Yakima Valley (see fig. 40 and 41). The eastward migration limit of the ancestral Columbia River during these two time periods was ~119°50' west longitude, suggesting that the Hog Ranch-Naneum Ridge anticline may have confined the river to the west of the 119°50' west longitude. The Hog Ranch-Naneum Ridge anticline may have controlled this river in coordination with the subsidence of the Toppenish Basin.

The presence of conglomerates along or near the present ridge crest of the Horse Heaven Hills uplift (e.g., conglomerates of the Selah interbed and the McBee conglomerate, see fig. 40 and 43) on first impression would seem to indicate that the area was a low. This is locally true (e.g., between Chandler anticline and the Kiona anticline), however, in other areas (e.g., Chandler anticline), it is apparent from the trace of the gravel trains and isopach maps, that these crestal outcrops were controlled by structural highs associated with present structures but whose topographic crests were located slightly to the south of their present position. Thus, it is possible that the crestal portions of the folds have migrated with time to their present position and elevated the conglomerate.

5.0 GROWTH RATES

In certain studies, various growth rates of between 100 and 1,500 m/m.y. are roughly estimated for specific Yakima folds or the Yakima folds as a whole during post Columbia River Basalt Group time (see appendix F, table F-2). Other studies in the vicinity of the Pasco Basin use variations in thicknesses of Columbia River Basalt Group flows and sedimentary interbeds at "instances in time" to calculate vertical growth rates of between 40-250 m/m.y. from Columbia River Basalt Group time to the present (see table F-2). The latter more detailed studies outline a pattern of decreasing growth rates from Grande Ronde time to the present (Reidel et al. 1983b; Reidel 1984).

Using the approach described by Reidel (1984), it is possible to calculate vertical growth rates for portions of the Horse Heaven Hills uplift relative to the lower Yakima Valley syncline and the Piening syncline. Basically, the cumulative relief that has developed across a fold (calculated using data from section 4.0; see tables D-1 through D-4) can be plotted against absolute age dates of individual Columbia River Basalt Group members (see table D-5) which give a rate of combined vertical uplift and subsidence for Wanapum and Saddle Mountains time. Because of the hiatus between the deposition of the Ellensburg Formation sediments and the Pleistocene sediments, there are no stratigraphic units for this period to gage growth rates; therefore, growth rates have to be extrapolated to the present time. In addition, no reference line is confidently delineated from which subsidence and uplift can be differentiated. Several assumptions are necessary when using thickness data and age dates when calculating the growth rates. These assumptions are reviewed in appendix D.

Results of the growth rate calculations are shown in figures 44 through 47. In all four traverses, the rate of development of the relief is <70 m/m.y. Additionally, all four curves indicate a decrease in the growth rate with decrease in age during the Wanapum and Saddle Mountains time. Extrapolation of the growth rates to the present approximates the cumulative relief developed since at least Wanapum time suggesting a uniform growth rate of the folds since Columbia River Basalt Group time to present. However, it is emphasized that at present there is no concrete evidence in the study area to indicate whether this growth occurred at higher or lower rates than the shown extrapolated rates. The three curves that represent development between the Horse Heaven Hills uplift and the lower Yakima Valley syncline all have approximately the same growth rates, with a slightly higher rate determined for the Kiona anticline-lower Yakima Valley syncline traverse. It is indicated from figure 47 that relief developed at a lower rate between the Prosser anticline and the Piening syncline.

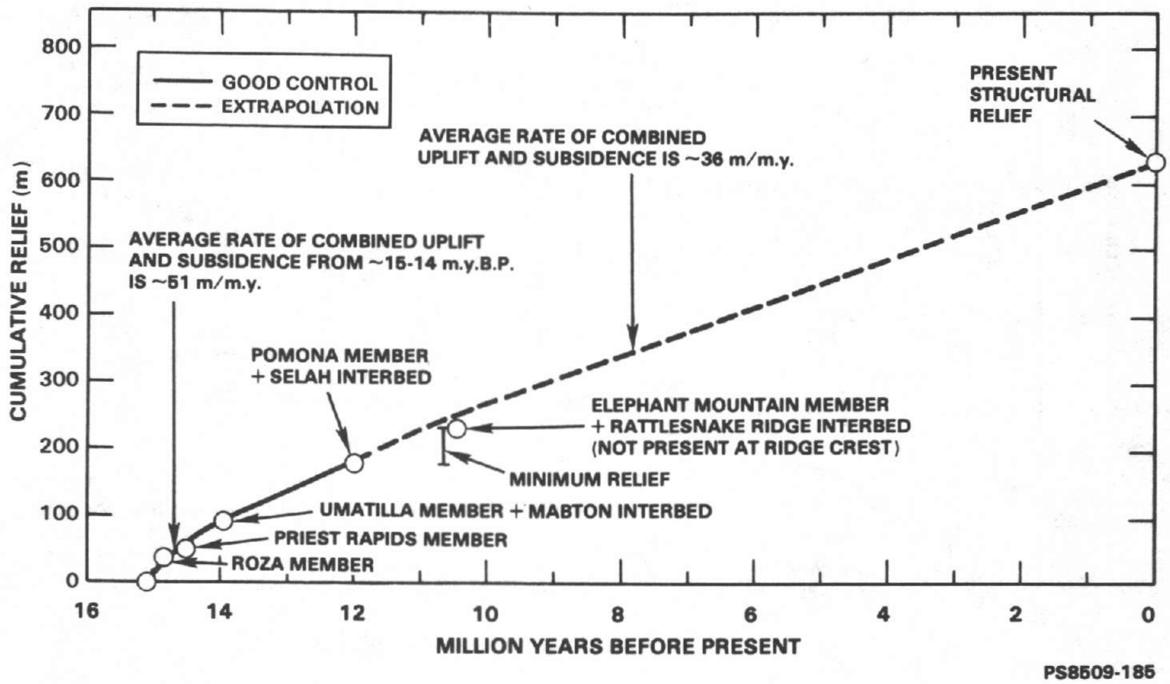

Figure 44. Curve Showing Rate of Relief Development between the Prosser Anticline and the Lower Yakima Valley Syncline during a Portion of Columbia River Basalt Group Time and Extrapolation to the Present. Age dates used in constructing the curves are subject to error ranges that could alter the shape of the curve locally, but not the general trend.

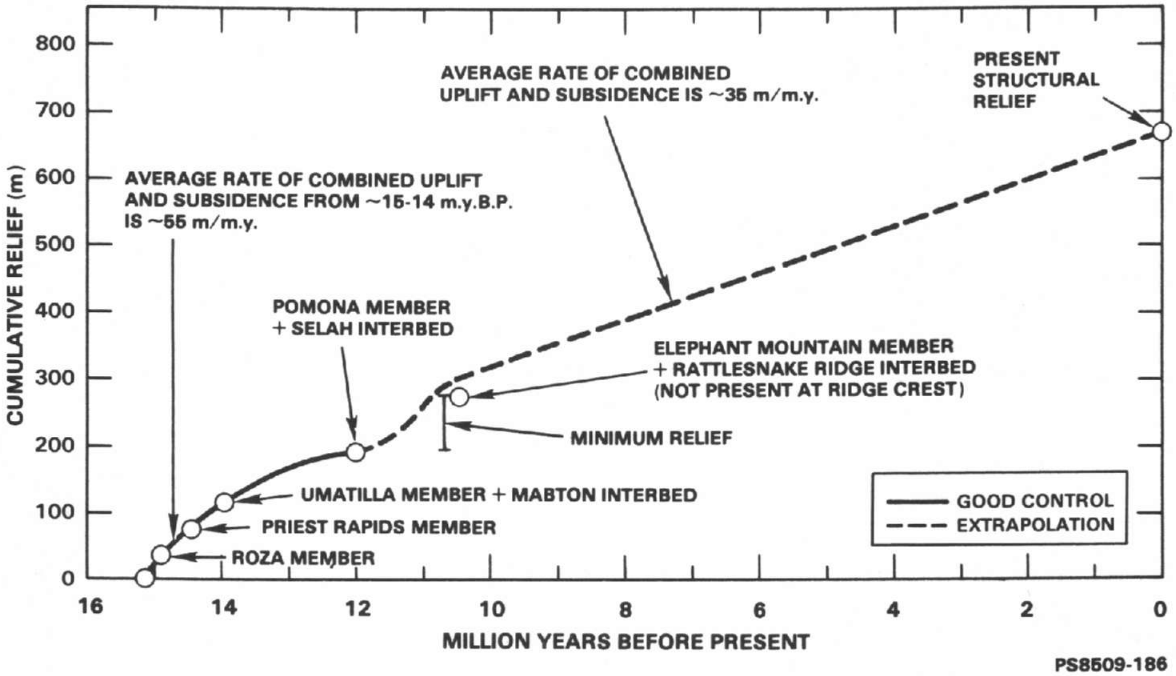

Figure 45. Curve Showing the Rate of Relief Development between the Chandler Anticline and the Lower Yakima Valley Syncline during a Portion of Columbia River Basalt Group Time and Extrapolation to the Present. Age dates used in constructing the curves are subject to error ranges that could alter the shape of the curve locally, but not the general trend.

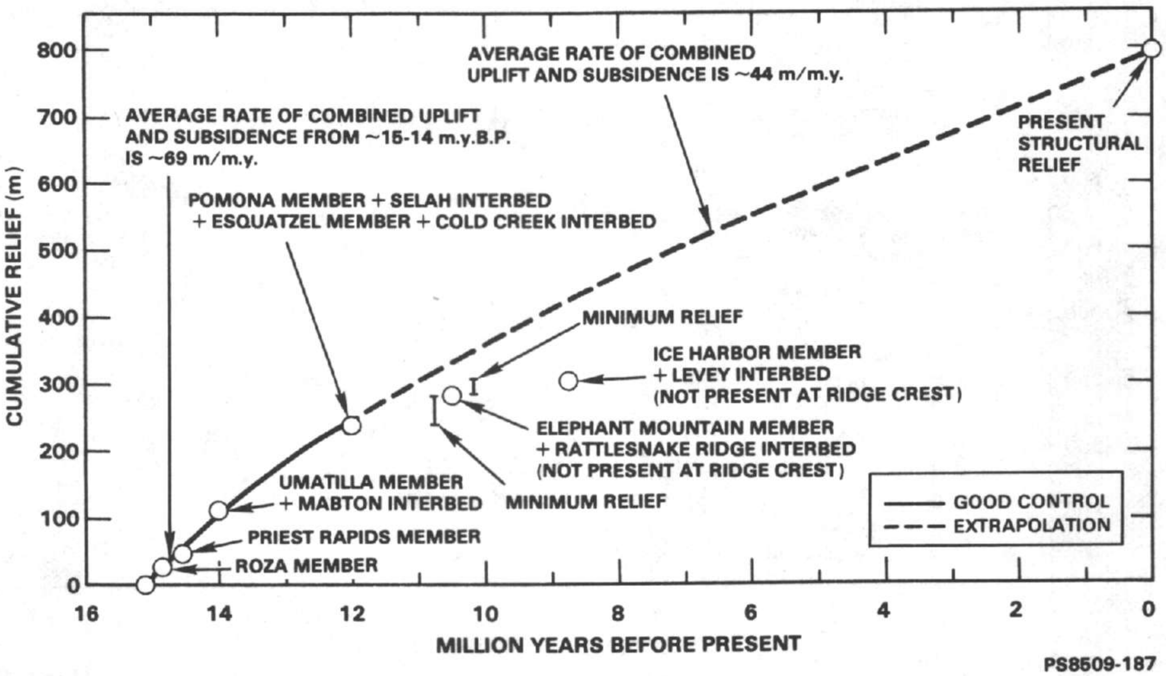

Figure 46. Curve Showing the Rate of Relief Development between the Kiona Anticline and the Lower Yakima Valley Syncline during a Portion of Columbia River Basalt Group Time and Extrapolation to the Present. Age dates used in constructing the curves are subject to error ranges that could alter the shape of the curve locally, but not the general trend.

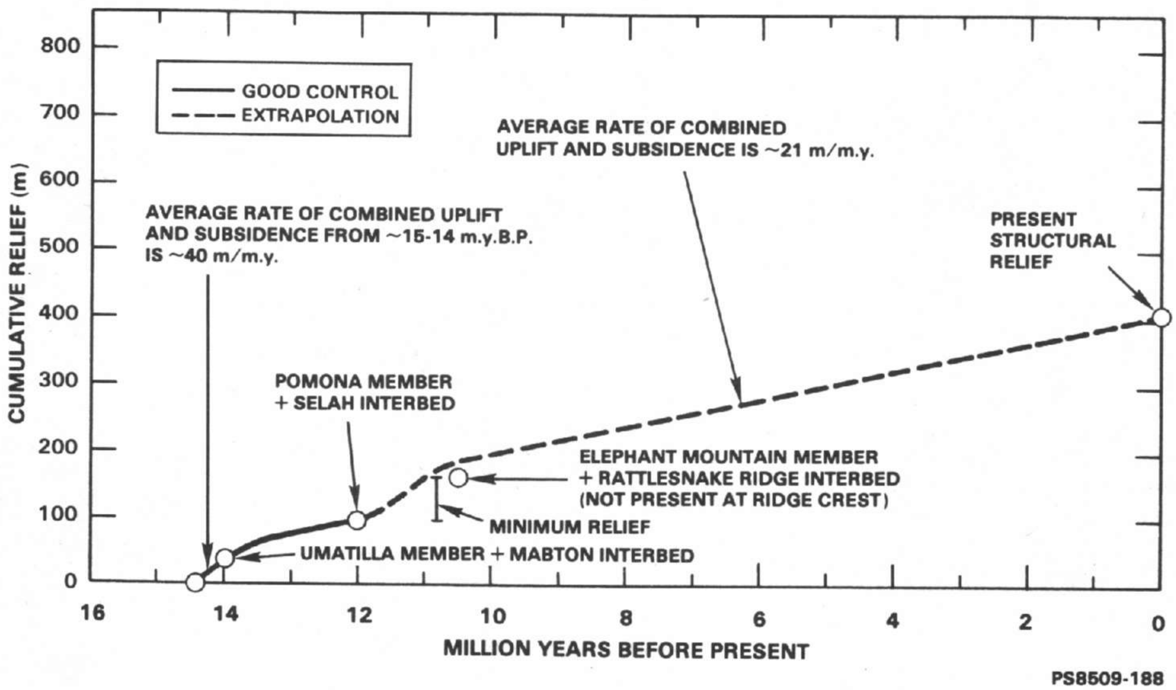

Figure 47. Curve Showing Rate of Relief Development between the Prosser Anticline and the Piening Syncline during a Portion of Columbia River Basalt Group Time and Extrapolation to the Present. Age dates used in constructing the curves are subject to error ranges that could alter the shape of the curve locally, but not the general trend.

6.0 CONSTRAINTS ON TECTONIC MODELS FOR THE DEVELOPMENT OF THE HORSE HEAVEN HILLS UPLIFT

Many tectonic models published to date address the genesis of the various east-west-trending and northwest-trending folds of the Yakima Fold Belt (see appendix F, table F-3). These models also imply directly or indirectly an origin for the Horse Heaven Hills uplift. Choosing one of these tectonic models (or a new one) for the Horse Heaven Hills uplift is beyond the scope of this study; however these tectonic models or future tectonic models can be constrained by the findings of this study. This section contains a brief evaluation of these tectonic models as they apply to the Horse Heaven Hills uplift, followed by some suggested constraints. More detailed reviews of such tectonic models are also presented in Davis (1981), Price (1982), and Duncan (1983).

It is generally agreed that the Yakima folds developed under approximately north-south compression based on the orientations of surficial structures (e.g., folds, dikes), and that these folds are presently deforming under north-south compression (Campbell and Bentley 1981; Rohay and Davis 1983). However, the origin of the folding has been debated (see table F-3). Published tectonic models for the Yakima folds can be fit into the following several categories (see fig. 48): (1) differential horizontal displacement of a coupled Columbia River Basalt Group layer and sub-basalt layer (includes wrench models), (2) horizontal contraction within a detached Columbia River Basalt Group layer (includes decollement models), (3) horizontal contraction involving coupled Columbia River Basalt Group and sub-basalt layers and, (4) differential vertical displacement (includes drape fold models).

An interpretation of recently collected magnetotelluric data suggests that the sub-basalt rock is composed of an upper sediment sequence and a lower crystalline rock layer (Mitchell and Bergstrom 1983). The rheological differences between these two sub-basalt layers may cause a different accommodation to stress; however, for the purposes of this discussion these two layers are considered as a homogeneous sub-basalt medium or basement.

6.1 EAST-WEST-TRENDING FOLDS

Formation of the Horse Heaven Hills uplift from horizontal contraction within a detached basalt layer (thin-skinned folds) is suggested by the uplift's long, linear trend, thrusting along its flanks, and the uplift's lack of structural deviation over a strong regional gravity gradient aligned with the 120° west longitude meridian (Konicek 1975, Finn et al. 1984) and thought by Konicek to represent an eastward increase in thickness of basalt. In addition, along a north-south transect the fold pattern of east-west-trending Yakima folds as a whole might suggest the presence of thin-skinned tectonics. East-west-trending Yakima folds are thought to form over local detachments or ramps from regional detachments (Davis 1981 and Price 1982; see table F-1).

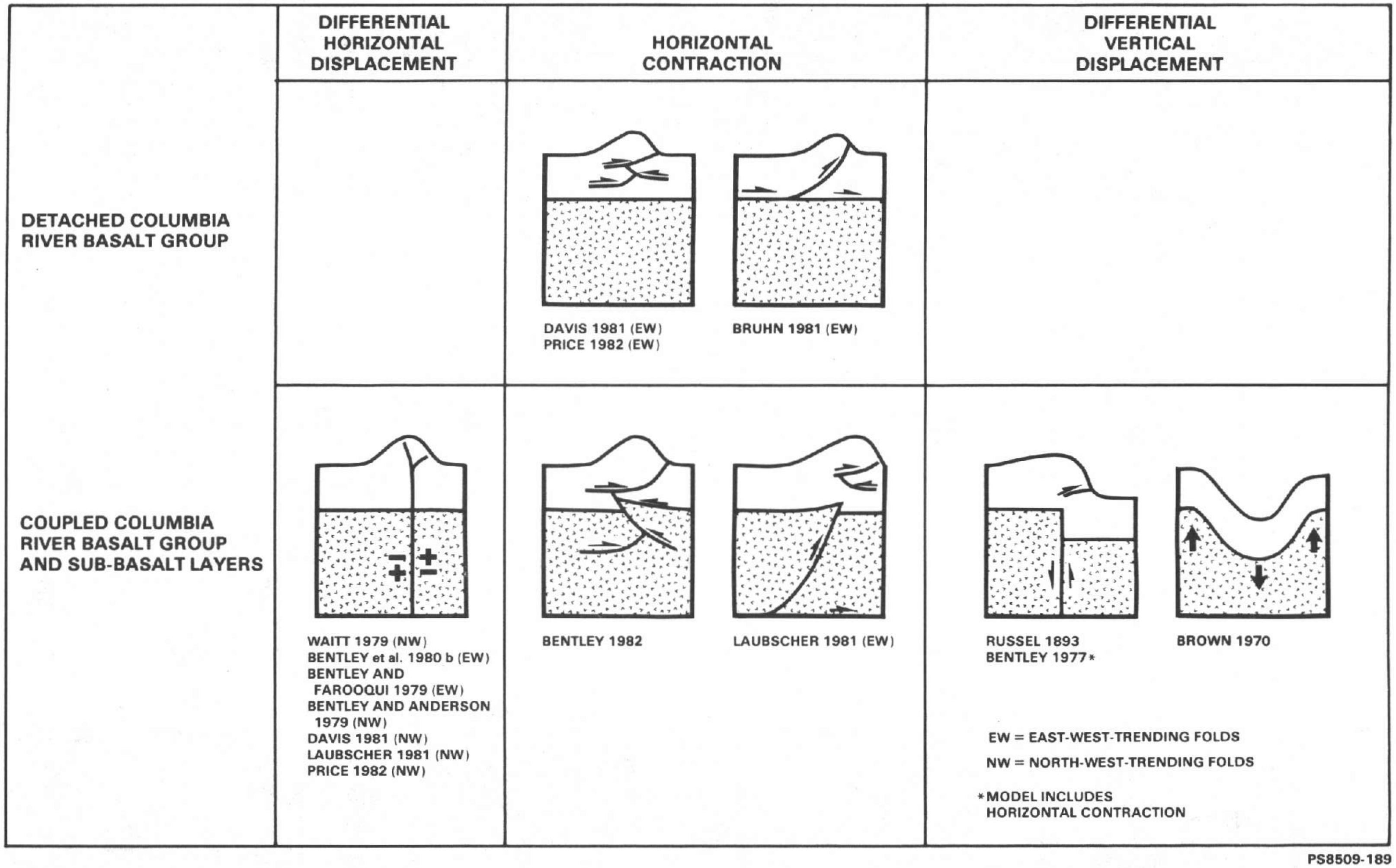

Figure 48. Tectonic Model Classification.

Data are also available that suggest coupling between the basalt and sub-basalt rock. Along the Rattlesnake Hills, the 3.2-km-deep RSH-1 well is interpreted by Reidel et al. (1982) not to encounter a fault consistent with decollement and supports the presence of a high-angle fault at depth. In addition, a thrust fault along the Columbia Hills (Swanson et al. 1979a) is observed to steepen with depth similar to that interpreted for the Rattlesnake Hills area. Also, magnetotelluric data in the Pasco Basin area indicate high relief at the base of the basalt which is interpreted to indicate a lack of decollement at the base of the basalt (Mitchell and Bergstrom 1983). Moreover, seismicity suggests that the basement and the basalt react as though coupled (Duncan 1983).

Differential horizontal displacement (left-lateral wrenching) involving a coupled Columbia River Basalt Group layer and sub-basalt layer along the northeast trend of the Horse Heaven Hills uplift (as proposed for other east-west folds, Bentley and Farooqui 1979; Bentley et al. 1980b) is suggested by the presence of left-stepping en echelon anticlines (e.g., Gibbon anticline and Chandler anticline). The importance of this en echelon relationship (in the absence of more concrete data) as a surficial indicator for wrenching is questionable when one observes that other east-west folds (e.g., the Simcoe Mountains, Alder Ridge, and Paterson Ridge) contain en echelon folds oriented in a right-stepping sense. In addition, clockwise rotation is found from paleomagnetic vectors along the northeast trend of the Horse Heaven Hills uplift (see appendix E), the east-west-trending Saddle Mountains, the Gable Mountain trend, and the northwest-trending folds of the ARW and RAW (Reidel et al. 1984).

Reidel et al. (1984) use this consistent clockwise rotation along both east-west- and northwest-trending folds to dismiss models that call for sinistral faulting (sinistral faulting would suggest counterclockwise rotations). Also, seismicity along east-west folds and at trending folds indicates, that presently, reverse or thrust faults lie along these folds (Rohay and Davis 1983).

The asymmetric and near-monoclinal fold geometry, along with the presence of thrust and reverse faults along the folds of the northeast trend of the Horse Heaven Hills uplift (see section 2.0) resembles folds originating from horizontal contraction and/or vertical displacement along faults in the basement (e.g., Rattlesnake Mountain, Wyoming, (Brown 1984)). This type of folding and faulting is consistent with seismic data (Rohay and Davis 1983) and what is known of the angle of faulting as constrained by RSH-1 and the thrust fault along the Columbia Hills, mentioned previously. Overturned limbs, the possible migration of ridge crests with time (see section 4.0), and the hypothesized north-south oriented compression during the Miocene and Pliocene indicate that uplift may not be caused strictly by vertical displacement.

6.2 NORTHWEST-TRENDING FOLDS

It is proposed here, that based on their proximity, parallel nature, similar lengths, similar structural forms, and timing of development, the structures along the ARW (including the northwest trend of the Horse Heaven

Hills uplift) and portions of the RAW are genetically related, and thus, tectonic models concerned with the origin of the RAW (as well as structures coincident with the OWL) are applicable to the northwest trend of the Horse Heaven Hills uplift.

The development of the aligned and en echelon brachyanticlines along the RAW is attributed to dextral wrenching (differential horizontal displacement involving both sub-basalt and Columbia River Basalt Group layers) based on their similarities to other wrench-produced folds (see Davis 1981). There is a similar alignment along the ARW (see fig. 12); however, a "sense of step" for the en echelon folds is not clearly indicated. Paleomagnetic data, which indicate clockwise rotation has occurred along folds of both the ARW and RAW, can be explained by dextral shear along these two structural trends (Reidel et al. 1984). In addition, the Wallula Gap fault which lies along the RAW is suggested to be a dextral fault, although Gardner et al. (1981) indicate that the fault is predominantly dipslip with minor strike-slip movement. According to Rohay and Davis (1983) earthquake hypocenters and focal mechanisms in the vicinity of the RAW do not support contemporary right-lateral movement along the RAW. Thus, although several workers propose the presence of strike-slip faults along the RAW, evidence is not demanding that this is the case.

6.3 CONSTRAINTS

Data from this study provide further constraints for the tectonic models discussed above. Both the northwest and northeast trends of the Horse Heaven Hills uplift were developing simultaneously and at similar rates (at least in Wanapum and Saddle Mountains time) under generally north-south compression. In addition, structural forms along both trends are very similar (see section 3.0). Based on these observations, it is proposed that folding along the northwest and northeast trends of the Horse Heaven Hills uplift were formed by the same tectonic process. These data would require reconsideration of models that attribute different tectonic conditions to the formation of the east-west trends and the northwest trends (e.g., detached deformation along one trend and basement-involved deformation along the other trend).

This hypothesis does not consider the structural implications of the numerous northwest-trending dextral faults and folds mapped along the southwestern portion of the Yakima fold belt (Swanson et al. 1979b). Based on available data, there is no apparent relationship between these northwest-trending faults and folds and the RAW and ARW. In support of this difference, there is a change in orientation of the axis of least compression from vertical in the central Columbia Plateau (study area) to an east-west orientation of the axis in the western portion of the Columbia Plateau. This suggests that present deformation at the western margin is predominantly produced by strike-slip movement on northwest-southeast-oriented fault planes (Rohay and Davis 1983).

Similarities of structural forms and timing of deformation between the Horse Heaven Hills uplift and other folds such as Umtanum Ridge (described in detail by Price 1982), the Saddle Mountains (Reidel 1984), and the Rattlesnake Mountain (Fecht et al. 1984) may also imply that these folds had a similar mechanical development.

Another structural feature that must be accommodated within a tectonic model for the Horse Heaven Hills uplift (and other Yakima folds) is the simultaneous growth of the Hog Ranch-Naneum Ridge anticline with the Horse Heaven Hills uplift during at least Saddle Mountains time. Other studies infer a pre-Columbia River Basalt Group age for the Hog Ranch-Naneum Ridge anticline to the north (see table F-2). Tabor et al. (1982) indicate that the Hog Ranch-Naneum Ridge anticline is related to basement structure along the northern margin of the Columbia Plateau. Campbell (1984) proposes that the "Naneum High" (a pre-Columbia River Basalt Group high structure coincident with the Hog Ranch-Naneum Ridge anticline) to the north of the study area, limited the eastward extent of the Cascade volcaniclastic sediments. The extension of the Hog Ranch-Naneum Ridge anticline in the lower Yakima Valley may have limited the westward progression of much of the Columbia River basalts, such as found in the northern Pasco Basin (Reidel and Fecht 1981). The north-south gravity gradient paralleling the 120° west longitude meridian is thought by Konicek (1975) to represent a progressive west to east thickening of the basalt. The projection of the Hog Ranch-Naneum Ridge anticline into the lower Yakima Valley roughly parallels this gravity gradient and may be related to this increase in thickening of the basalt.

The structural and tectonic relationships between the north-northwest-trending Hog Ranch-Naneum Ridge anticline, and the east-west- and northwest-trending Yakima folds remains unclear, and further work is needed to ascertain their relationship.

7.0 CONCLUSIONS

Basalt flows of the Grande Ronde, Wanapum, and Saddle Mountains Basalts of the Columbia River Basalt Group were mapped along and in the immediate vicinity of the Horse Heaven Hills uplift. Borehole data provided additional information away from principal exposures. The Grande Ronde Basalt consists of flows of the Sentinel Bluffs sequence; the Wanapum Basalt consists of flows of the Frenchman Springs, Roza, and the Priest Rapids Members; the Saddle Mountains Basalt consists of flows of the Umatilla, Esquatzel, Pomona, Elephant Mountain, and Ice Harbor Members. Several sedimentary interbeds of the Ellensburg Formation are intercalated with these flows in the study area. Additional sedimentary units of the Ellensburg Formation, such as the Snipes Mountain conglomerate, McBee conglomerate, or undifferentiated Ellensburg sediments occur above the Columbia River Basalt Group. A depositional hiatus occurs within the study area between the late Miocene and Pleistocene epochs.

Within the study area, the Horse Heaven Hills uplift consists of two distinct intersecting trends, a northwest (N50°-55°W) and a northeast (N60°-70°E) structural trend. The northwest-trending portion forms a part of the Anderson Ranch-Wallula structural alignment that parallels the Rattlesnake-Wallula structural alignment (part of the Olympic Wallowa Lineament). Each trend consists of aligned or en echelon anticlines and monoclines. At the intersection of the northwest and northeast trends, two major anticlines, the Chandler anticline (part of the northeast trend) and the Kiona anticline (part of the northwest trend) merge. As the northwest-trending Kiona anticline is traced into the intersection, the trace of its axis gradually changes to a more westerly direction and is accompanied by tear faults in the northern flank of the anticline. This portion of the Kiona anticline could represent (1) the northwest-plunging nose of the anticline, or (2) a change in trend of the anticline as a result of local differential stresses caused by the interference of folding along the northwest and northeast trends.

Along the crest of the Horse Heaven Hills uplift, a series of asymmetric (north vergence) eroded, usually double-hinged anticlines or monoclines are present. Some of these anticlines or monoclines are paralleled to the immediate north by a lower-relief anticline or monocline. All folds either are, or approach, monoclines in geometry. Also, along certain folds there is a transition between the monoclinal and the anticlinal geometries.

Surface faults along the uplift generally represent strain caused by folding. Reverse faults parallel the folds and are commonly found or inferred along the base of the northern limb of anticlines or monoclines, in the hinge zone of monoclines, and in the northern hinge zone of the double-hinged anticlines. Reverse faults are rarely observed along the southern hinge or the interhinge limb of a double-hinged anticline. Tear faults are coincident with marked changes in fold wavelength and/or changes in strikes of fold axes. Layer-parallel faults are common in steeply dipping strata along stratigraphic contacts or zones of preferred weakness in the intraflow structures, but are also locally found along stratigraphic contacts of low dip. Observations indicate that much of the landsliding along northern fronts of the folds was precipitated or facilitated by the presence of fault-shattered basalt and interbeds situated along steeply dipping limbs.

The geometry is strikingly similar between the northwest and northeast trends of the Horse Heaven Hills uplift. In addition, the magnitude of relief between the major folds (those that compose the ridge crest of the uplift) of the two trends and between the minor folds of the two trends is similar.

Uplift along the Horse Heaven Hills during portions of the middle and late Miocene was concentrated on the major folds that are now present. Growth occurred simultaneously along folds of both the northwest and northeast trends. Local structural lows occurred between certain major folds of each trend and also between the northwest and northeast trends themselves. Other structures such as the lower Yakima Valley syncline, the Piening syncline, and the Hog Ranch-Naneum Ridge anticline were also developing simultaneously with the Horse Heaven Hills uplift. Because of a lack of a depositional geologic record between the late Miocene and the Pleistocene, it is not possible to determine the details of the growth of these structures during that time. However, it is apparent that the Horse Heaven Hills uplift continued to grow to its present-day relief either uniformly or intermittently. Also, the lower Yakima Valley syncline appears to have structurally "risen" in relation to the Pasco and Toppenish Basins after the Miocene. The uplift of the Hog Ranch-Naneum Ridge anticline within the study area may have slowed after Elephant Mountain time and is related to the relative rise of the lower Yakima Valley syncline.

Combined uplift and subsidence rates between the Horse Heaven Hills uplift and the lower Yakima Valley syncline for Wanapum and Saddle Mountains time are <70 m/m.y. and between the Horse Heaven Hills uplift and the Piening syncline are <40 m/m.y. Growth rates appear to decrease during Wanapum to Saddle Mountains time. Extrapolation of growth rates to the present approximates the cumulative relief developed since at least Wanapum time and supports the possibility that the folds developed at a uniform or nearly uniform rate from Columbia River Basalt Group time to the present. However, this does not preclude intermittent growth (thus higher or lower rates of growth).

An evaluation of the diverse group of published tectonic models proposed for the Yakima folds indicates that choosing a tectonic model for the Horse Heaven Hills uplift is not possible with the available data. However, constraints can be placed on such models from data gathered in this study. These models must consider (1) the monoclinal or near-monoclinal fold geometry and associated reverse faults, (2) the development of the folds along both trends of the Horse Heaven Hills uplift occurring simultaneously and at similar rates (at least during Wanapum and Saddle Mountains time), (3) the folds along the northwest trend of the Horse Heaven Hills uplift are genetically related and formed simultaneously with at least portions of the RAW, (4) the uplift was developing simultaneously with the north-northwest-trending Hog Ranch-Naneum Ridge anticline as well as other

Yakima folds, and (5) the preliminary results indicate that clockwise rotation is found at sites along folds of both the northwest and northeast trends of the Horse Heaven Hills uplift. From these constraints it is proposed that the northeast and northwest trends of the Horse Heaven Hills uplift were generated by the same tectonic process.

Further work of this type, elsewhere in the Yakima fold belt, will help determine if these constraints are applicable to other Yakima folds. Present studies suggest they are. Future subsurface data, as it becomes available, in coordination with this type of work will further constrain tectonic models for the Columbia Plateau.

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APPENDIX A

CHEMICAL ANALYSES

Chemical analyses of Columbia River Basalt Group samples are shown in table A-1. Most of the analyses are for major oxide concentrations and are determined by the x-ray fluorescence method, completed at Washington State University under the direction of Dr. Peter Hooper under contract to Rockwell Hanford Operations. Concentrations of the trace element chromium are taken from Beeson et al. (1985).*

*Beeson, M. H., K. R. Fecht, S. P. Reidel, and T. L. Tolan, 1985, Stratigraphy of the Frenchman Springs Member of the Wanapum Basalt of the Columbia River Basalt Group, RHO-BW-SA-440, Rockwell Hanford Operations, Richland, Washington.

Table A-1. Chemical Analyses of Columbia River Basalt Group Flows in the Study Area. (sheet 1 of 6)

Sentinal Bluffs Sequence											
Sample number	SiO_2	Al_2O_3	FeO[a]	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	
SS158015	53.14	14.98	11.95	4.77	8.62	2.63	1.18	1.99	0.34	0.21	
SS158816	52.79	15.63	11.77	5.05	8.66	2.56	1.01	1.83	0.30	0.20	
C 8376	54.10	15.14	11.00	4.62	8.69	2.66	1.33	1.76	0.30	0.19	
Frenchman Springs Member											
Ginkgo flow											
Sample number	SiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	
SS144014	49.56	14.45	14.85	4.38	8.43	2.93	1.00	3.11	0.62	0.23	
SS152015	50.85	14.22	14.25	4.38	8.04	2.85	1.30	3.06	0.61	0.24	
C 8375	51.58	14.22	14.20	4.21	8.05	2.38	1.33	3.03	0.60	0.21	
Silver Falls flow											
Sample number	SiO_2	Al_2O_3	FeO^+	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Cr[b]
MH83SS132030	51.45	13.89	14.00	4.50	8.53	2.52	1.05	3.10	0.53	0.22	15.90
MH83SS138040	52.14	14.07	14.38	3.66	8.38	2.33	1.21	3.06	0.54	0.21	16.90
Sand Hollow flow											
Sample number	SiO_2	Na_2O	FeO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Cr
MH82H206	51.26	14.77	13.69	4.51	8.05	2.48	1.51	2.82	0.50	0.21	
MH82H207	51.15	14.66	13.81	4.56	8.10	2.46	1.48	2.87	0.49	0.22	
MH82H220	51.55	14.65	13.67	4.38	7.93	2.84	1.19	2.90	0.50	0.20	

Table A-1. Chemical Analyses of Columbia River Basalt Group Flows in the Study Area. (sheet 2 of 6)

Sand Hollow flow (cont.)

Sample number	SiO_2	Na_2O	FeO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Cr
SS105010	50.23	14.69	13.93	4.52	8.60	2.69	1.00	3.04	0.53	0.24	
MH83SS124050	51.70	13.48	14.23	4.39	8.65	2.44	1.29	2.88	0.53	0.22	37.40
C 8373	52.53	14.73	12.74	4.04	8.59	2.32	1.27	2.86	0.48	0.18	
C 8374	51.51	14.42	13.85	4.63	8.20	2.37	1.30	2.84	0.48	0.20	

Sentinal Gap flow

Sample number	SiO_2	Na_2O	FeO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Cr
MH81089	51.11	14.41	13.97	4.09	8.21	3.03	1.18	3.08	0.51	0.20	
MH82HH16	49.72	15.29	12.86	4.49	9.20	3.17	1.05	3.21	0.59	0.22	
MH82H205	51.53	14.96	13.27	4.10	8.03	2.52	1.50	3.11	0.56	0.22	
MH82H218	51.54	14.78	13.83	4.09	7.79	2.58	1.44	2.98	0.55	0.21	
MH82H219	51.80	15.46	12.06	4.18	8.73	2.69	1.09	3.10	0.52	0.17	
SS960970	51.44	14.28	13.89	4.17	8.11	2.76	1.44	2.92	0.56	0.23	
MH83SS810820	51.57	14.22	13.85	4.51	8.19	2.19	1.36	3.15	0.55	0.22	
SS960970	51.44	14.28	13.89	4.17	8.11	2.76	1.44	2.92	0.56	0.23	16.10
C 8371	51.66	14.06	14.17	4.24	8.02	2.49	1.39	3.03	0.53	0.20	
C 8372	51.90	14.09	14.15	4.07	7.76	2.72	1.42	2.91	0.57	0.21	

Priest Rapids Member

Rosalia Flow

Sample number	SiO_2	Na_2O	FeO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO
MH81083	48.82	14.35	14.24	5.14	9.03	3.23	0.98	3.12	0.66	0.22
MH81087	49.80	15.21	13.08	4.40	9.28	3.07	0.89	3.22	0.65	0.20

Table A-1. Chemical Analyses of Columbia River Basalt Group Flows in the Study Area. (sheet 3 of 6)

Rosalia Flow (cont.)

Sample number	SiO_2	Na_2O	FeO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO
MH82H179	49.38	14.44	14.01	5.12	9.02	2.56	1.12	3.22	0.70	0.23
MH82H185	50.34	14.89	13.12	4.96	8.95	2.53	0.94	3.19	0.65	0.23
SS620630	50.82	14.78	12.80	5.19	8.54	2.54	1.12	3.13	0.65	0.22
SS750760	50.59	14.34	14.61	4.63	7.68	2.71	1.27	3.06	0.68	0.23
C 8370	50.51	14.36	13.59	4.80	8.86	2.41	1.17	3.24	0.67	0.20

Lolo Flow

Sample number	SiO_2	Na_2O	FeO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO
MH81086	49.68	14.14	13.23	4.15	9.67	3.26	0.81	3.92	0.72	0.20
MH82HH75	51.11	16.48	13.58	3.82	7.33	2.72	0.36	3.52	0.69	0.20
MH82H175	50.59	14.18	14.41	4.34	7.94	2.69	1.22	3.53	0.68	0.22
MH82180	50.18	14.72	14.09	4.27	8.42	2.60	0.99	3.63	0.65	0.24

Umatilla Member

Umatilla Flow

Sample number	SiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO
MH82HH21	53.05	15.36	12.18	3.27	6.42	2.93	2.63	3.05	0.72	0.19
MH82HH67	51.59	14.74	12.94	3.36	7.74	2.32	2.97	3.20	0.72	0.22
MH82HH69	53.62	15.54	11.86	2.83	6.39	3.07	2.48	3.15	0.71	0.16
MH82H154	53.88	15.15	12.31	2.91	6.25	2.90	2.49	2.98	0.74	0.18
MH82H166	54.66	15.54	10.10	2.72	7.04	2.88	2.56	3.22	0.75	0.30
MH82H176	53.12	14.93	12.72	3.18	6.30	3.22	2.35	3.08	0.73	0.19

Table A-1. Chemical Analyses of Columbia River Basalt Group Flows in the Study Area. (sheet 4 of 6)

Umatilla Flow

Sample number	SiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO
MH82H189	53.28	15.07	12.60	3.23	6.33	2.79	2.60	2.94	0.76	0.21
MH82H234	53.07	15.04	12.79	2.89	6.32	3.34	2.46	2.94	0.75	0.20
MH82H235	53.07	14.65	13.72	3.28	5.86	2.79	2.50	3.03	0.75	0.16
MH82H279	53.27	14.98	12.34	3.00	6.53	2.99	2.74	3.01	0.75	0.19
SS470480	53.07	15.40	12.76	3.30	6.10	2.83	2.49	2.92	0.73	0.20
C 8369	53.80	14.66	12.70	2.93	6.37	2.93	2.51	3.00	0.71	0.17

Sillusi Flow

Sample number	SiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO
MH81062	53.73	15.13	12.55	2.87	6.01	3.23	2.60	2.71	0.78	0.19
MH82H159	53.87	15.32	12.56	2.72	5.75	3.19	2.70	2.64	0.85	0.20
MH82H174	53.88	15.19	12.37	2.66	5.92	2.88	3.11	2.61	0.88	0.21
MH82H182	54.45	15.21	12.37	2.63	5.87	2.79	2.77	2.64	0.88	0.18
MH82H183	54.31	15.65	11.35	2.80	6.18	2.53	3.22	2.66	0.89	0.20
SS350360	54.13	15.25	12.33	2.97	5.96	2.69	2.00	2.63	0.87	0.22

Esquatzel Member

Sample number	SiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO
MH81063	53.64	14.89	11.55	3.74	7.80	2.90	1.66	3.05	0.37	0.19
MH82HH38	51.85	15.23	12.72	3.65	7.97	2.73	1.66	3.34	0.47	0.18
MH82HH45	52.79	15.56	11.43	3.87	7.80	2.68	1.84	3.22	0.43	0.18
MH82HH56	51.65	14.76	13.70	3.78	7.56	2.62	1.92	3.22	0.41	0.20

Table A-1. Chemical Analyses of Columbia River Basalt Group Flows in the Study Area. (sheet 5 of 6)

Esquatzel Member										
Sample number	SiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO
MH82HH64	49.61	13.98	14.23	3.67	10.26	2.46	1.78	3.20	0.40	0.20
MH82HH65	51.67	14.29	13.41	4.03	7.59	2.87	2.09	3.17	0.42	0.25
MH82HH72	53.51	15.21	12.95	3.72	6.17	2.64	1.83	3.08	0.49	0.19
MH82HH87	48.44	15.29	14.29	3.80	10.59	2.15	1.04	3.55	0.48	0.18
Pomona Member										
Sample number	SiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO
MH81035	51.66	15.32	10.45	6.68	10.43	2.83	0.41	1.60	0.24	0.18
MH81045	51.44	15.35	10.20	6.86	10.56	2.88	0.49	1.62	0.21	0.18
MH81055	51.56	15.76	9.79	6.64	11.01	2.90	0.21	1.62	0.22	0.18
MH81057	53.43	15.63	10.97	5.03	8.82	2.89	0.78	1.80	0.25	0.18
MH81064	51.74	16.23	11.73	6.38	10.74	2.75	0.17	1.66	0.23	0.17
MH81065	50.16	15.10	11.19	6.93	10.84	3.04	0.38	1.73	0.25	0.19
MH81071	51.20	15.49	10.75	6.81	10.35	2.83	0.40	1.59	0.21	0.18
MH81072	51.36	15.67	10.35	6.49	10.56	2.98	0.38	1.61	0.22	0.18
MH81092	51.37	15.32	10.27	6.57	10.72	3.01	0.53	1.62	0.22	0.18
MH81093	51.42	15.77	10.02	6.25	10.86	2.93	0.51	1.63	0.22	0.18
MH81100	51.54	15.52	10.30	6.72	10.37	2.84	0.55	1.57	0.21	0.18
MH81101	51.60	15.42	10.35	6.53	10.50	2.88	0.53	1.60	0.22	0.18
MH82HH34	51.22	15.90	10.08	6.68	10.91	2.29	0.56	1.72	0.27	0.17
MH82HH35	51.59	15.98	10.28	6.49	10.34	2.39	0.57	1.71	0.26	0.17
MH82HH37	50.99	15.98	10.10	6.55	10.93	2.49	0.45	1.85	0.29	0.18
MH82HH46	51.44	15.91	10.30	6.54	10.49	2.26	0.63	1.78	0.27	0.18
MH82HH49	51.01	15.78	10.08	6.76	10.77	2.70	0.46	1.82	0.27	0.17

Table A-1. Chemical Analyses of Columbia River Basalt Group Flows in the Study Area. (sheet 6 of 6)

Pomona Member										
Sample number	SiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO
MH82HH58	50.83	15.75	10.30	6.80	10.57	2.80	0.49	1.81	0.28	0.18
MH82HH60	52.37	16.26	10.27	6.42	9.60	2.14	0.56	1.73	0.27	0.17
MH82HH61	50.94	15.89	10.37	6.81	10.60	2.29	0.67	1.76	0.26	0.19
MH82HH76	53.05	16.57	9.72	6.62	9.00	2.46	0.37	1.60	0.26	0.16
MH82HH77	52.31	16.04	10.18	6.57	10.35	1.99	0.32	1.65	0.24	0.16
MH82H102	51.46	15.78	10.35	6.92	10.32	2.23	0.57	1.73	0.25	0.17
MH82H124	52.06	16.42	10.89	5.61	11.50	2.58	0.56	1.69	0.24	0.26
MH82H152	51.65	15.39	10.71	6.66	10.50	2.05	0.67	1.72	0.23	0.23
MH82H153	51.23	15.82	10.91	6.62	10.25	2.28	0.54	1.72	0.26	0.18
MH82H276	51.51	15.73	11.20	6.41	10.37	2.20	0.21	1.75	0.26	0.17
MH82H280	51.74	15.66	10.54	6.46	10.51	2.22	0.53	1.69	0.26	0.17
SS170180	51.59	15.73	10.69	6.90	10.08	2.17	0.55	1.69	0.23	0.18

Elephant Mountain Member										
Sample number	SiO_2	Al_2O_3	FeO^+	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO
MH82H100	49.62	14.24	14.83	4.45	8.52	2.45	1.38	3.58	0.51	0.21
MH82H101	51.01	15.01	13.17	4.41	8.60	2.31	1.00	3.63	0.48	0.20
MH82H252	50.30	14.38	14.19	4.46	8.31	2.79	1.19	3.49	0.48	0.21
MH82H253	50.03	14.23	14.67	4.10	8.58	2.58	1.24	3.64	0.52	0.21
MH82H278	50.62	14.41	14.11	4.43	8.39	2.43	1.09	3.61	0.48	0.22
MH82H283	50.65	14.28	15.10	3.89	8.10	2.38	1.18	3.51	0.51	0.21
SS8090	49.85	14.32	14.74	4.59	8.38	2.23	1.00	3.63	0.50	0.22

NOTE: *All values in wt.%
[1]FeO = FeO + .9 (Fe_2O_3)
[2]All chrome data is from Beeson et al. 1985. All values in p/m.

APPENDIX B

BOREHOLE LOGS

BOREHOLE GEOPHYSICAL LOGS

Methods for identifying Columbia River Basalt Group flows and Ellensburg Formation interbeds from borehole geophysical logs (fig. B-1 through B-31) in this study are based on a series of reports, theses, and articles prepared by the faculty, staff, and students of Washington State University, College of Engineering (Crosby and Anderson 1971; Crosby et al. 1972; Anderson et al. 1973; Siems et al. 1973; Lobdell and Brown 1977; Brown 1978; Strait 1978; Sylvester 1978; Biggane 1982). Their work was concerned with characterizing the geohydrologic regime beneath portions of the Columbia Plateau.

The majority of borehole geophysical logs were gathered from the Washington State University College of Engineering. Some logs were also from the Washington State Department of Ecology, Rockwell Hanford Operations (Rockwell), and the U.S. Geological Survey in Tacoma, Washington (table B-1). In addition, Rockwell conducted borehole geophysical logging of the Chandler well (fig. B-21).

Generally, the most useful logs in this study are the radiation logs (gamma-gamma, neutron-gamma, neutron-epithermal, neutron, and natural gamma) which are used to pinpoint stratigraphic contacts and identify basalt flows. Caliper and electric logs are also contained in certain suites of logs, but are not included in the appendix. If prior stratigraphic interpretations of pertinent logs had been done by other workers, they were reevaluated by the author.

The gamma-gamma, neutron-gamma, and neutron-epithermal neutron logs measure radioactive emissions reflected off the wall rock from a downhole probe source. These logs reflect the density (gamma-gamma) and porosity (moisture content; neutron-gamma, neutron-epithermal neutron) of the wall rock. In this study, the logs are used for locating stratigraphic contacts.

The natural gamma log is a recording of the natural radioactive (primarily ^{40}K) emission of the rock in the borehole. Since this emission is directly related to the concentration of total potassium in the wall rock, the natural gamma log can be used to identify individual basalt flows. Major variations in K_2O between individual basalt members (e.g., Umatilla and Pomona Members) are reflected in the natural gamma log (see text fig. 5). Sedimentary interbeds of the Ellensburg Formation often, but not always, contain potassium-rich clays which provide a high gamma "kick" in the natural gamma log.

Drillers' logs are available for many of the geophysically logged boreholes; geologists' logs are rare (e.g., Paterson Test Well, Pearson 1973). Both were consulted during interpretations of the borehole geophysical logs.

Drill cuttings of the Columbia River Basalt Group were collected from the Moon #1 well and were cursorily inspected to ascertain their identities. Cuttings from several intervals were then analyzed for their major oxide concentrations to confirm identities. X-ray fluorescence analyses of basalt were also available for the Horse Heaven Test well. Basalt samples extracted from boreholes DC-15 and DDH-3, located in the Pasco Basin, have been chemically analyzed in detail to confirm basalt flow identities and serve as reference boreholes for correlating geophysical logs.

Although the Wanapum Basalt was frequently penetrated by boreholes, certain chemical and physical factors thwarted confident identification of the Wanapum basalt flows. These factors were (1) immeasurable differences in K_2O content between the Priest Rapids, Roza, and Frenchman Springs Members; (2) multiple vesicular zones within an individual basalt flow; (3) variations in the total number of flows within a member; (4) the discontinuous nature of the interbedded sediments; and (5) the non-uniform thickness of the basalt flows and sedimentary interbeds. However, this problem was overcome in two boreholes (Grandview City and Prosser Experiment Station) by correlating the borehole geophysical logs with those of boreholes DDH-3 and DC-15.

DRILLERS' LOGS

Drillers' logs provided additional control for constructing isopach maps. Although drillers' logs are one of the least reliable tools for identifying stratigraphic units, they can, with caution, be most effective. Over 90 drillers' logs were used for this study. Logs were obtained from both the Washington State Department of Ecology and from Rockwell Hanford Operations.

Successful identification of Columbia River Basalt Group flows or Ellensburg Formation sediments using drillers' logs is dependent primarily upon a driller's ability to differentiate sedimentary interbeds from the basalt flows, and secondarily, on that person's ability to recognize variations in the physical properties of the sediments or basalt (e.g., vesicular flow top). The driller is able to do this by noting differences in the drilling rate and in drill cuttings. Identification of the stratigraphic units takes into account the local stratigraphy determined from field mapping from this and other studies and borehole geophysical logs. In addition, it is necessary to become acquainted with the diverse terminology used for describing drill cuttings. During an evaluation of these drillers' logs, many logs were discarded because of lack of credibility.

Interpretations were complicated by (1) inconsistencies in the quality and style of reporting found in the drillers' logs, (2) proximity of well sites to complex or unknown structures, (3) lack of stratigraphic control nearby, (4) the discontinuous nature of sedimentary interbeds (e.g., Selah interbed), and (5) localized flows (e.g., Esquatzel Member). As is the case with the borehole geophysical logs, drillers' logs are commonly inadequate in delineating Wanapum Basalt flows and intercalated sedimentary interbeds.

LEGEND

Ti = ICE HARBOR MEMBER
Telv = LEVY INTERBED
Tem = ELEPHANT MOUNTAIN MEMBER
Ter = RATTLESNAKE RIDGE INTERBED
Tp = POMONA MEMBER
Tes = SELAH INTERBED
Te = ESQUATZEL MEMBER
Tecc = COLD CREEK INTERBED
Tu = UMATILLA MEMBER
Tema = MABTON INTERBED

Tpr = PRIEST RAPIDS MEMBER
Teq = QUINCY INTERBED
Tr = ROZA MEMBER
Tsc = SQUAW CREEK INTERBED
Tf = FRENCHMAN SPRINGS MEMBER
Tgr = UNDIFFERENTIATED GRANDE RONDE BASALT
—▽— = WATER TABLE
● = SAMPLED FOR CHEMICAL ANALYSIS

PS8509-197

Figure B-1. Legend for Borehole Geophysical Logs.

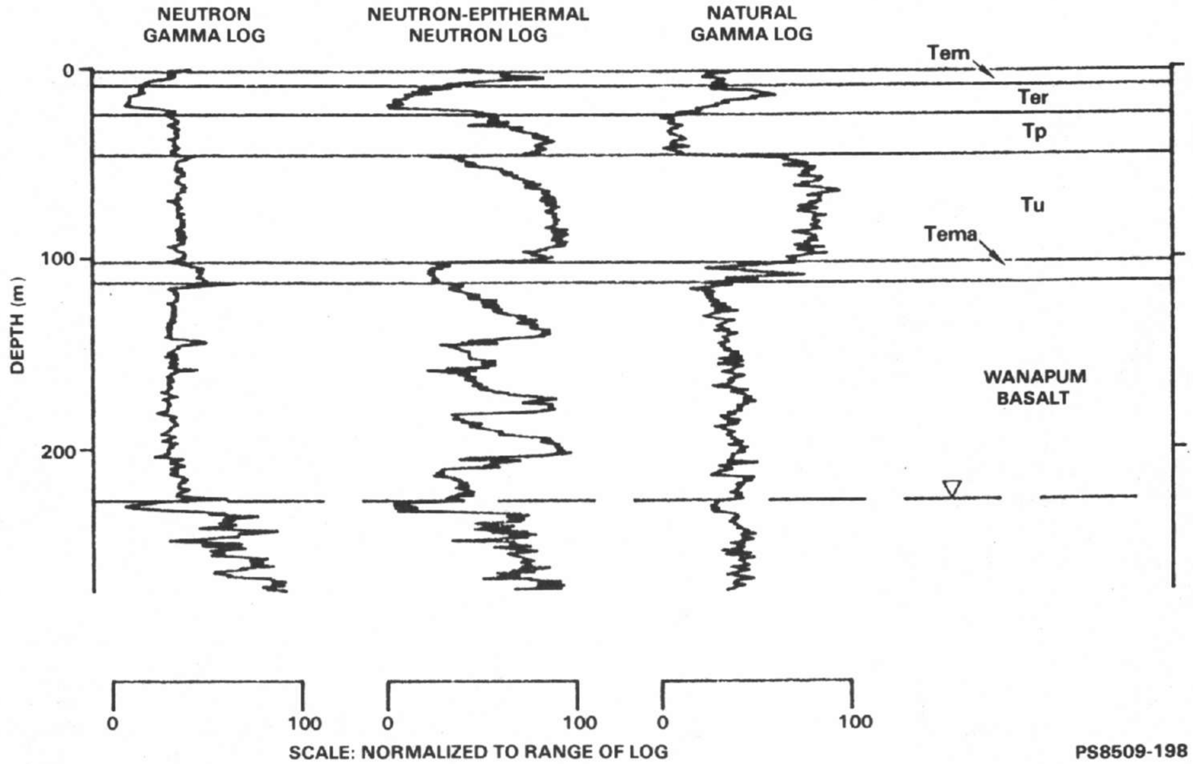

Figure B-2. Borehole Geophysical Logs of the Sharpe Well. (See fig. B-1 for legend.)

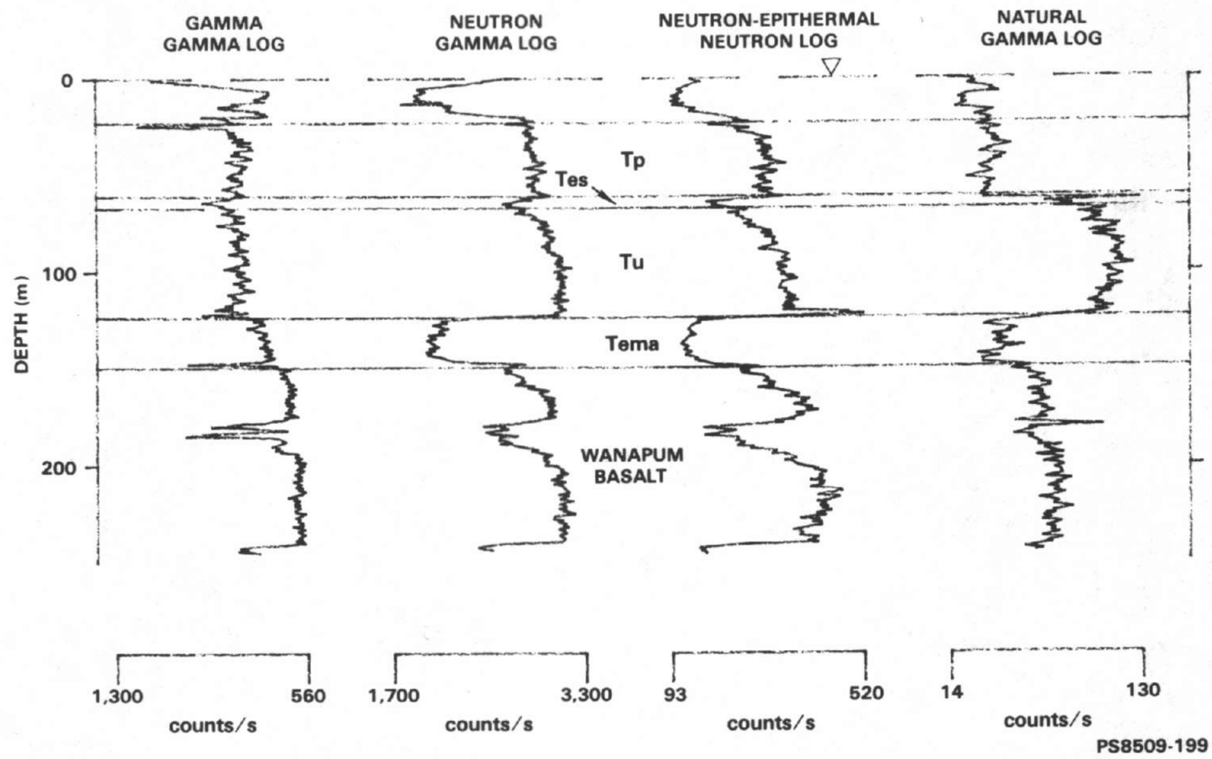

Figure B-3. Borehole Geophysical Logs of the Chesley Well. (See fig. B-1 for legend.)

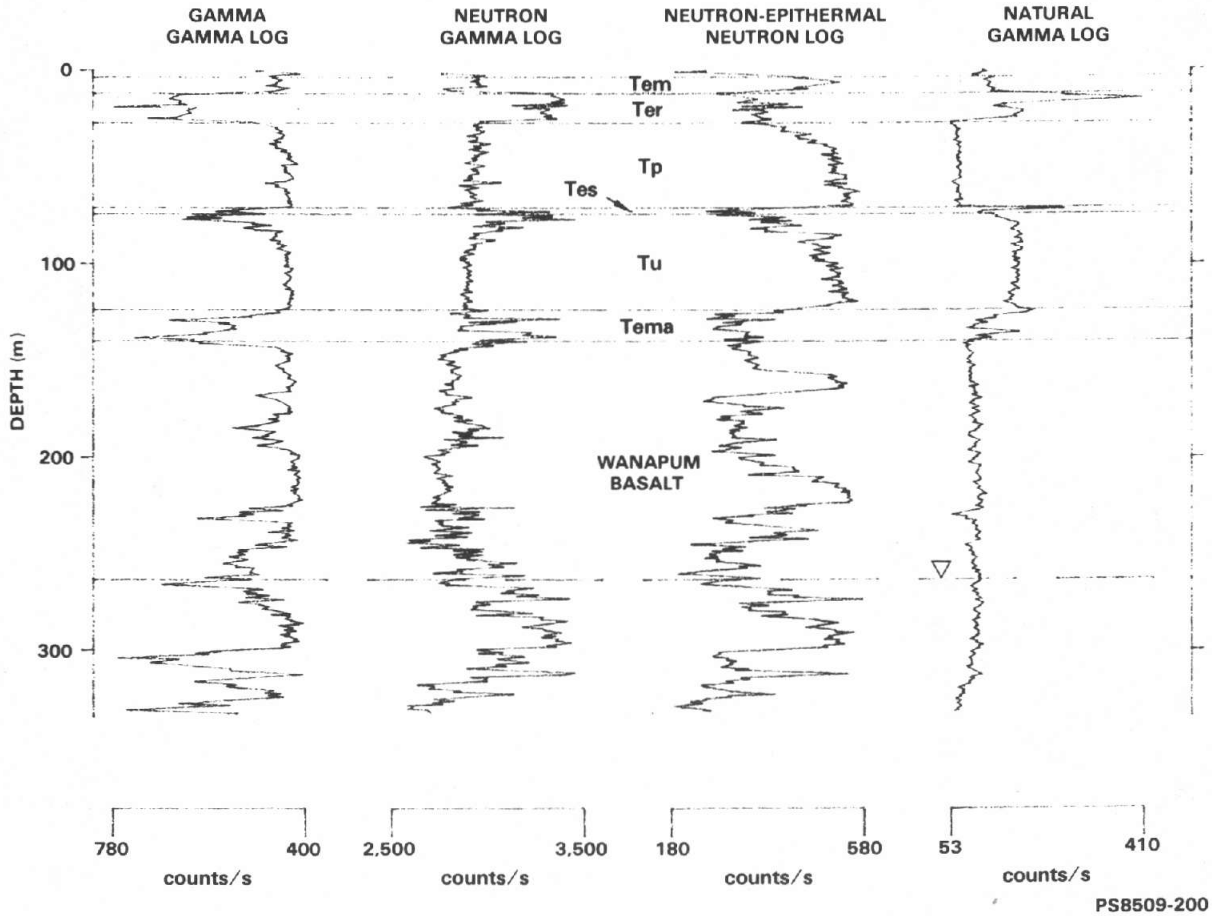

Figure B-4. Borehole Geophysical Logs of the Horrigan Farms Well. (See fig. B-1 for legend.)

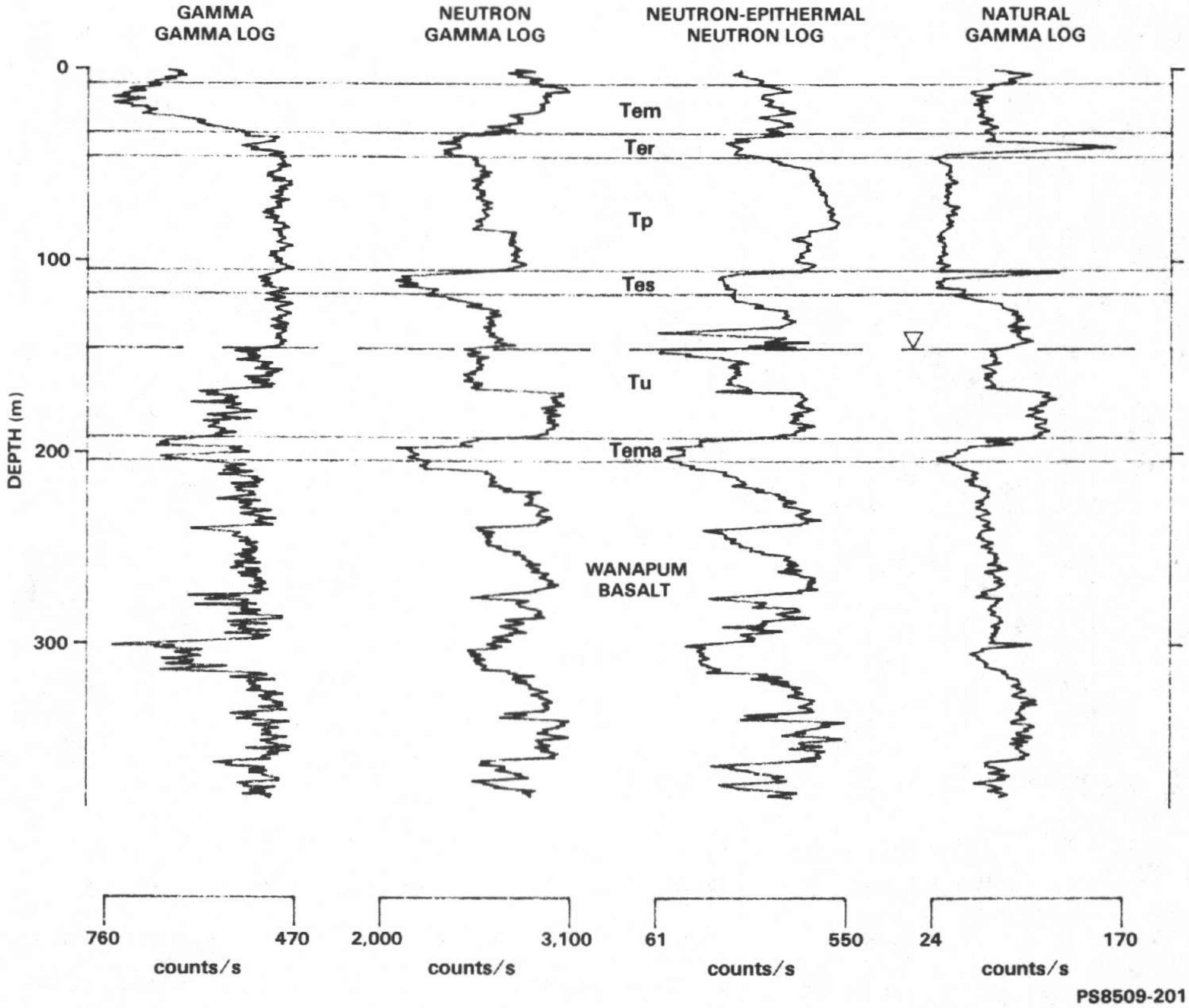

Figure B-5. Borehole Geophysical Logs of the Palmer 2 Well. (See fig. B-1 for legend.)

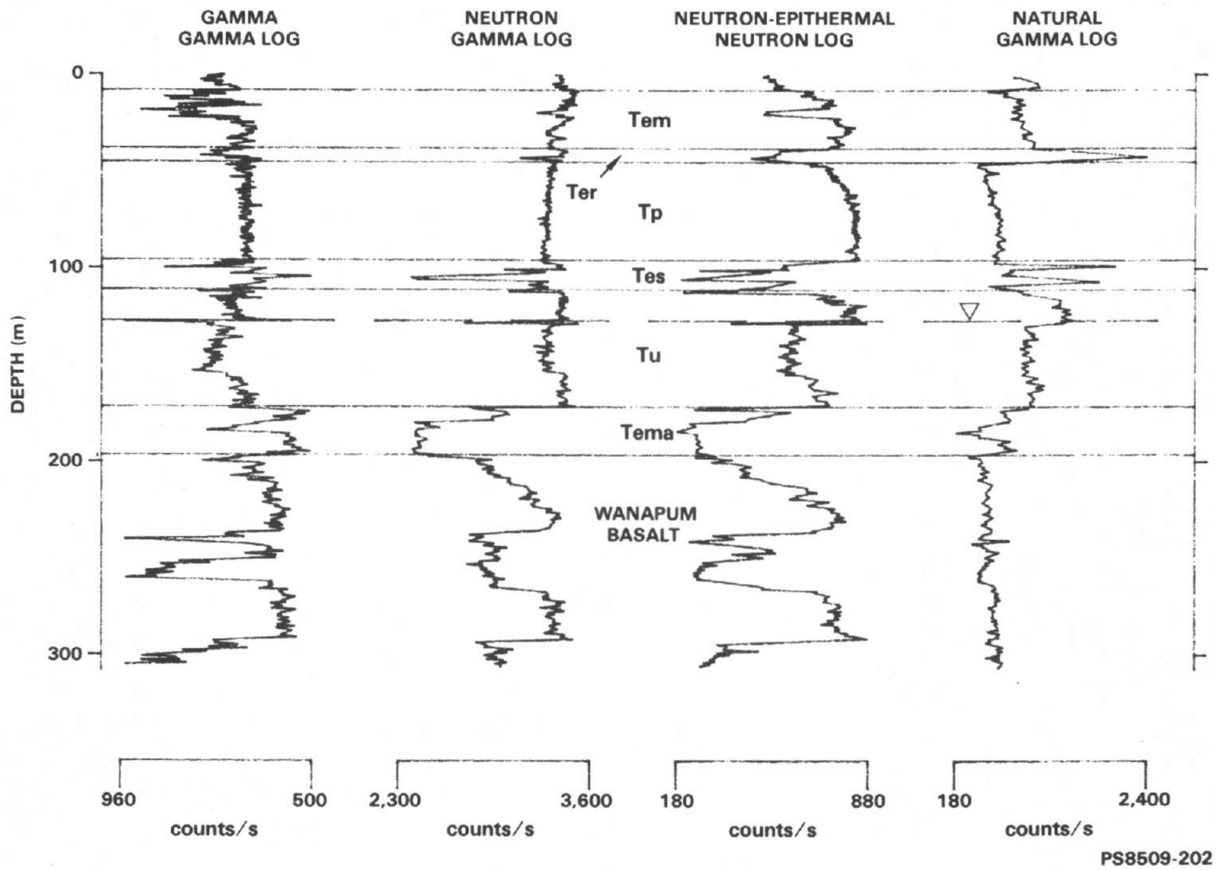

Figure B-6. Borehole Geophysical Logs of the Palmer Well. (See fig. B-1 for legend.)

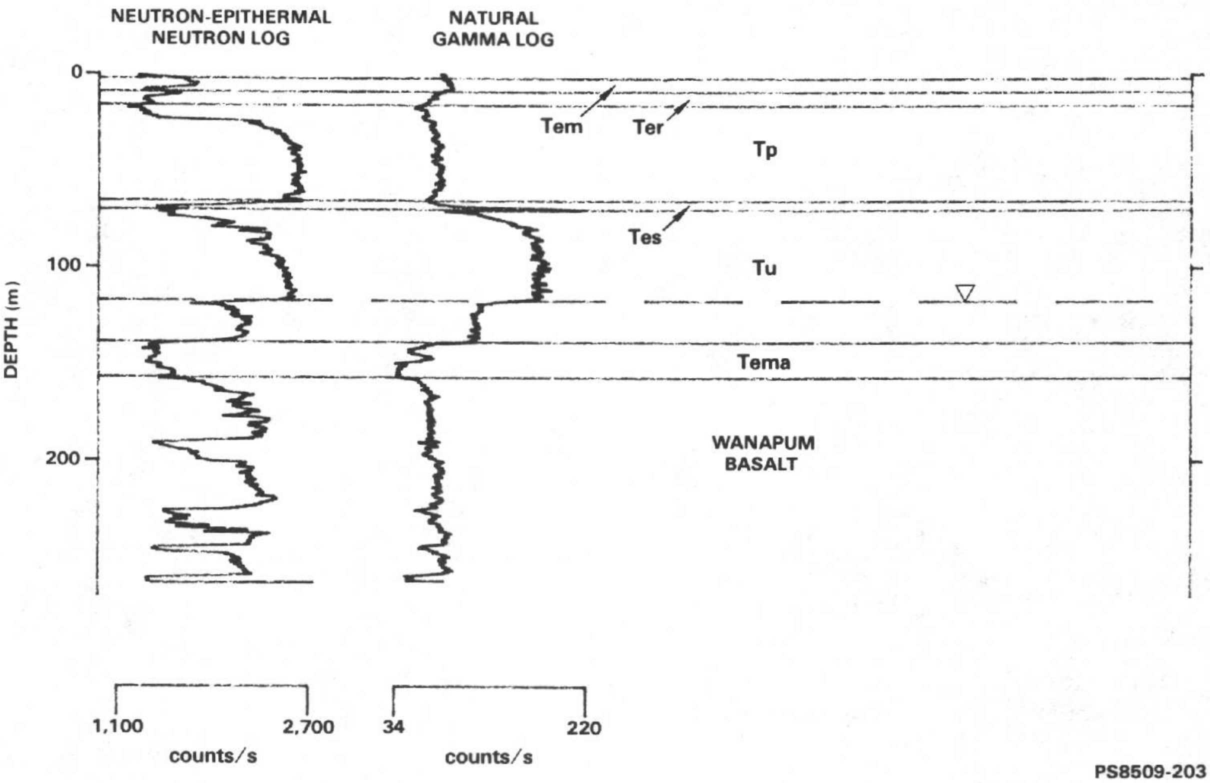

Figure B-7. Borehole Geophysical Logs of the Barber 2 Well. (See fig. B-1 for legend.)

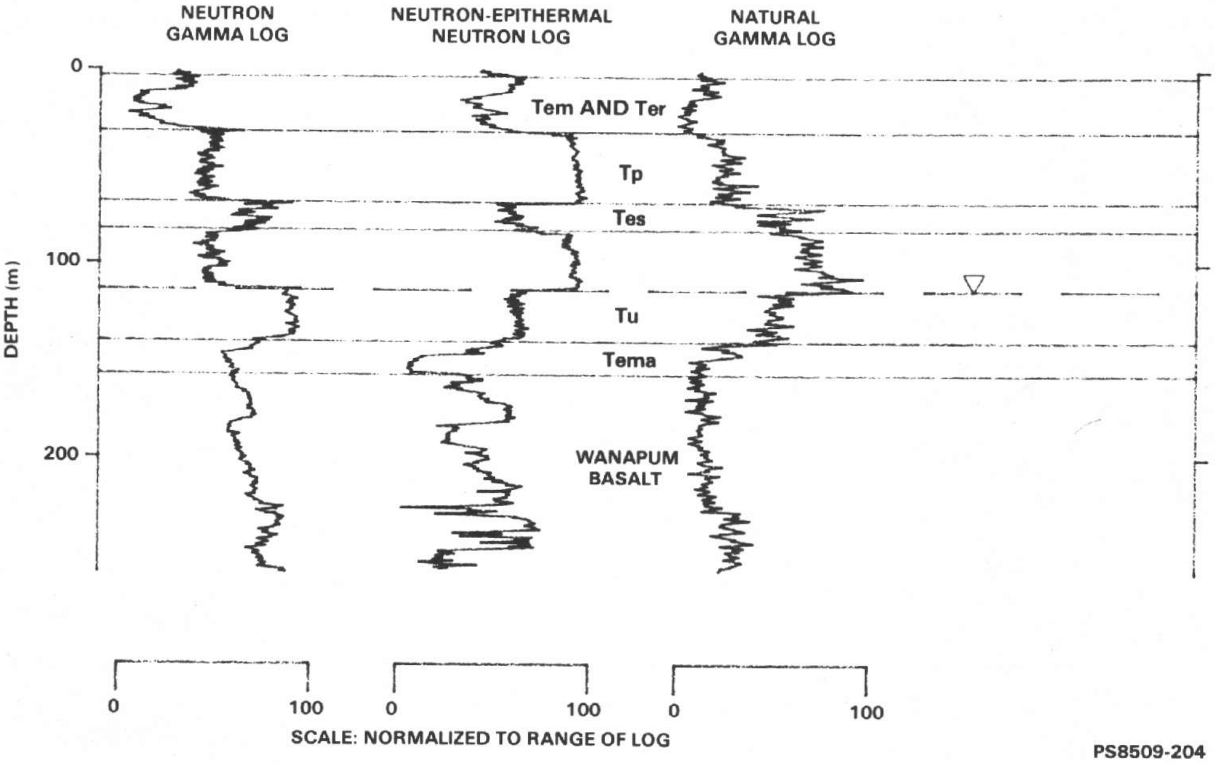

Figure B-8. Borehole Geophysical Logs of the Paterson Test Well. (See fig. B-1 for legend.)

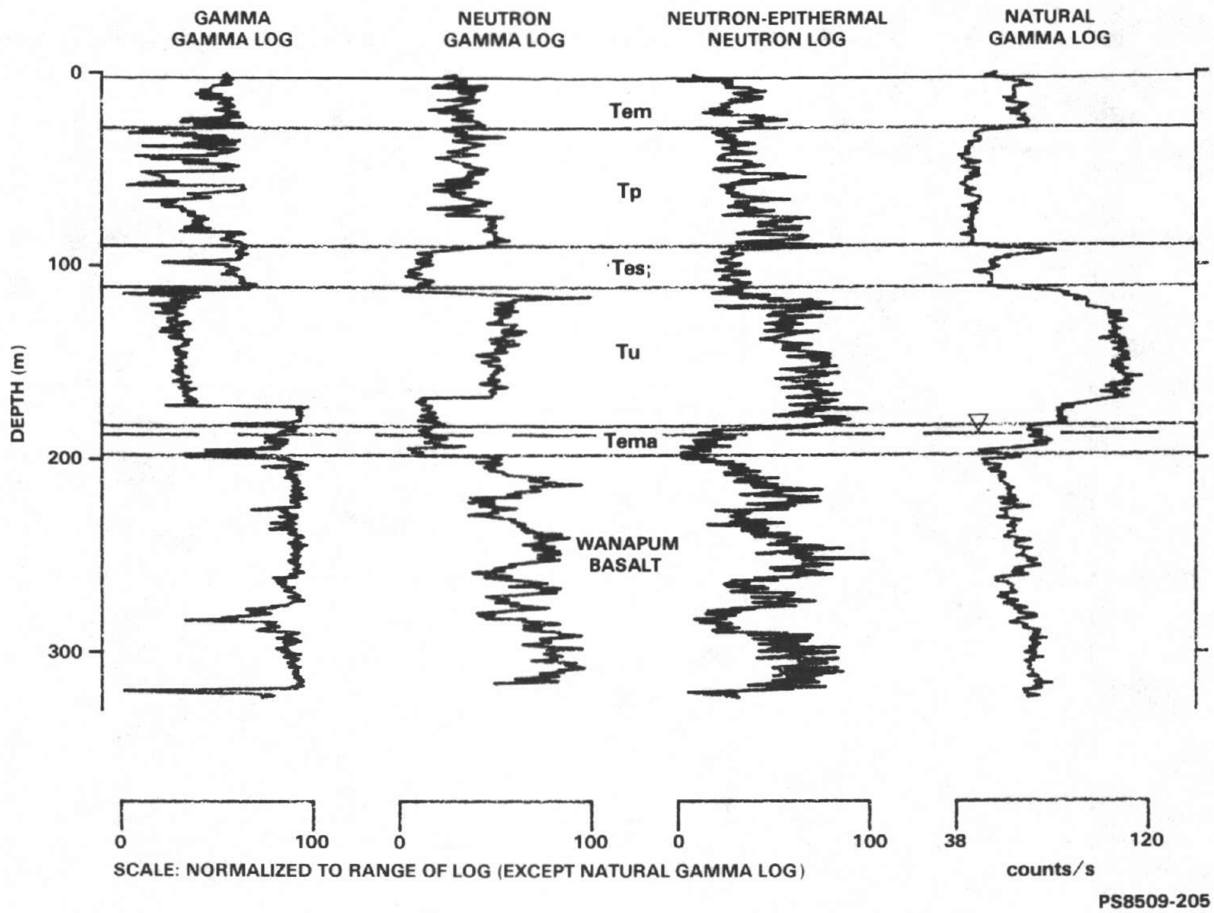

Figure B-9. Borehole Geophysical Logs of the Moon Well. (See fig. B-1 for legend.)

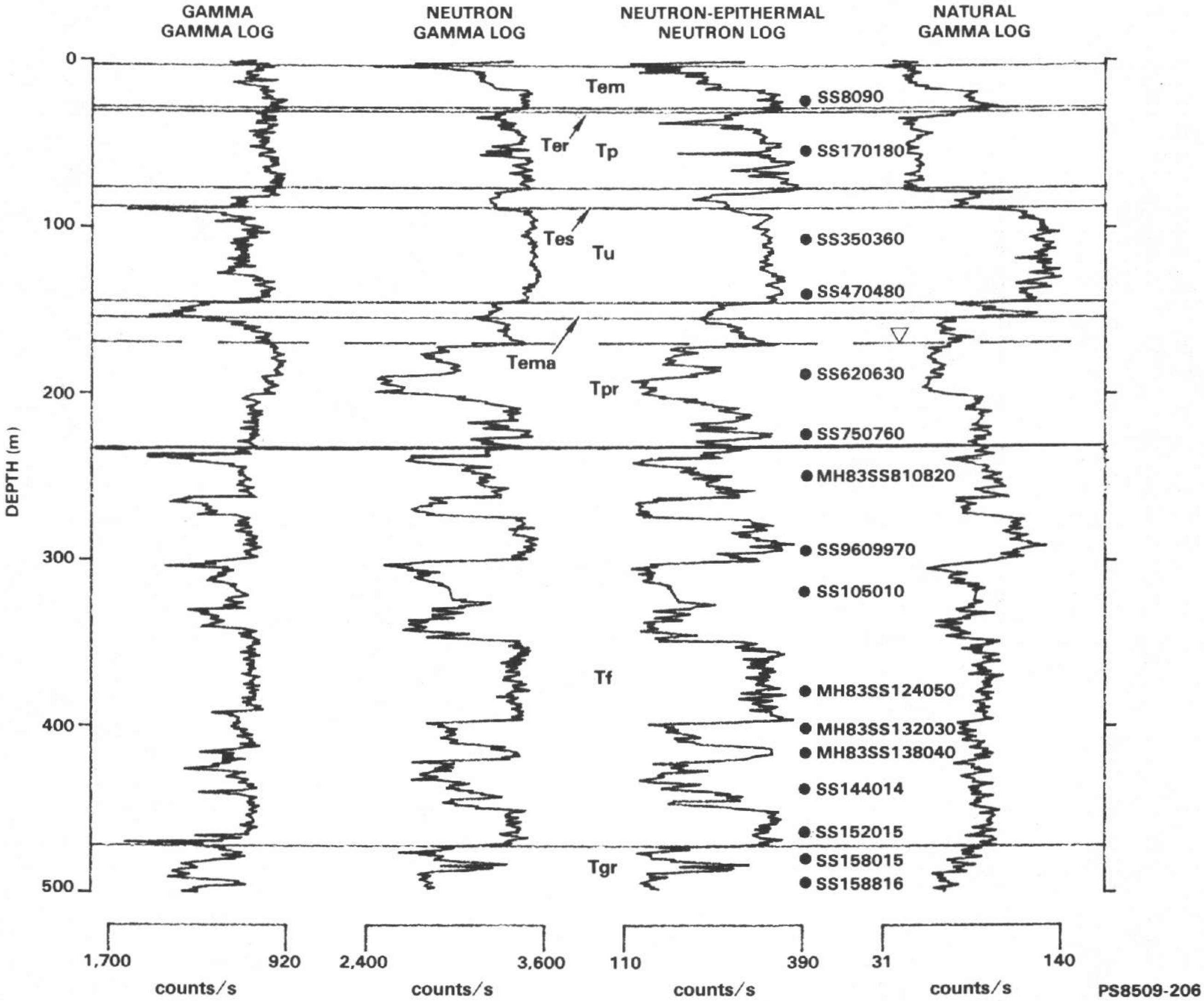

Figure B-10. Borehole Geophysical Logs of the Moon 1 Well. (See fig. B-1 for legend.)

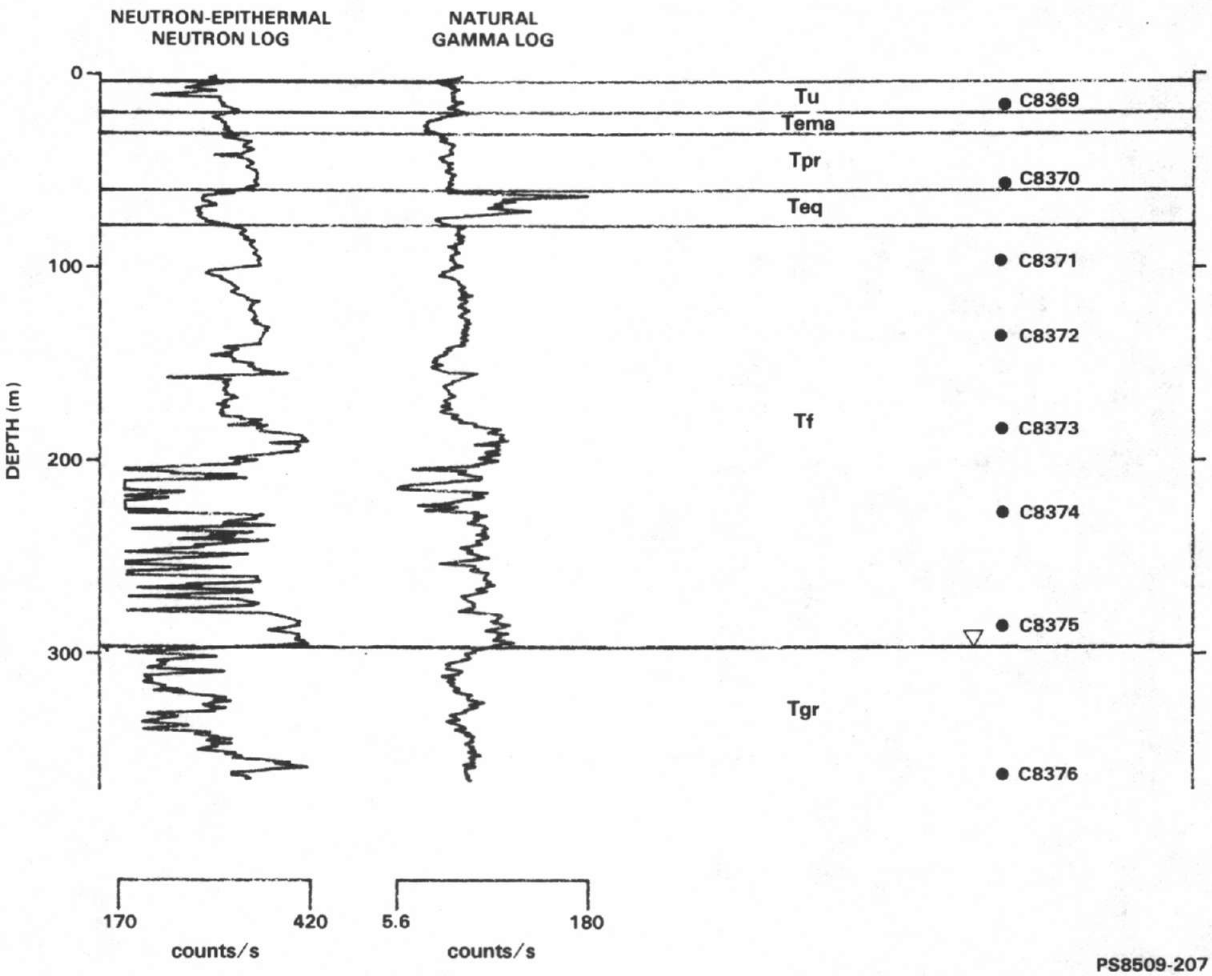

Figure B-11. Borehole Geophysical Logs of the Horse Heaven Test Well. (See fig. B-1 for legend.)

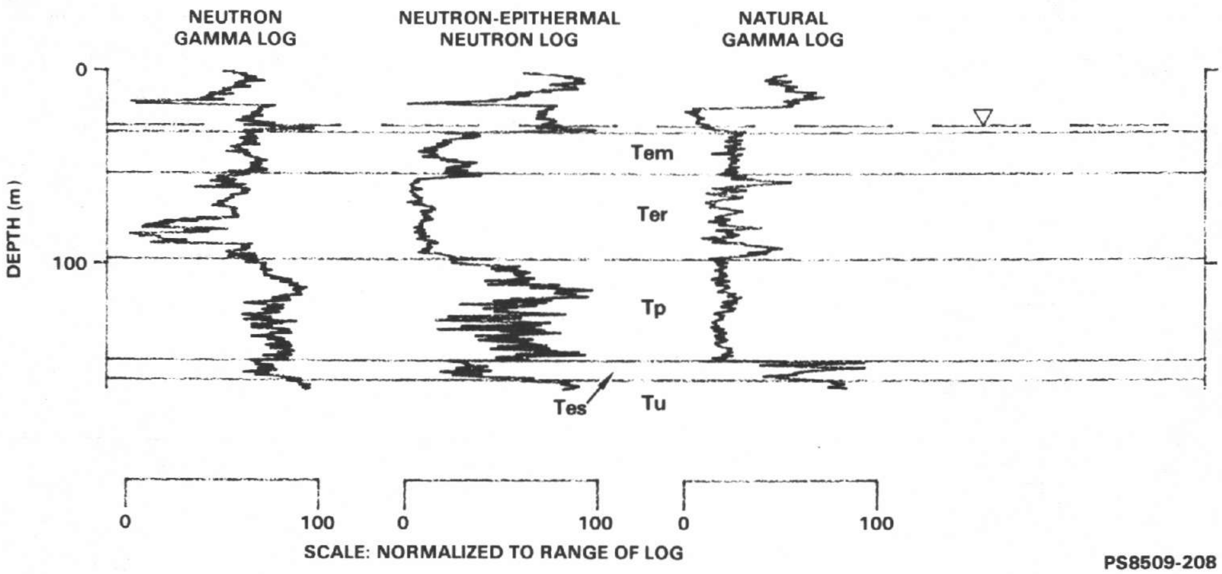

Figure B-12. Borehole Geophysical Logs of the Flower Well. (See fig. B-1 for legend.)

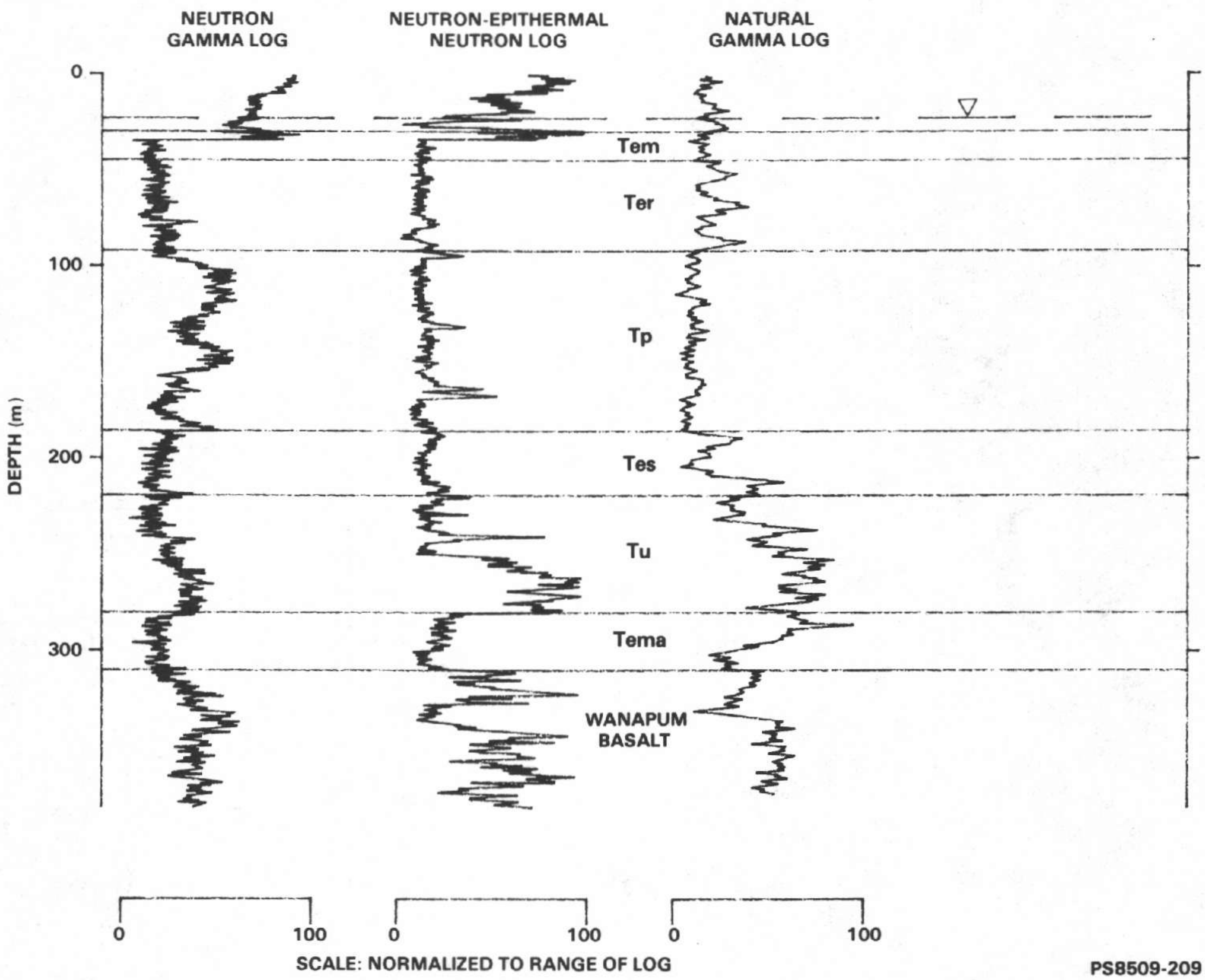

Figure B-13. Borehole Geophysical Logs of the Prosser Municipal Well. (See fig. B-1 for legend.)

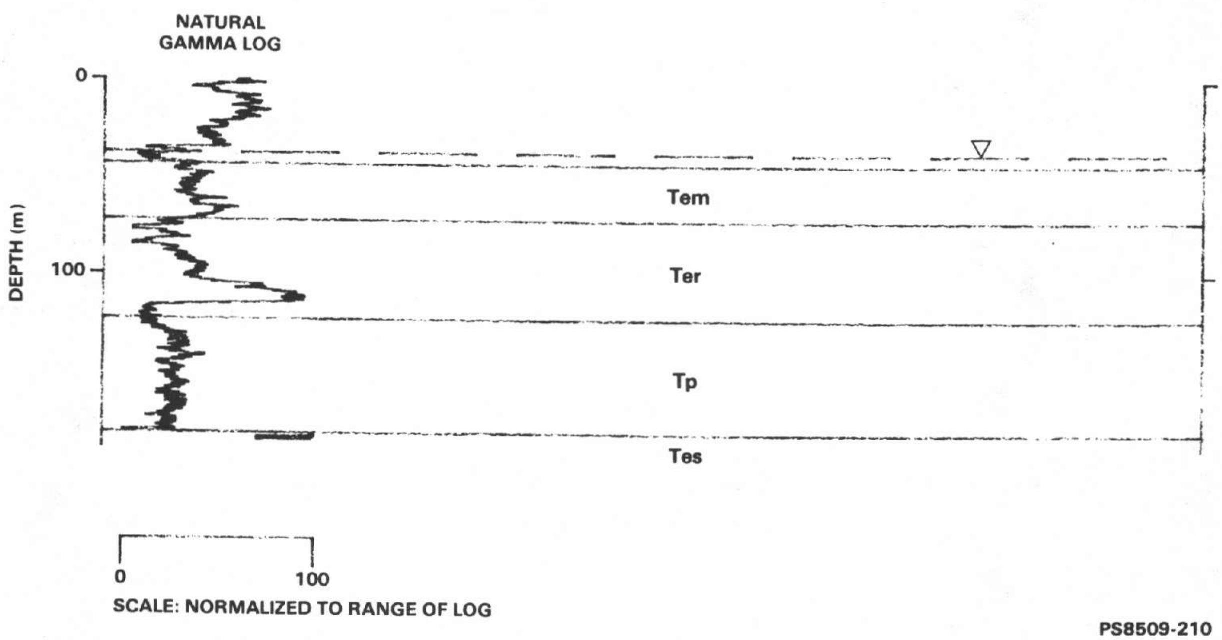

Figure B-14. Borehole Geophysical Logs of the Long Well. (See fig. B-1 for legend.)

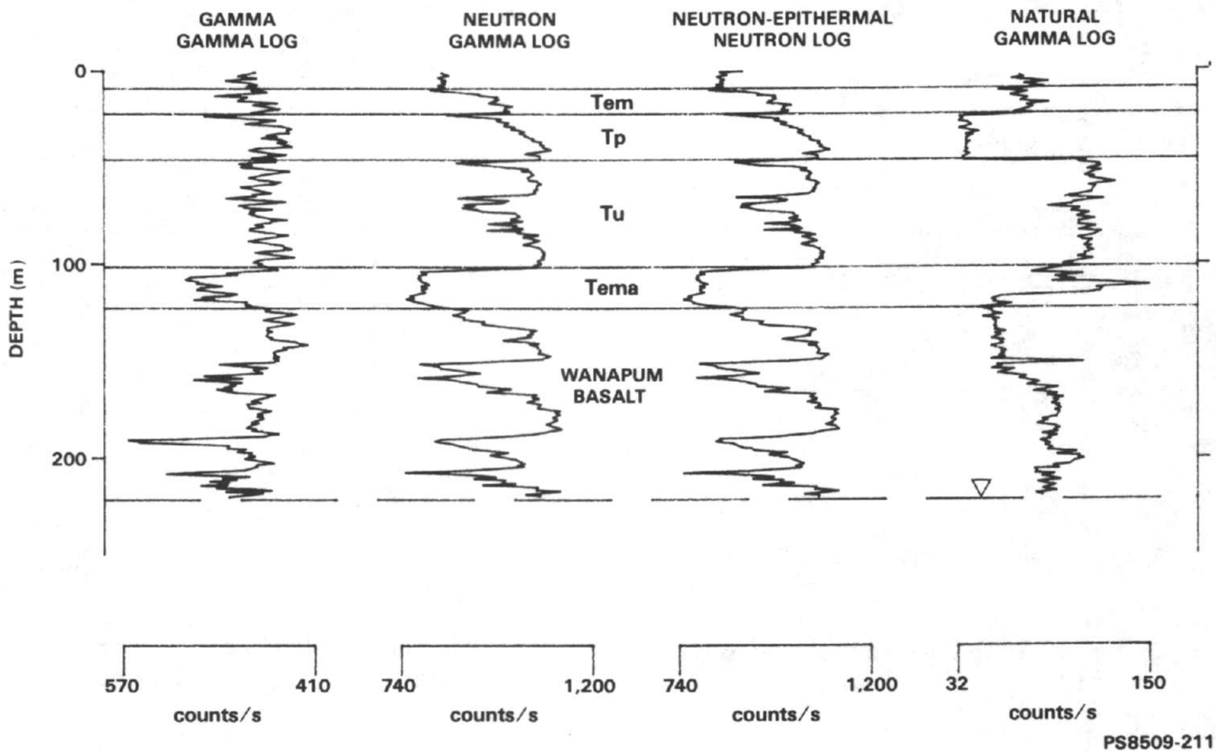

Figure B-15. Gorehole Geophysical Logs of the Smith Well. (See fig. B-1 for legend.)

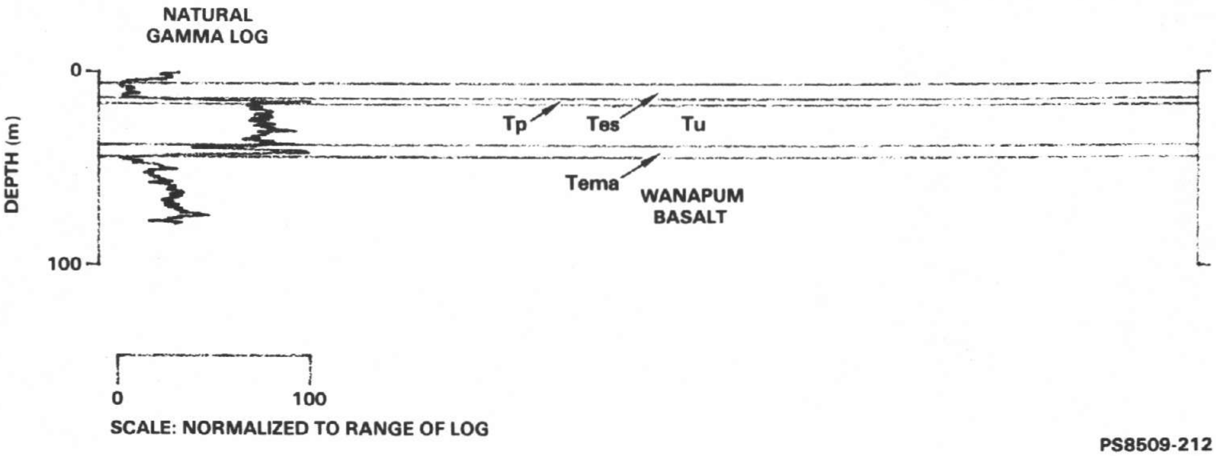

Figure B-16. Borehole Geophysical Log of the Miller Well. (See fig. B-1 for legend.)

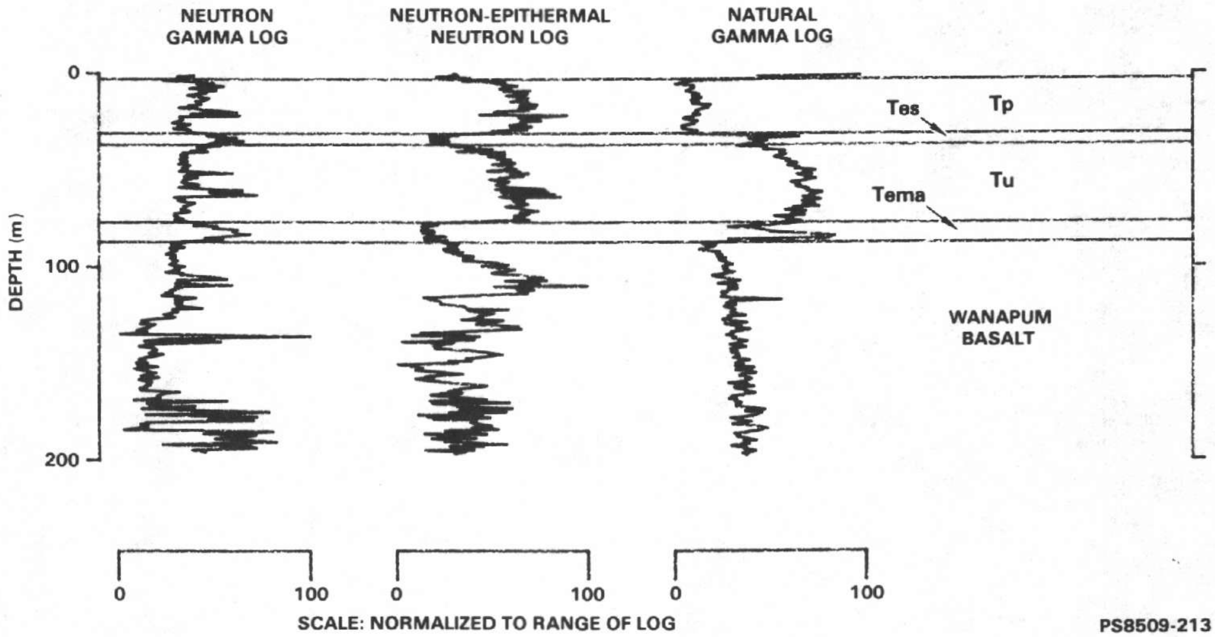

Figure B-17. Borehole Geophysical Logs of the Clodfelter Well. (See fig. B-1 for legend.)

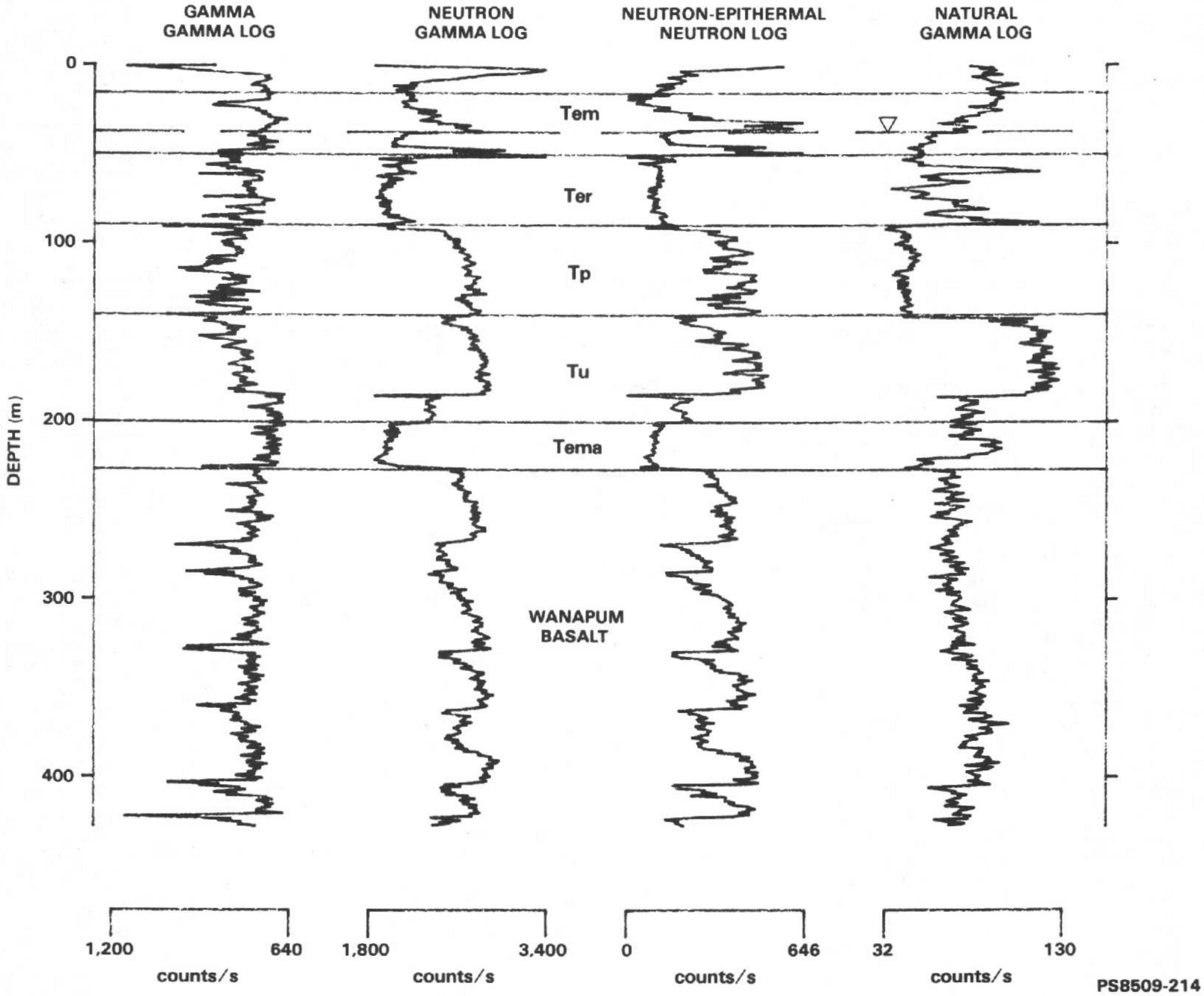

Figure B-18. Borehole Geophysical Logs of the Grandview City Well. (See fig. B-1 for legend).

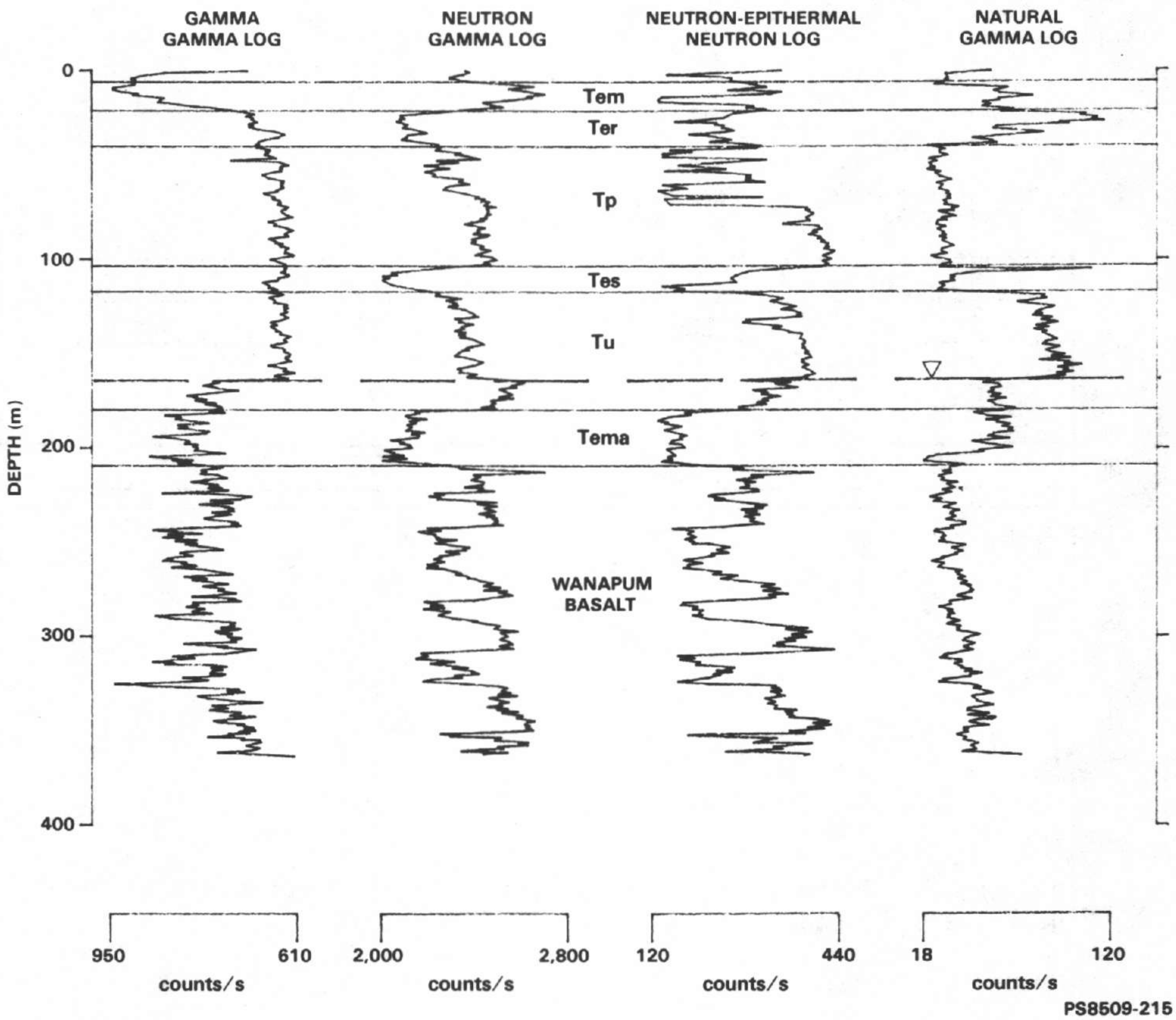

Figure B-19. Borehole Geophysical Logs of the Prosser Experiment Station Well. (See fig. B-1 for legend.)

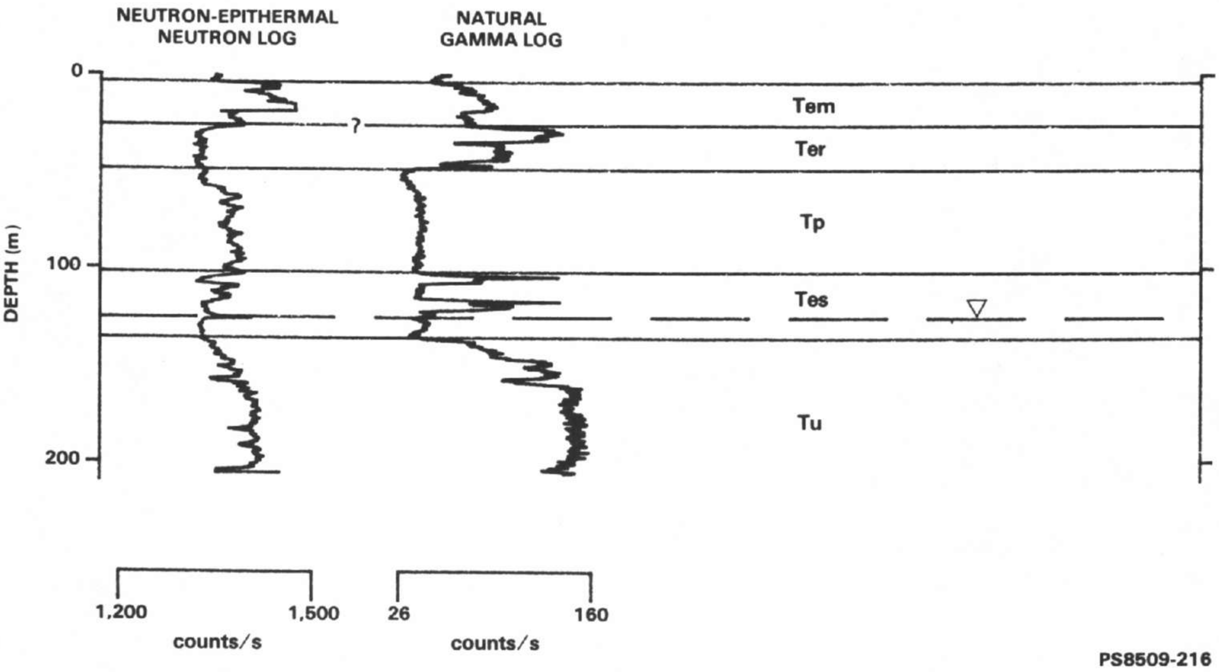

Figure B-20. Borehole Geophysical Logs of the Goroch Well. (See fig. B-1 for legend.)

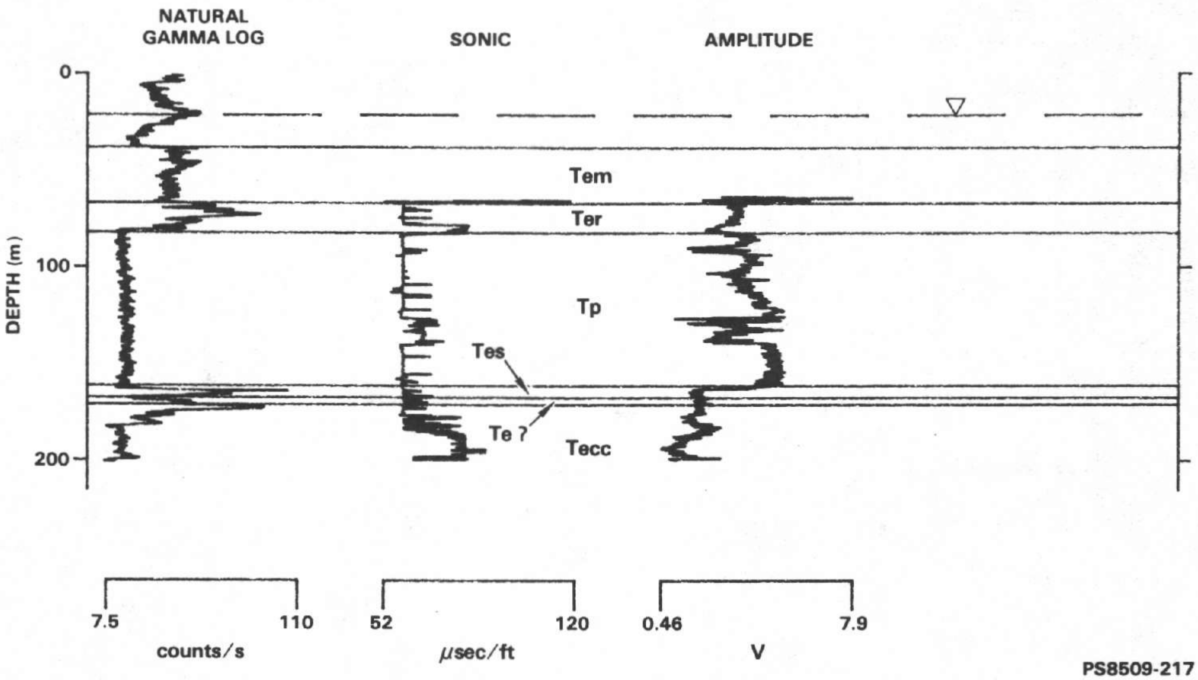

Figure B-21. Borehole Geophysical Logs of the Chandler Well. (See fig. B-1 for legend.)

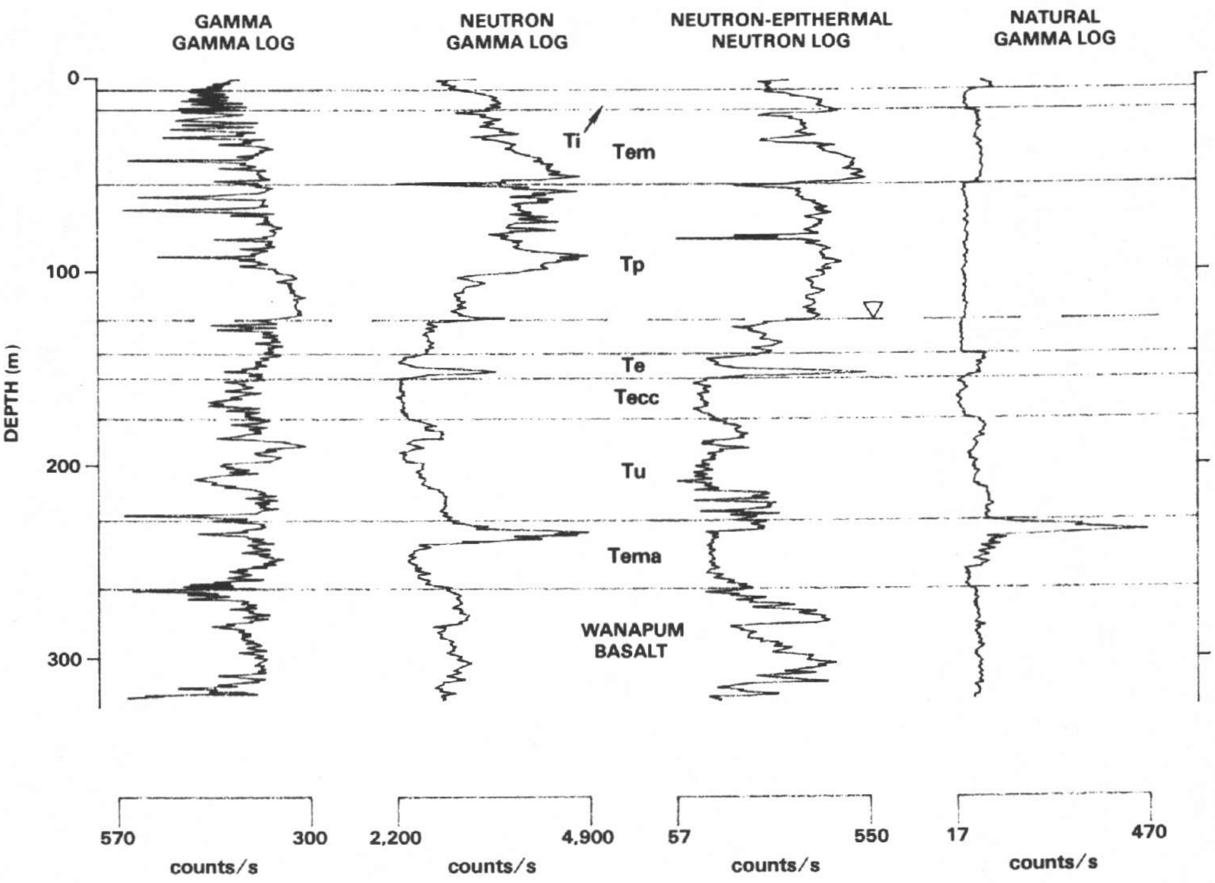

Figure B-22. Borehole Geophysical Logs of the 79-07 Well. (See fig. B-1 for legend)

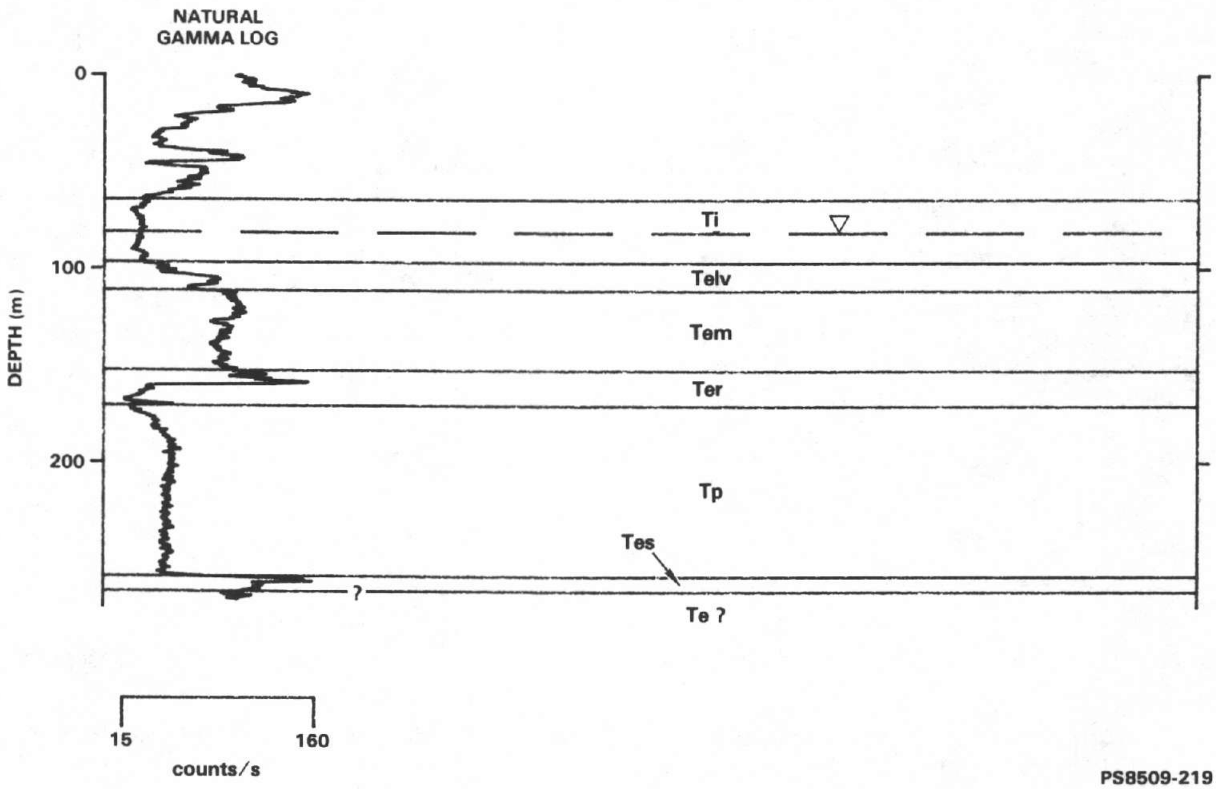

Figure B-23. Borehole Geophysical Log of the Bauder Well. (See fig. B-1 for legend.)

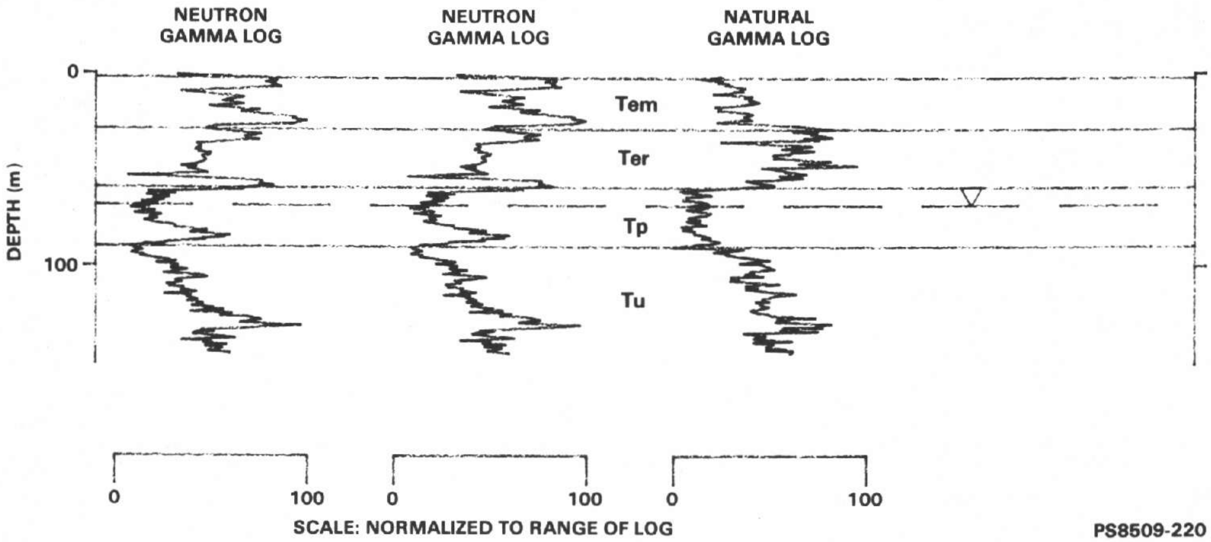

Figure B-24. Borehole Geophysical Logs of the Yakima Valley College Well. (See fig. B-1 for legend.)

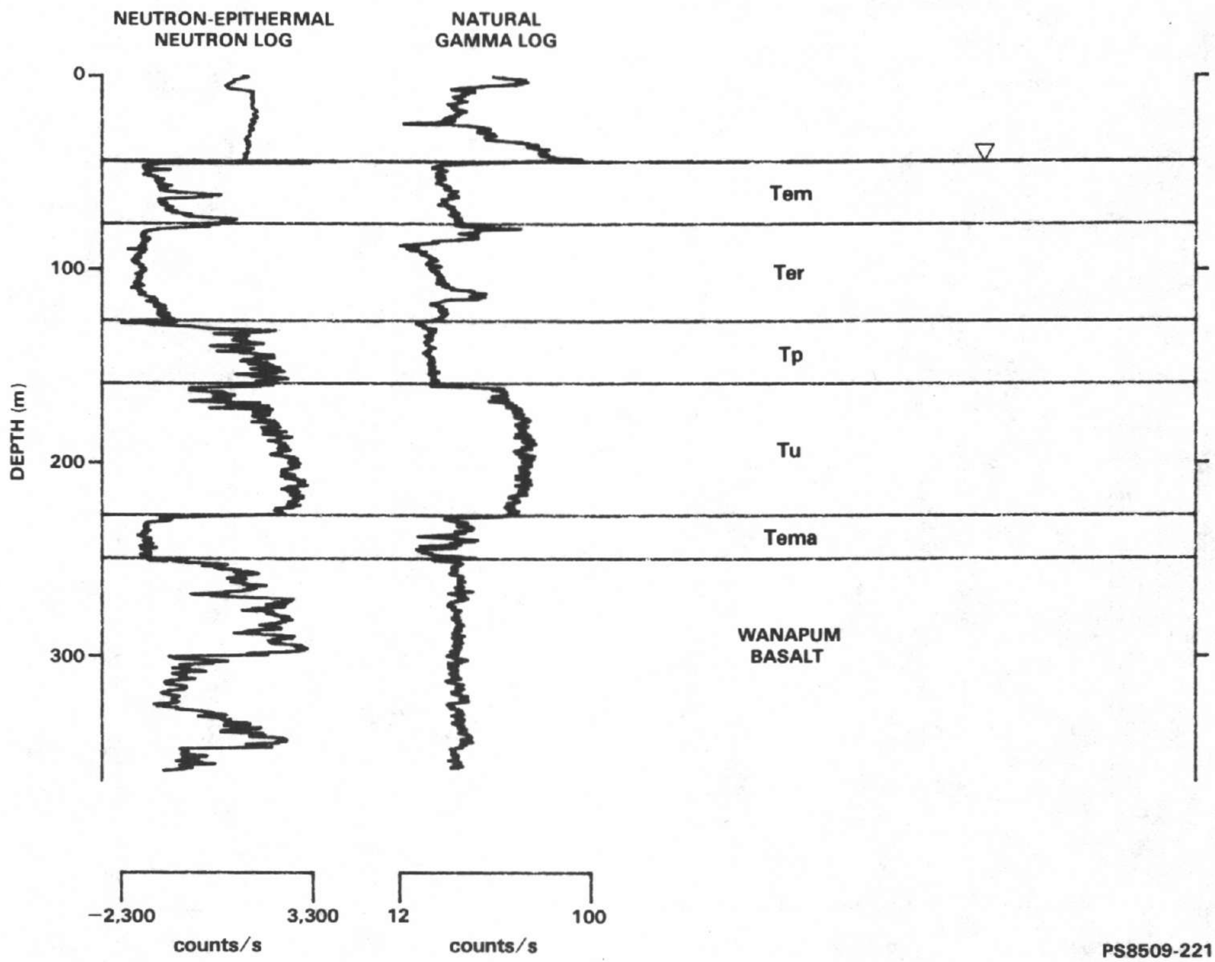

Figure B-25. Borehole Geophysical Logs of the Stout Well. (See fig. B-1 for legend.)

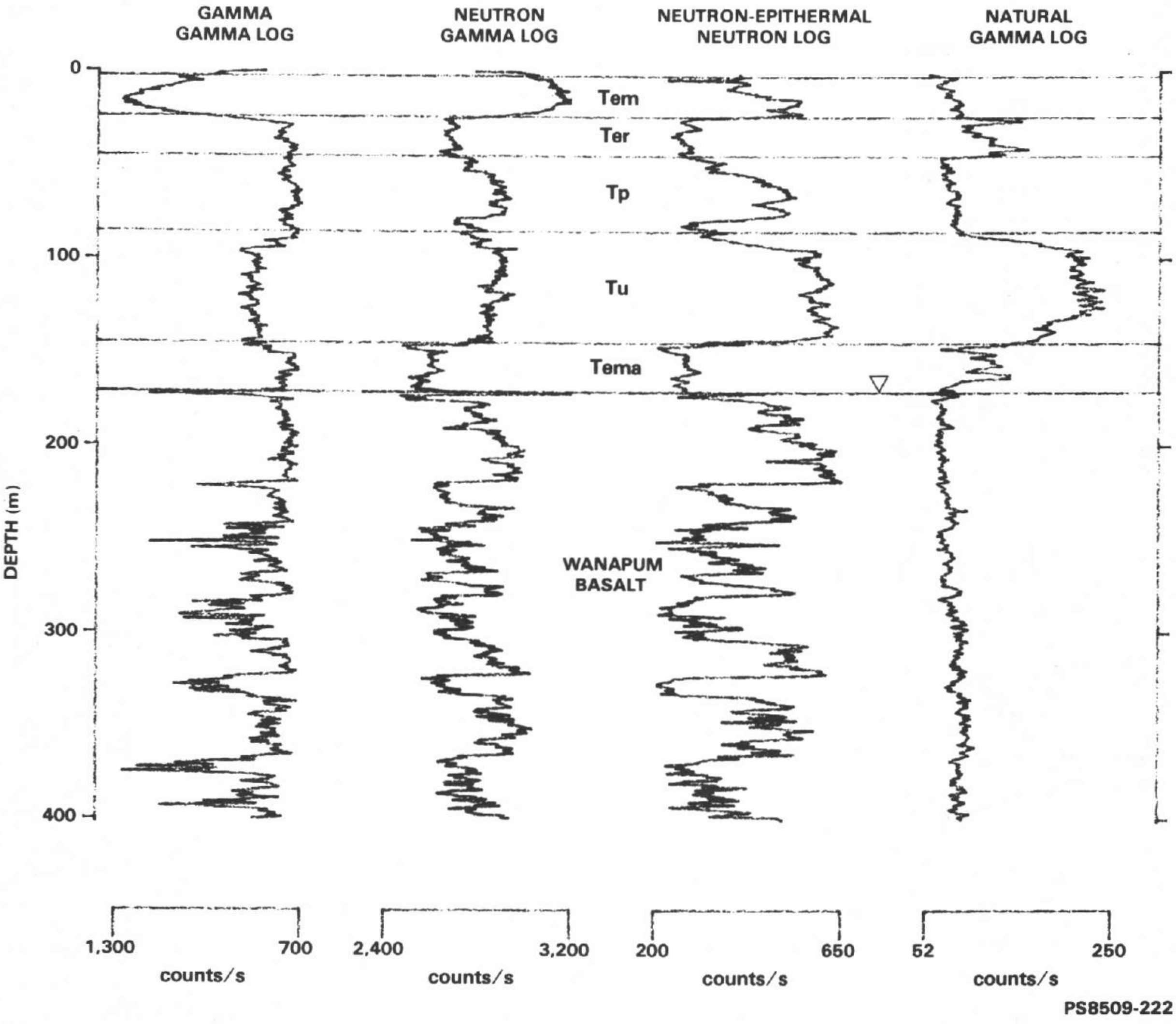

Figure B-26. Borehole Geophysical Logs of the Evans Well. (See fig. B-1 for legend.)

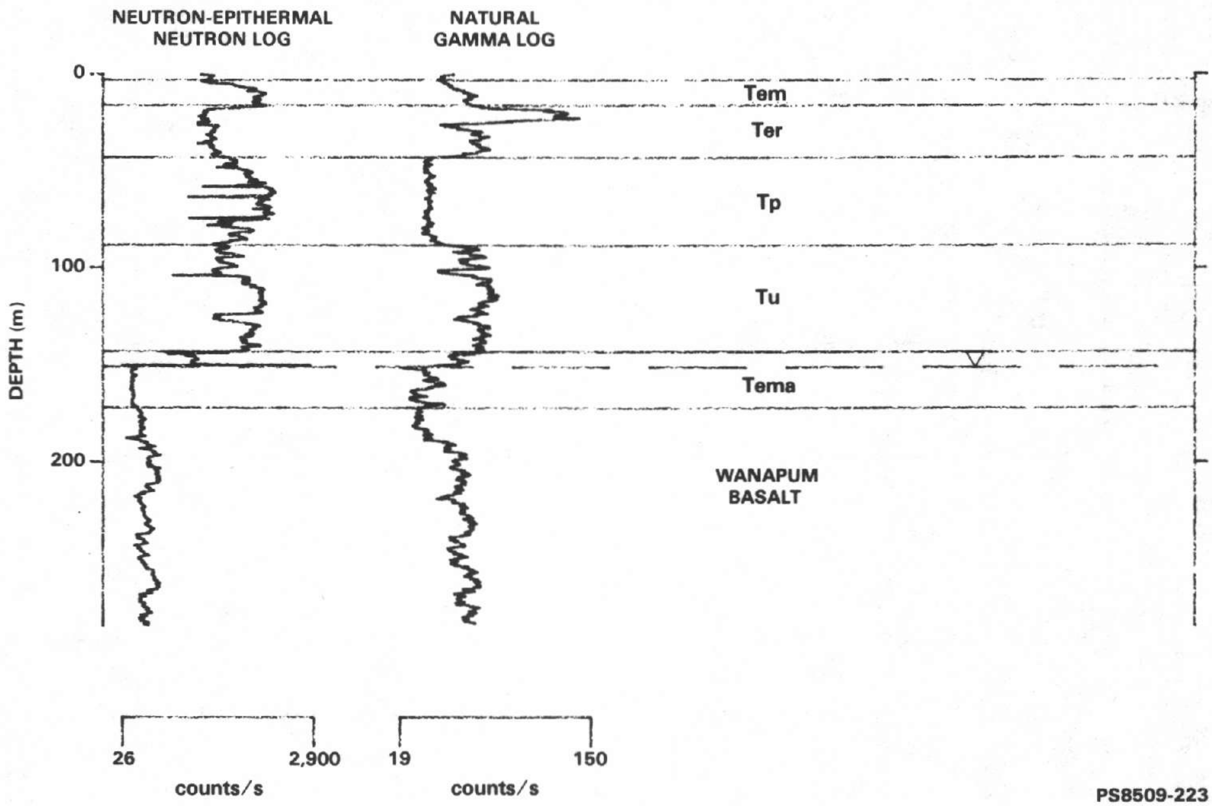

Figure B-27. Borehole Geophysical Logs of the White Well. (See fig. B-1 for legend.)

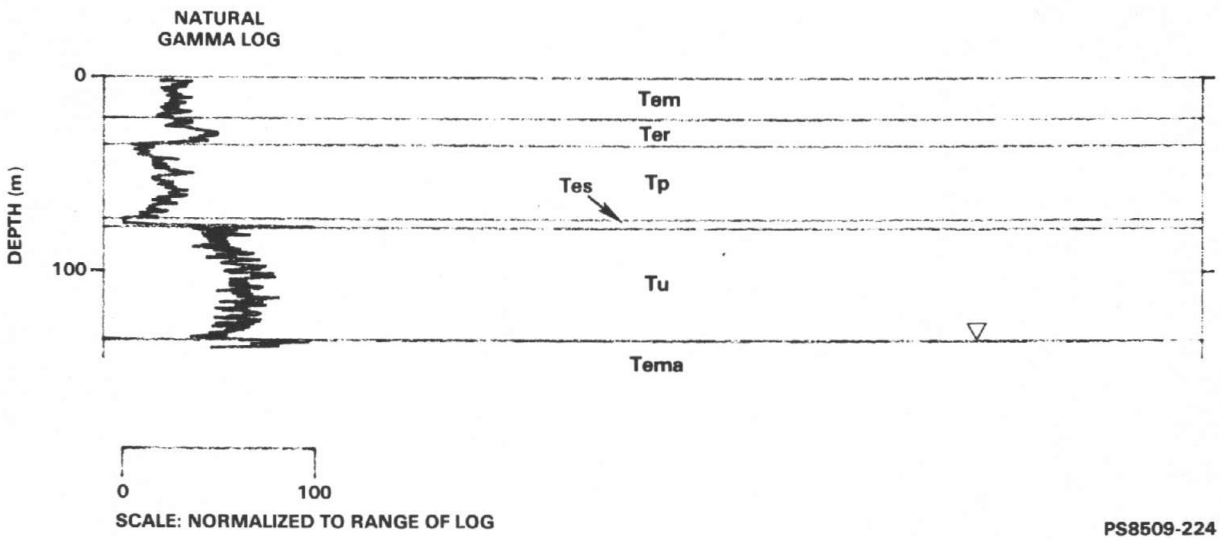

Figure B-28. Borehole Geophysical Log of the Aarons Well. (See fig. B-1 for legend.)

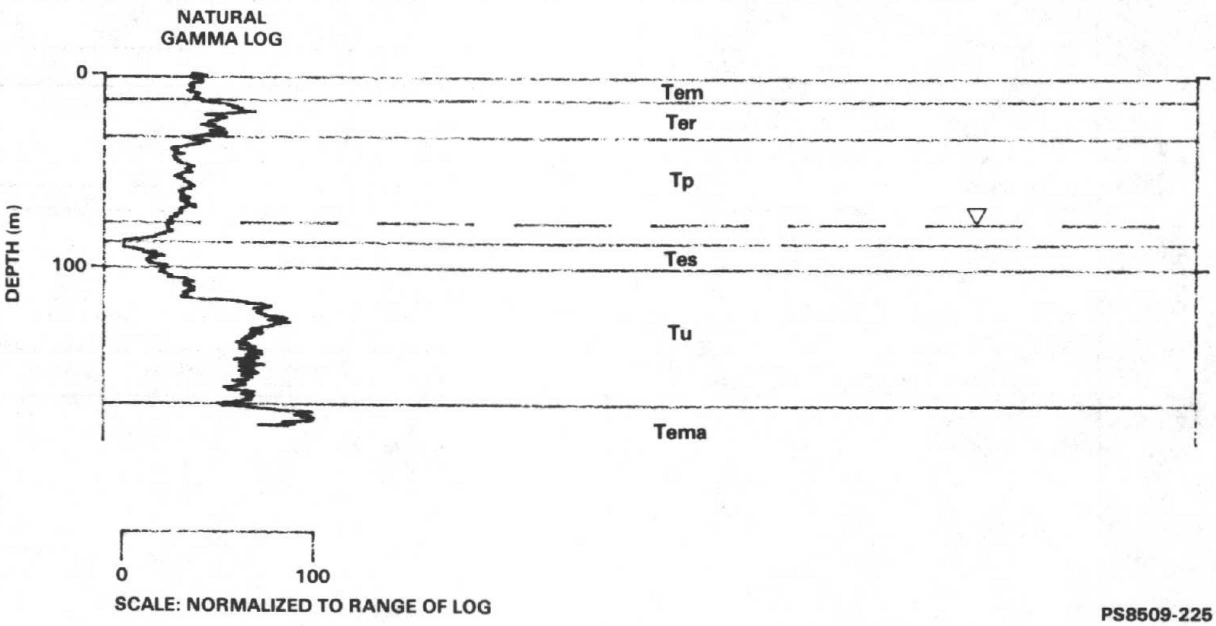

Figure B-29. Borehole Geophysical Log of the Nakamura Well. (See fig. B-1 for legend.)

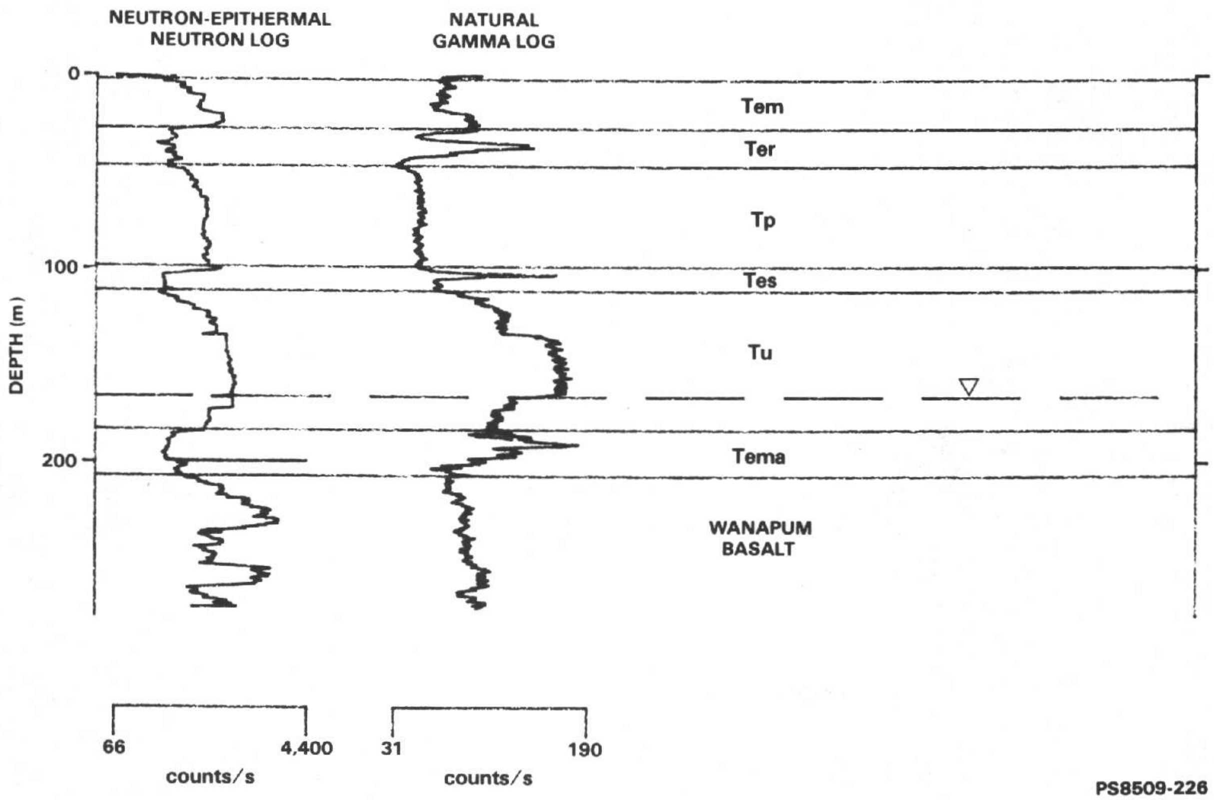

Figure B-30. Borehole Geophysical Logs of the J & R Orchards Well. (See fig. B-1 for legend.)

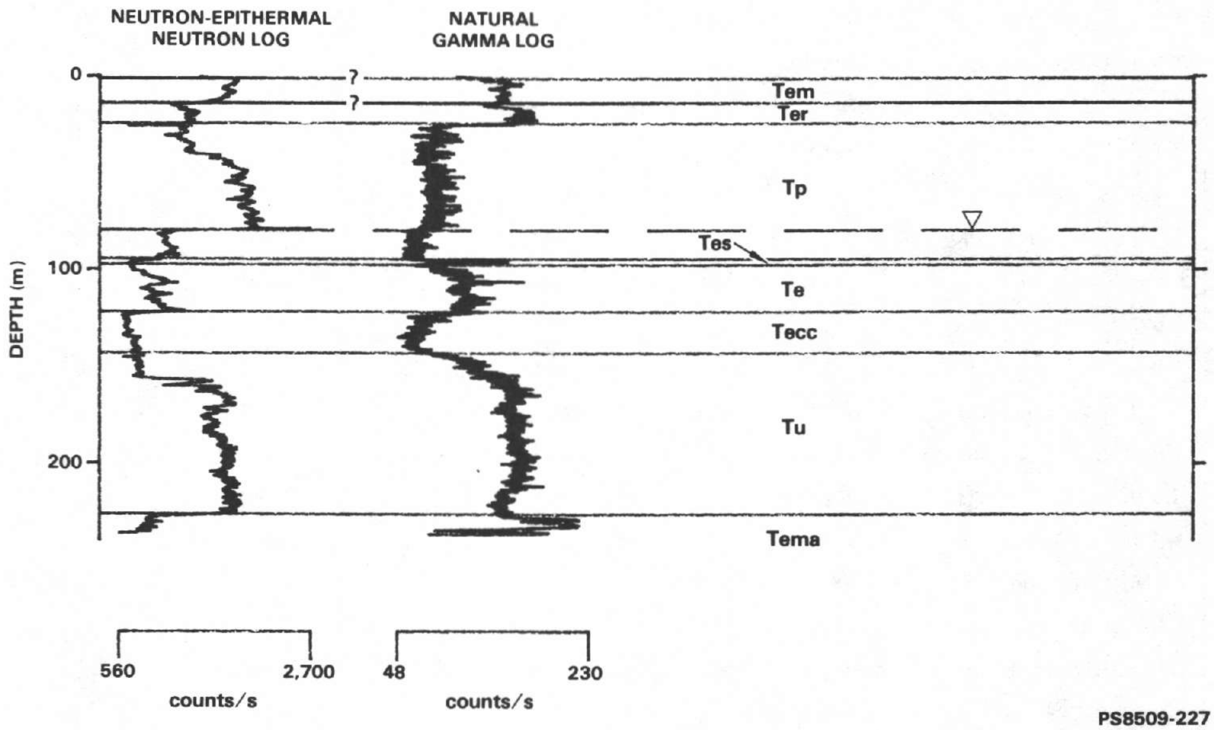

Figure B-31. Borehole Geophysical Logs of the Shaw Well. (See fig. B-1 for legend.)

Table B-1. Borehole Geophysical Logs Used In Study.

Location	Bottom-hole depth (m)	Well designation	Log source	Prior stratigraphic interpretation
T. 7 N., R. 22 E., sec. 23B	990.0	Sharpe	WSU	a
T. 7 N., R. 23 E., sec. 36R	245.4	Chesley	WSU	a
T. 7 N., R. 24 E., sec. 08D	329.5	Horrigan Farms	WSU	
T. 7 N., R. 25 E., sec. 23F	380.7	Palmer #2	WSU	
T. 7 N., R. 25 E., sec. 35M	307.2	Palmer	WSU	
T. 7 N., R. 25 E., sec. 36F	264.3	Barber #2	WSU	
T. 7 N., R. 25 E., sec. 36N	256.0	Paterson Test Well	WSU	b
T. 7 N., R. 26 E., sec. 05B	327.7	Moon	WSU	b
T. 7 N., R. 26 E., sec. 30R	159.4	Moon #1	WSU	
T. 7 N., R. 27 E., sec. 36A	368.5	Horse Heaven Test Well	WSU	e
T. 8 N., R. 22 E., sec. 11J	161.5	Flower	WSU	d
T. 8 N., R. 24 E., sec. 01J	381.0	Prosser Municipal Well	WSU	c
T. 8 N., R. 24 E., sec. 10N	188.1	Long	USGS	
T. 8 N., R. 27 N., sec. 29Q	221.0	Smith	WSU	
T. 8 N., R. 28 E., sec. 28N	508.4	Miller	WSU	
T. 8 N., R. 28 E., sec. 34C	197.2	Clodfelter	WSU	b
T. 9 N., R. 23 E., sec. 22J	429.5	Grandview City	WSU	
T. 9 N., R. 25 E., sec. 06B	366.4	Prosser Experiment Station	WSU	
T. 9 N., R. 25 E., sec. 07J	206.7	Goroch	WSU	
T. 9 N., R. 26 E., sec. 20A	209.4	Bauder (Chandler)	Rockwell	
T. 9 N., R. 27 E., sec. 25M	322.2	79-07	Rockwell	
T. 9 N., R. 28 E., sec. 34H	271.0	Bauder	Rockwell	
T. 10 N., R. 23 E., sec. 04L	150.3	Yakima Valley College	Rockwell	
T. 10 N., R. 23 E., sec. 17B	359.7	Stout	Rockwell	c
T. 10 N., R. 23 E., sec. 36A	401.1	Evans	Rockwell	c
T. 10 N., R. 23 E., sec. 36G	283.5	White	Rockwell	
T. 10 N., R. 24 E., sec. 24F	140.2	Aarons	USGS	
T. 10 N., R. 25 E., sec. 25E	184.1	Nakamura	USGS	
T. 10 N., R. 25 E., sec. 33N	275.5	J & R Orchards	WSU	
T. 10 N., R. 26 E., sec. 27Q	236.2	Shaw	WSU	c
T. 10 N., R. 28 E., sec. 14F	1,079.0	DDH-3	Rockwell	f
T. 11 N., R. 28 E., sec. 35F	1,293.2	DC-15	Rockwell	f

NOTE: WSU = Washington State University
USGS = U.S. Geological Society
Rockwell = Rockwell Hanford Operations.

a. Brown 1978.
b. Crosby et al,.1972.
c. Lobdell and Brown 1977.
d. Washington State University, (Albrook Laboratory).
e. Washington State Department of Ecology.
f. Landon 1985.

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APPENDIX C

DESCRIPTIVE GEOLOGIC CROSS SECTIONS

The cross sections shown in this appendix (fig. C-1 through C-6) depict as clearly as possible the structure that can be observed in the field. These data were used to construct the cross sections interpreted within the Structure section (section 3.0 of basic text).

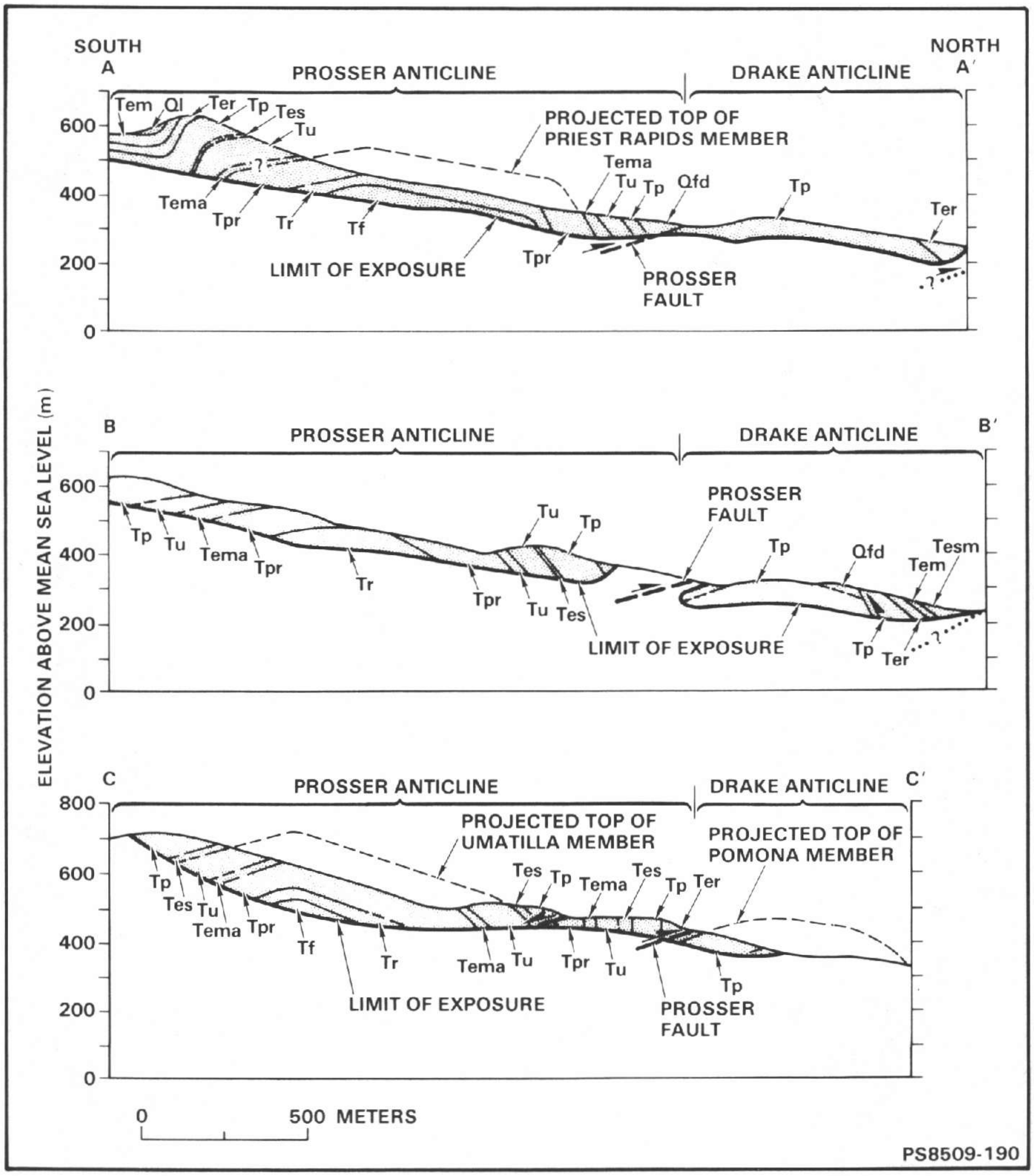

Figure C-1. Descriptive Geologic Cross Sections through the Horse Heaven Hills Uplift within the Byron Segment (see fig. 15 for location and fig. 17 for legend).

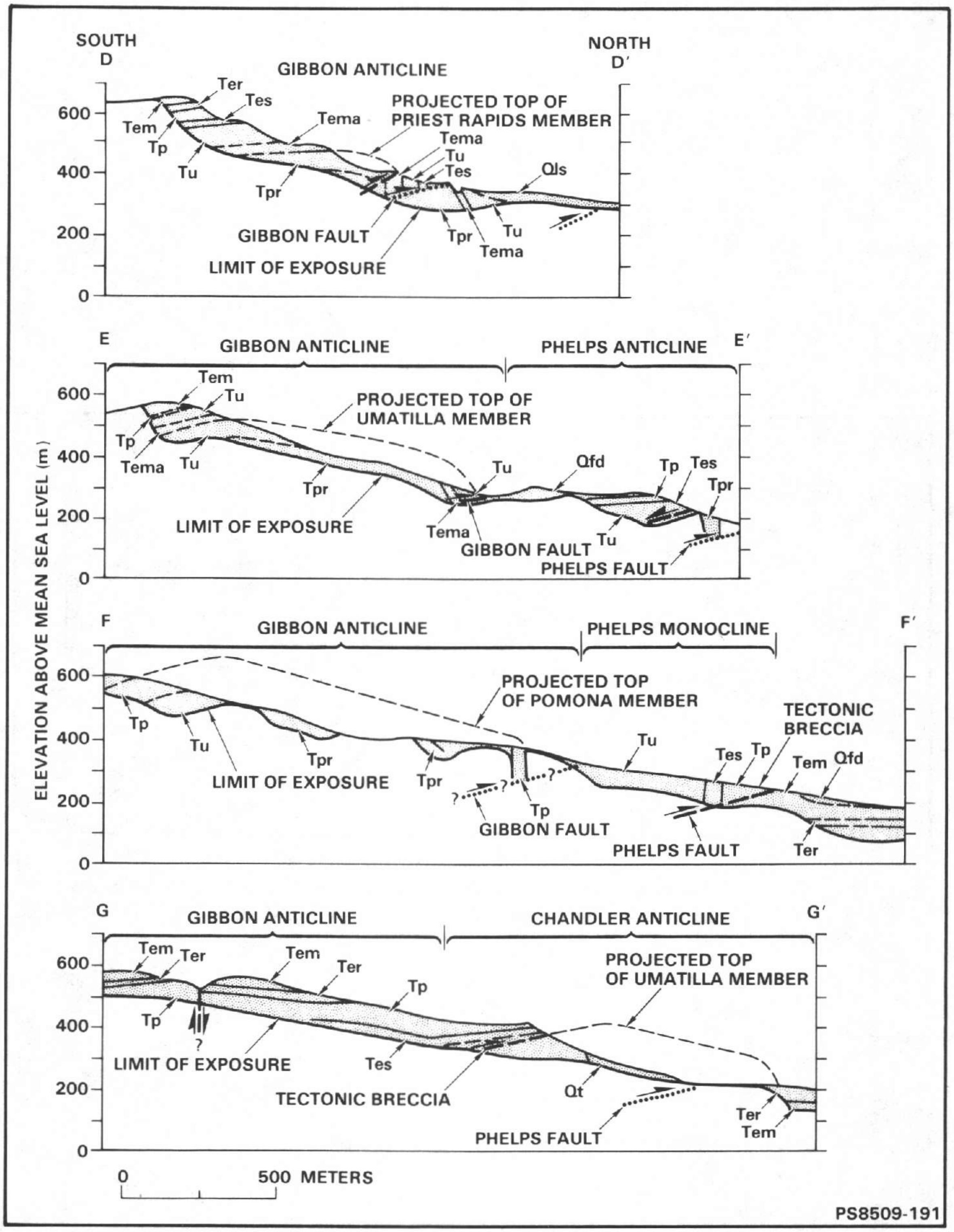

Figure C-2. Descriptive Geologic Cross Sections through the Horse Heaven Hills Uplift within the Gibbon Segment (see fig. 15 location and fig. 17 for legend).

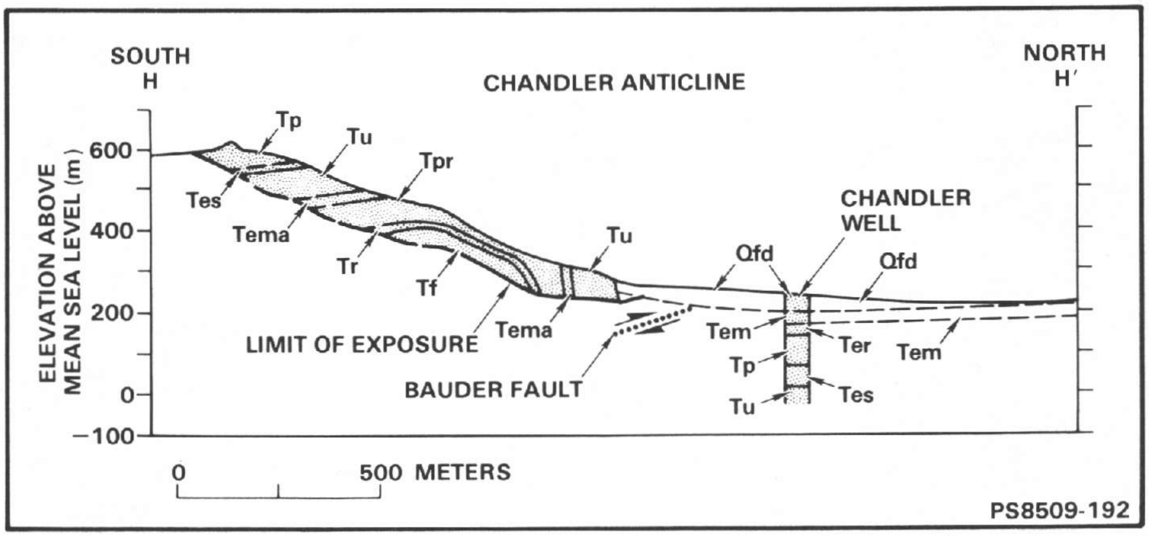

Figure C-3. Descriptive Geologic Cross Section through the Horse Heaven Hills Uplift within the Chandler Segment (see fig. 15 for location and fig. 17 for legend).

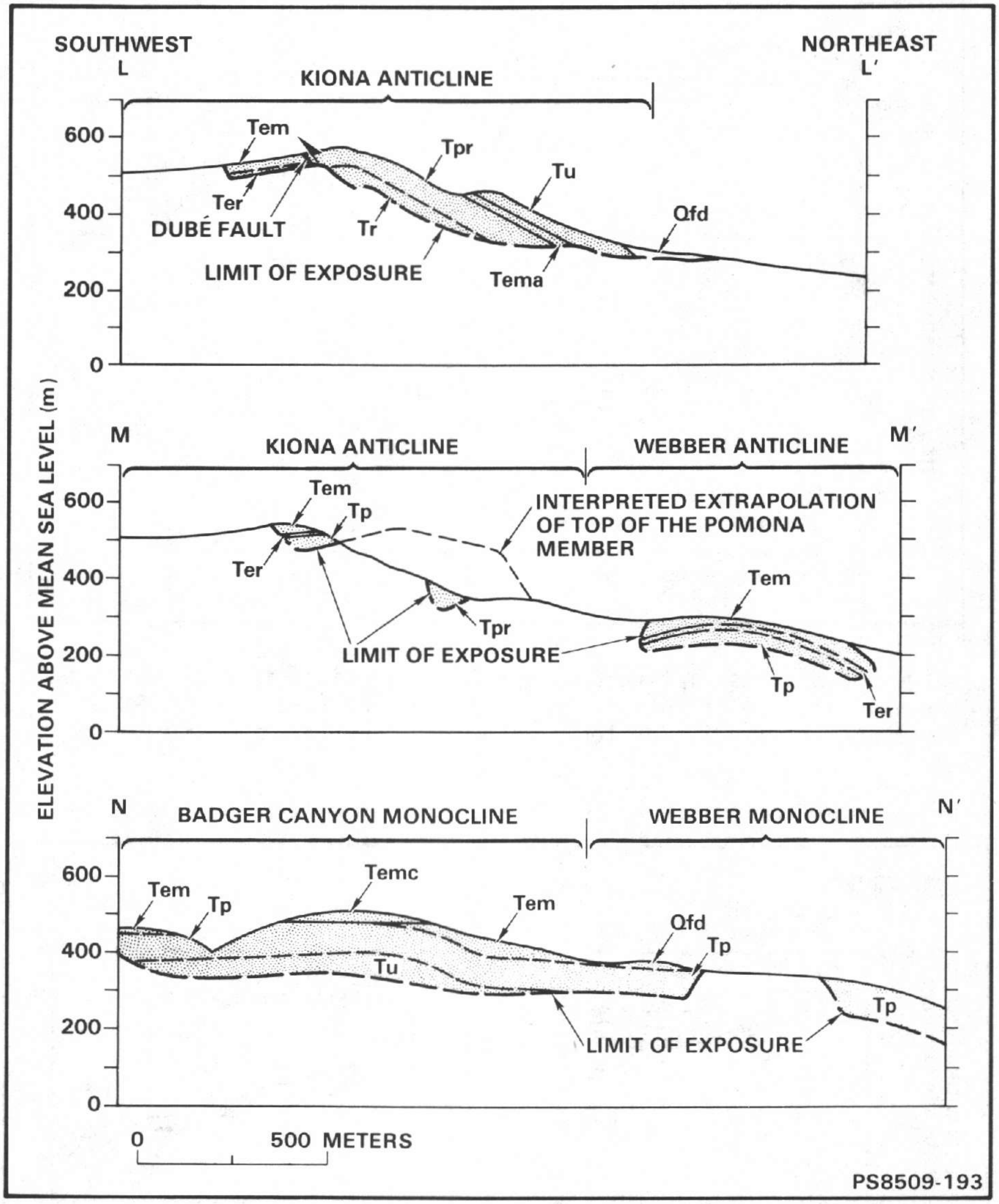

Figure C-4. Descriptive Geologic Cross Sections through the Horse Heaven Hills Uplift within the Webber Segment (see fig. 15 for location and fig. 17 for legend).

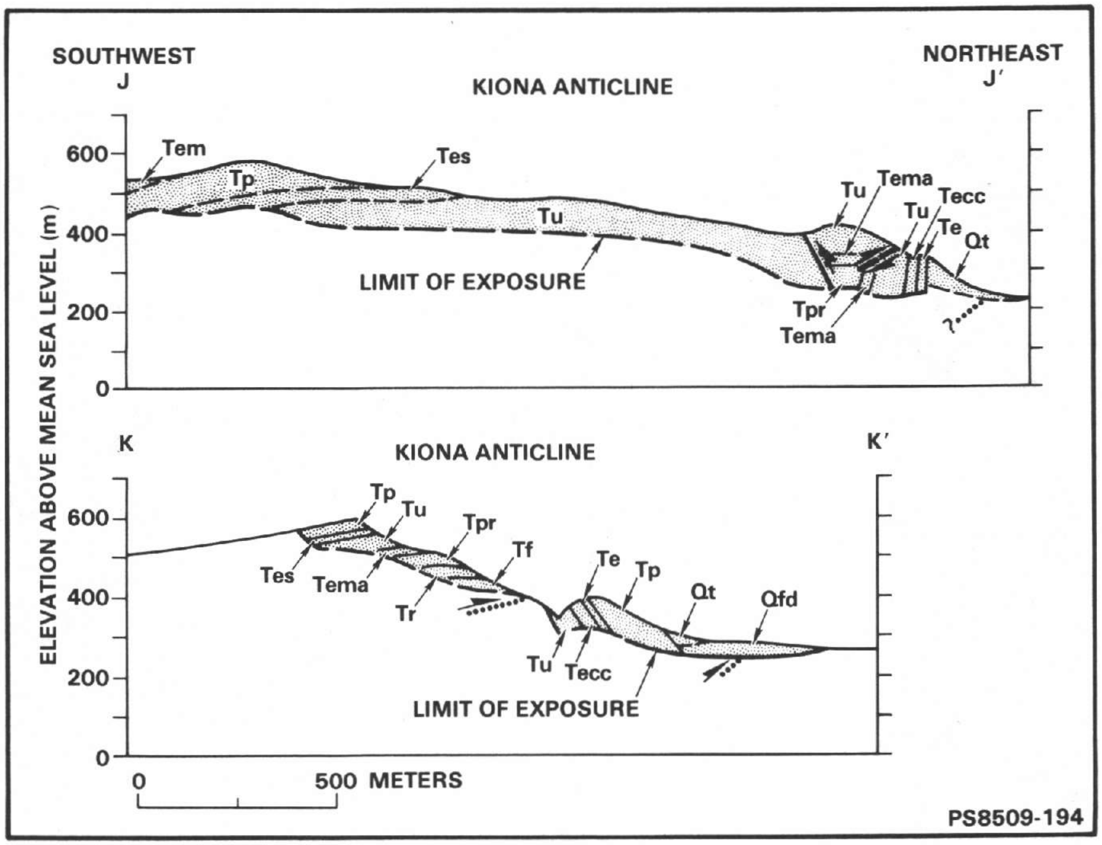

Figure C-5. Descriptive Geologic Cross Sections through the Horse Heaven Hills Uplift within the Kiona Segment (see fig. 15 for location and fig.17 for legend).

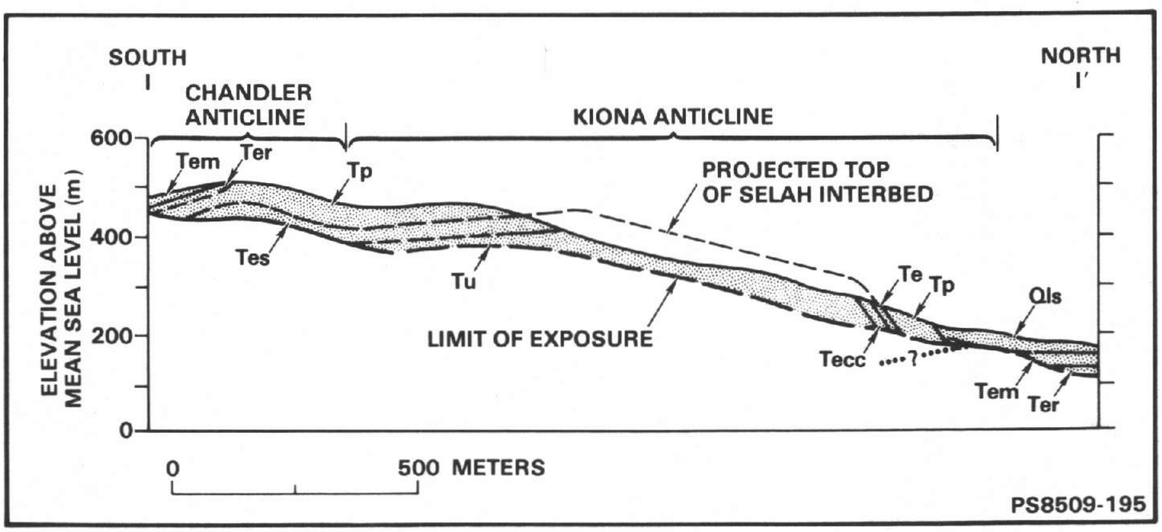

Figure C-6. Descriptive Geologic Cross Section through the Horse Heaven Hills Uplift within the Junction Segment (see fig. 15 for location and fig. 17 for legend).

APPENDIX D

ASSUMPTIONS USED IN CALCULATING GROWTH RATES

SECTION THICKNESSES

According to Reidel (1984), the following assumptions must be made when using thicknesses of basalt flows to calculate rates of growth: (1) Columbia River Basalt Group flows had low viscosities (Waters 1961, Shaw and Swanson 1970) and their flow tops are an indicator of paleohorizontality (Shaw and Swanson 1970); (2) the thickness variations in the Columbia River Basalt Group flows record existing topography and structure and do not represent normal variations in the flow or erosion. It has been demonstrated by Reidel (1984) for the Pasco Basin, that such normal variations in individual Columbia River Basalt Group members have a one standard deviation of ~4 m or less for certain members of the Saddle Mountains or Wanapum Basalt; (3) folding or faulting has not altered the original flow thickness since the time of emplacement, that is, structural thickening can be recognized. Section thicknesses used in the calculations are shown in tables D-1 through D-4.

Section thicknesses of Columbia River Basalt Group flows and Ellensburg sedimentary interbeds were measured in the field, from borehole geophysical logs, and from drillers' logs. In all cases, measurements were made after delineating the stratigraphy and structure.

Table D-1. Thickness Data Used in Calculating the Combined Rate of Uplift and Subsidence for the Prosser Anticline and the Lower Yakima Valley Syncline.

Unit	Lower Yakima Valley syncline			Prosser anticline		Paleo-relief (m)
	Data type	Location	Unit thickness (m)	Location	Unit thickness (m)	
Elephant Mountain member	G.L.	*	34.0	T. 8 N., 24 E., sec. 14L	0.0	34.0
Rattlesnake Ridge interbed	G.L.	T. 8 N., 24 E., sec. 01J	47.2	T. 8 N., 24 E., sec. 14L	0.0	47.2
Pomona member	G.L.	T. 8 N., 24 E., sec. 01J	93.9	T. 8 N., 24 E., sec. 14L	43.3	50.6
Selah interbed	G.L.	T. 8 N., 24 E., sec. 01J	33.2	T. 8 N., 24 E., sec. 14L	1.5	31.5
Umatilla member	G.L.	T. 8 N., 24 E., sec. 01J	61.3	T. 8 N., 24 E., sec. 14L	31.4	29.9
Mabton interbed	G.L.	T. 8 N., 24 E., sec. 01J	29.9	T. 8 N., 24 E., sec. 14L	15.8	14.1
Priest Rapids member	F.M.	T. 8 N., 25 E., sec. 07M	62.5	T. 8 N., 24 E., sec. 14L	3.0	27.5
Roza member	F.M.	**	47.0	T. 8 N., 25 E., sec. 07M	3.0	45.0

NOTE: Present structural relief = 393 m.

*Thickness extrapolated between geophysically logged Grandview City well and the Prosser well.

**Thickness extrapolated between the geophysically logged Grandview City well and the driller-logged Irrigated Agriculture Research and Extension Center (IAREC) wells (T. 9 N., 25 E., sec. 19B, T. 9 N., 25 E., sec. 19C), and the Heintz well (T. 9 N., 25 E., sec. 19D).

D.L. = data from drillers' logs.
G.L. = data from borehole geophysical logs.
F.M. = data from field measurements.

Table D-2. Thickness Data Used in Calculating the Combined Rate of Uplift and Subsidence for the Chandler Anticline and the Lower Yakima Valley Syncline.

Unit	Lower Yakima Valley syncline			Chandler anticline			Paleo-relief (m)
	Data type	Location	Unit thickness (m)	Data type	Location	Unit thickness (m)	
Elephant Mountain member	G.L.	T. 9 N., 26 E., sec. 20A	29.0	F.M.	T. 9 N., 26 E., sec. 20R	0.0	29.0
Rattlesnake Ridge interbed	G.L.	T. 10 N., 25 E., sec. 25E	19.2	F.M.	T. 9 N., 26 E., sec. 20R	0.0	19.2
Pomona member	G.L.	T. 9 N., 26 E., sec. 20A	79.2	F.M.	T. 9 N., 26 E., sec. 20R	29.6	49.6
Selah interbed	G.L.	T. 9 N., 26 E., sec. 20A	45.7	F.M.	T. 9 N., 26 E., sec. 20R	18.5	27.2
Umatilla member	F.M.	T. 9 N., 26 E., sec. 20G	107.3	F.M.	T. 9 N., 26 E., sec. 20P	77.7	29.6
Mabton interbed	F.M.	T. 9 N., 26 E., sec. 20H	28.7	F.M.	T. 9 N., 26 E., sec. 20P	7.6	21.1
Priest Rapids member	F.M.	T. 9 N., 26 E., sec. 20G	61.6	F.M.	T. 9 N., 26 E., sec. 20P	50.9	10.7
Roza member	G.L.	*	48.8	F.M.	T. 9 N., 26 E., sec. 20P	12.2	36.6

NOTE: Present structural relief = 406 m.

*Thickness extrapolated between DC-15/DDH-3 and the Prosser Experimental Station wells.

G.L. = data from borehole geophysical logs.
F.M. = data from field measurements.

Table D-3. Thickness Data Used in Calculating the Combined Rate of Uplift and Subsidence for the Kiona Anticline and the Lower Yakima Valley Syncline.

Unit	Lower Yakima Valley syncline			Kiona anticline			Paleo-relief (m)
	Data type	Location	Unit thickness (m)	Data type	Location	Unit thickness (m)	
Ice Harbor member	D.L.	T. 10 N., 26 E., sec. 26J	3.7	F.M.	T. 9 N., 26 E., sec. 23E	0.0	3.7
Levey interbed	D.L.	T. 10 N., 26 E., sec. 26J	5.8	F.M.	T. 9 N., 26 E., sec. 23E	0.0	5.8
Elephant Mountain member	D.L.	T. 10 N., 26 E., sec. 33F	23.5	F.M.	T. 9 N., 26 E., sec. 23E	0.0	23.5
Rattlesnake Ridge interbed	D.L.	T. 10 N., 26 E., sec. 33F	21.3	F.M.	T. 9 N., 26 E., sec. 23E	0.0	21.3
Pomona member	G.L.	T. 10 N., 26 E., sec. 27Q	86.0	F.M.	T. 9 N., 26 E., sec. 23F	4.6	81.4
Selah interbed	G.L.	T. 10 N., 26 E., sec. 27Q	3.0	F.M.	T. 9 N., 26 E., sec. 23F	4.6	-1.6
Esquatzel member	G.L.	T. 10 N., 26 E., sec. 27Q	24.4	F.M.	T. 9 N., 26 E., sec. 23F	0.0	24.4
Cold Creek interbed	G.L.	T. 10 N., 26 E., sec. 27Q	21.3	F.M.	T. 9 N., 26 E., sec. 23F	0.0	21.3
Umatilla member	G.L.	T. 10 N., 26 E., sec. 27Q	83.2	F.M.	T. 9 N., 26 E., sec. 23G	33.0	50.2
Mabton interbed	D.L.	**	19.0	F.M.	T. 9 N., 26 E., sec. 23G	2.4	16.6
Priest Rapids member	G.L.	*	52.0	F.M.	T. 9 N., 26 E., sec. 23Q	30.5	21.5
Roza member	G.L.	*	48.0	F.M.	T. 9 N., 26 E., sec. 23F	19.8	28.2

NOTE: Present structural relief = 408.

*Thickness extrapolated between geophysically logged DC-15/DDH-3 and the Prosser Experiment Station wells.
**Thickness averaged from driller-logged well located at T. 10 N., 26 E., sec. 33D and T. 10 N., 26 E., sec. 33F.

D.L. = data from drillers' logs.
G.L. = data from borehole geophysical logs.
F.M. = data from field measurements.

Table D-4. Thickness Data Used in Calculating the Combined Rate of Uplift and Subsidence for the Prosser Anticline and the Piening Syncline.

Unit	Piening syncline			Prosser anticline			Paleo-relief (m)
	Data type	Location	Unit thickness (m)	Data type	Location	Unit thickness (m)	
Elephant Mountain member	D.L.	T. 8 N., 25 E., sec. 36B	42.7	F.M.	T. 8 N., 24 E., sec. 14L	0.0	42.7
Rattlesnake Ridge interbed	D.L.	T. 8 N., 25 E., sec. 36B	19.8	F.M.	T. 8 N., 24 E., sec. 14L	0.0	19.8
Pomona member	G.L.	T. 7 N., 26 E., sec. 05B	61.0	F.M.	T. 8 N., 24 E., sec. 14L	43.3	10.0
Selah interbed	D.L.	T. 8 N., 25 E., sec. 36B	38.1	F.M.	T. 8 N., 24 E., sec. 14L	1.5	36.6
Umatilla member	G.L.	T. 7 N., 26 E., sec. 05B	71.6	F.M.	T. 8 N., 24 E., sec. 14L	31.4	40.2
Mabton interbed	G.L.	T. 7 N., 26 E., sec. 05B	15.2	F.M.	T. 8 N., 24 E., sec. 14L	15.8	-0.4

NOTE: Present structural relief = 253 m.

D.L. = data from drillers' logs.
G.L. = data from borehole geophysical logs.
F.M. = data from field measurements.

Field measurements of basalt flows and sedimentary interbeds were gathered using a surveying tape, a Paulin altimeter, or, in some cases, a Brunton compass. Measurements were made where both the upper and lower contacts could be delineated. The presence or absence of erosion in the basalt was determined by the observation of primary physical features (e.g., vesicular flow top). Where the exact location of the stratigraphic contact could not be pinpointed, it was sometimes possible to measure a maximum or minimum thickness. Measurements were corrected for structural tilt where necessary. Caution was exercised in determining whether section thicknesses were "increased" by invasive flows.

Thickness data interpreted from borehole geophysical logs are deemed quite accurate as stratigraphic contacts are easily pinpointed.

RADIOMETRIC AGE DATES

Two methods of radiometric age dating were used to determine absolute ages for Columbia River Basalt Group flows: potassium-argon and argon-argon. Argon loss in the older Columbia River Basalt Group flows gives abnormally young potassium-argon age estimates (Long and Duncan 1982). Argon-argon dating techniques achieve better age dates for these older Columbia River Basalt Group flows (Long and Duncan 1982). The two dating techniques give similar age dates for the younger basalts, but different ages for the older basalts. In this study, age dates from the argon-argon technique were used for the Grande Ronde Basalt.

Table D-5 shows the age dates used in the construction of the growth curves. Age dates from certain flows must be estimated since there are no available radiometric age dates.

Table D-5. Age Dates Used in Calculating Development Rates of the Horse Heaven Hills Uplift.

CRBG[a] member or stratigraphic boundary	Age (m.y.B.P.)	Dating method	Source
Ice Harbor	8.5	K-Ar	McKee et al. (1977)
Elephant Mountain	10.5	K-Ar	McKee et al. (1977)
Pomona	12.0	K-Ar	McKee et al. (1977)
Umatilla	14.0	b	
Priest Rapids	14.5	K-Ar	Watkins and Baksi (1974)
Roza	14.8	c	
Frenchman Springs	15.1	c	
Wanapum/Grande Ronde Contact	15.6+0.2	$^{40}Ar-^{39}Ar$	Long and Duncan (1982)

NOTE: Error range given for the dates of Long and Duncan (1982).
[a]CRBG - Columbia River Basalt Group.
[b]Age calculated by averaging eruption times of flows between the Pomona and Priest Rapids Members.
[c]Age calculated by averaging eruption times of flows between the Priest Rapids Member and the Wanapum/Grande Ronde Basalt contract.

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APPENDIX E

PRELIMINARY RESULTS OF PALEOMAGNETIC VECTOR ROTATION

A recent study (Reidel et al. 1984) in the Pasco Basin area evaluates vector rotation from the Pomona Member along Yakima folds. One of the findings of the study is that clockwise rotation occurred at sites along both east-west-trending folds and northwest-trending folds. This finding has important tectonic significance. It is the purpose of this section to compile available paleomagnetic results for the Pomona Member at sites located along folds of both trends of the Horse Heaven Hills to see if a similar clockwise rotation occurred.

A reference Pomona direction reported by Reidel et al. (1984), (inclination = -52.2°, declination = 189.7°, $\alpha95$ = 1.6°) is used as the stable magnetic vector direction to calculate mean rotational values (table E-1, fig. E-1). All but one of the sites record a clockwise rotation. Although the declination uncertainty for some of these sites is great, clockwise rotation along both trends of the Horse Heaven Hills uplift (including other folds of the Anderson Ranch-Wallula Structural alignment) is preliminarily indicated.

Table E-1. Compilation of Available Paleomagnetic Data for the Pomona Member within the Study Area.

Site	Location			α95	Stratigraphic direction			Source
	Township	Range	Section		Declination (degree)	Inclination (degree)	ΔD (degree)	
IW 59	9 N	26 E	NW NW 23	2.3	189.2	-56.4	4.2	a
IW 60	9 N	26 E	NW NW 23	2.9	192.5	-54.7	5.0	a
IW 61	9 N	26 E	SE SW 9	2.4	198.0	-56.5	4.4	a
IW 62	9 N	26 E	SE SW 9	2.4	190.7	-54.4	4.1	a
PO-4	9 N	26 E	SW NW 17	5.6	193.3	-50.1	8.8	b
PO-7	8 N	22 E	NW 35	10.9	192.9	-46.7	16.0	b
P1D1	9 N	26 E	SE SE 8	1.6	198.5	-51.0	2.5	c
F1	8 N	28 E	NW NW 35	3.0	203.0	-52.7	4.7	d
H1	8 N	27 E	NE SE 8	1.6	198.5	-50.6	2.6	d
K1	10 N	24 E	NW NE 2	2.1	196.6	-51.0	3.3	d
L1	10 N	25 E	NW SW 23	3.2	198.3	-50.6	5.0	d
HH1	8 N	24 E	SW NE 20	9.1	227.3	-65.8	22.8	d

NOTE: α95 = radius of 95% confidence.
ΔD = declination uncertainty ($\Delta D = \sin^{-1}(\sin \alpha95/\cos 1)$).
Stratigraphic direction = declination and inclination relative to paleohorizontal (rotated about strike line).

a. Simpson and Wells (1979).
b. Rietman (1966).
c. Van Alstine and Gillett (1981).
d. Reidel et al. (1984).

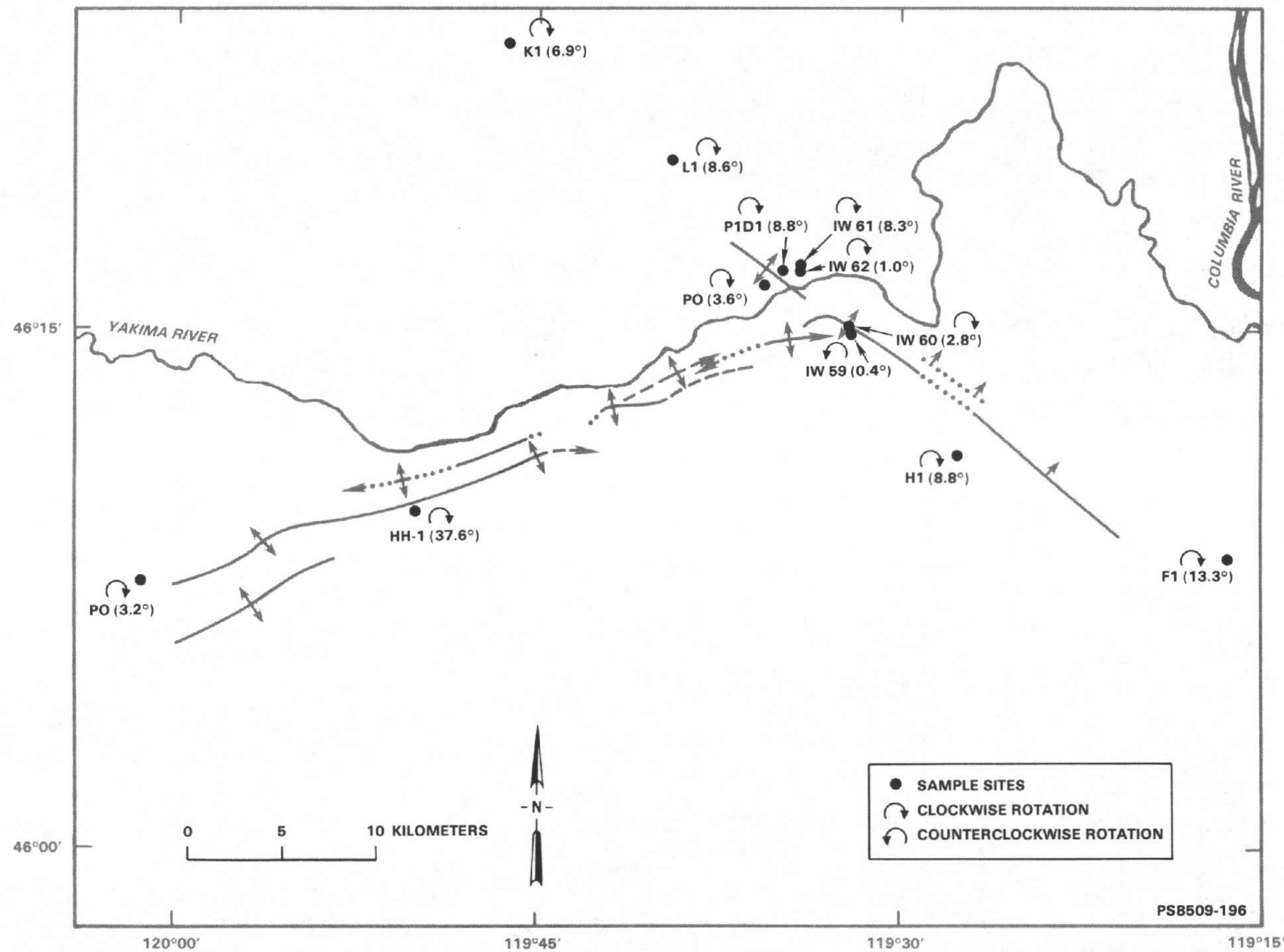

Figure E-1. Map of Paleomagnetic Sites and Mean Vector Rotation of the Sites Relative to the Reference Pomona Direction of Reidel et al. (1984).

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APPENDIX F

TECTONIC MODELS

A summary of published tectonic models that deal with the timing of growth, rate of growth, and origin of Yakima folds is presented in the following pages in table form (tables F-1 through F-3).

Table F-1. Summary of Models for the Timing of Development of Yakima Folds. (sheet 1 of 6)

Anderson (1980) Simcoe-Horse Heaven Hills. Deformation and associated faulting occurred during Vantage horizon time.

Barrash et al. (1983)

Yakima Folds. Mild, episodic anticlinal folding localized in the Yakima Ridges area (17-10 + 2 m.y.B.P.). Present structural relief is dominantly postbasalt (10 + 2 - 4 m.y.B.P.). Minor folding since 4 m.y.B.P., with simultaneous deformation of east-west folds and Cle Elum-Wallula Lineament structures.

Horse Heaven Hills Uplift. The Horse Heaven Hills uplift was developed after 10.5 m.y.B.P. The eastern segment (northwest trend) was developed after 8.5 m.y.B.P.

Bentley (1977)

Yakima Folds. Local substantial deformation occurred between 14 and 12 m.y.B.P., but the majority of the folds developed between 6 and 1.5 m.y.B.P.

Bentley (1980b)

Cle Elum-Wallula Lineament. Pre-Umatilla regional deformation occurred north of Yakima Ridge in the Cle Elum-Wallula Lineament.

Umtanum uplift. Two phases of deformation took place: post-Wanapum and post-Saddle Mountains time. Minor folding occurred in postbasalt time.

Bentley et al. (1980b)

Columbia Hills. Thrusting along the fold occurred during Grande Ronde time and, subsequently, before 10 m.y.B.P.

Biggane (1982)

Hog Ranch Fault Axis. Thinning and pinching occurred out of the Pomona Member towards the Hog Ranch Fault Axis, which separates the Moxee and Black Rock Valleys.

Table F-1. Summary of Models for the Timing of Development of Yakima Folds. (sheet 2 of 6)

Bond et al. (1978)

Pasco Basin Area. Most folds in southwestern Pasco Basin developed since Saddle Mountains time (minor uplift indicated in Umatilla-time Rattlesnake Mountain uplift).

Horse Heaven Hills Uplift. Possible development occurred in post-Pomona time.

Brown (1978)

Horse Heaven Plateau. The Horse Heaven Plateau was possibly tectonically active during late-Wanapum time.

Brown (1970)

Pasco Basin Area. Anticlinal uplift in Pasco Basin began in earliest Pliocene time--near the close of emission of the basalts and continuous to present. Uplift progressed roughly from north to south with the Horse Heaven Hills rising slower and/or later than the northerly anticlines. Variations in rate and time of rise also occurred along a single anticline.

Campbell (1984)

Hog Ranch-Naneum Ridge Anticline. The "Naneum high" is a prebasalt structure and lies below the 1-29 Bissa well.

Campbell and Bentley (1981)

Toppenish Ridge. Late Quaternary and Holocene faulting is found along the crest.

Davis (1981)

Yakima Folds. Contemporaneous deformation along east-west folds and Cle Elum-Wallula Lineament structures began about 14 m.y.B.P. and was continuous to the present. Most deformation is post-Pomona in age.

Fecht et al. (1985)

Hog Ranch-Naneum Anticline. Uplift of the "Hog Ranch structure" diverted the ancestral Columbia River to a more southerly course across the emerging Rattlesnake Hills.

Table F-1. Summary of Models for the Timing of Development of Yakima Folds. (sheet 3 of 6)

Gardner et al. (1981)

Horse Heaven Hills. Structural uplift began prior to extrusion of the Pomona flow.

Goff and Myers (1978)

Umtanum and Yakima Ridges. Anticlines began folding before extrusion of the Umatilla Member.

Hog Ranch-Naneum Ridge Anticline. Southward growth of the Hog Ranch anticline cuts off an ancient stream channel during Saddle Mountains time.

Jones and Landon (1978)

Horse Heaven Hills. Structural uplift began prior to extrusion of the Pomona and Elephant Mountain flows, but possibly even as early as Priest Rapids time.

Rattlesnake-Wallula Structural Alignment. The Rattlesnake-Wallula Structural Alignment is younger than the Horse Heaven Hills structure, and folding probably began in post-Elephant Mountain time and continued through Ice Harbor time.

Kienle et al. (1978)

Yakima Folds. The greatest amount of uplift on most structures took place after Elephant Mountain time.

Kienle (1980)

Horse Heaven Hills and Columbia Hills. The Horse Heaven Hills and Columbia Hills formed largely between 3.5 and 4.5 m.y.B.P.

Landon et al. (1982)

Hog Ranch-Naneum Ridge Anticline. Hog Ranch anticline, west of the Pasco Basin, was in existence by late Grande Ronde time.

Table F-1. Summary of Models for the Timing of Development of Yakima Folds. (sheet 4 of 6)

Laubscher (1981)

Yakima Folds. "The main part of the Yakima basalt deformation north of Yakima took place between about 3-1 m.y.B.P. with some deformation continuing into the younger Pleistocene and present. Yakima deformation began at the south and proceeded north."

Laval (1956)

Yakima Folds. Mild local warping occurred during the accumulation of the upper Yakima basalt formation. Intensified bedload warping and folding culminated during the early Pleistocene.

Mackin (1961)

Yakima Folds. Uplift occurred in part of Wanapum time.

Myers et al. (1979)

Yakima Folds. "Most folding is probably of late Miocene and Pliocene age."

Powell (1978)

Tygh Ridge. "Uplift along the Tygh Ridge structure appears to have occurred sporadically throughout the time of the extrusion of the Grande Ronde Basalt."

Price (1982)

Hog Ranch-Naneum Ridge Anticline. Hog Ranch was possibly present in Grande Ronde time in the Priest Rapids area.

Reidel (1984)

Saddle Mountains Uplift. The Saddle Mountains uplift was growing continuously from at least Grande Ronde time to at least 3.5 m.y.B.P. and probably into present.

Hog Ranch-Naneum Ridge Anticline. Hog Ranch was present in Grande Ronde time.

Table F-1. Summary of Models for the Timing of Development of Yakima Folds. (sheet 5 of 6)

Reidel et al. (1980)

Saddle Mountains Uplift and other Yakima Folds. The Saddle Mountains uplift was forming in early Wanapum time and most of the other Yakima folds in the Pasco Basin were active by late Wanapum/early Saddle Mountains time.

Reidel and Fecht (1981)

Yakima Folds in the Cold Creek Syncline Area, Pasco Basin. Relief was present by at least Wanapum time. "... any structural relief present during Grande Ronde time would have been obscured by the large volume of lava which was erupted over a short period of time."

Reidel et al. (1983)

Yakima Folds. Folds were growing in Grande Ronde time and were actually growing through much of Miocene time along anticlinal axes.

Schmincke (1964)

Saddle Mountains Area. Deformation began in two synclines along the north scarp of the Saddle Mountains at least by Priest Rapids time. "Cross folding along north-south axes was slightly earlier than, or contemporaneous with, the more prominent east-west warping shown by the Saddle Mountains anticline."

Shannon and Wilson (1973)

Northwest-Southeast Trending Structures in the Arlington, Oregon Area. These structures are interpreted to be at least pre-Roza in age.

Columbia Hills, Blue Mountains, and Horse Heaven Anticline. These structures, as well as their related synclines, were last deformed prior to middle Pleistocene time. The best bracket on the time of the major deformation of the region places it between 3.5 and 4.5 m.y.B.P."

Swanson and Wright (1978)

Yakima Folds. Formed during Saddle Mountains time.

Hog Ranch-Naneum Anticline. Naneum Ridge anticline in the Wenatchee Mountains was probably active as early as Grande Ronde time.

Table F-1. Summary of Models for the Timing of Development of Yakima Folds. (sheet 6 of 6)

Sylvester (1978)

East-West-Trending Structures. The Mosier syncline, the Horseshoe Bend anticline, and the Swale Creek syncline were initiated in the post-Priest Rapids time.

Northwest-Southeast-Trending Folds. The folds developed in the late Miocene to early Pliocene (Warwick, Snipes Butte, and Goldendale anticlines) and transect the east-west structures.

Tabor et al. (1982)

Hog Ranch-Naneum Ridge Anticline. Naneum Ridge anticline causes thinning of Vantage Member.

Tolan et al. (1984)

Yakima Folds. Yakima folds that extend through the Cascade Range control the course of the ancestral Columbia River as early as Frenchman Springs time.

Waters (1955)

Yakima Folds. Folds grew intensely during early Pliocene time.

Table F-2. Summary of Growth Rate Models for Yakima Folds.

Barrash et al. (1983)

Uplift of the Saddle Mountains occurred at an average rate of between 0.1 mm/yr (assuming deformation occurred between 10.5 and 4 m.y.B.P.) and 0.14 mm/yr (for the period of 8.5 to 4 m.y.B.P.). "Estimated average uplift rate for Rattlesnake Hills between 10.5 and 4 m.y.B.P. to be 0.14 to 0.20 mm/yr."

Brown (1970)

Anticlinal ridges grew at the rate of 0.1 mm/yr.

Caggiano et al. (1980)

Basalt deformation progressed at <1 mm/yr.

Kienle et al. (1978)

Yakima folds developed at 0.75 to 1.5 mm/yr for the period between 8 or 6 m.y.B.P. to 4 m.y.B.P.

Reidel (1984)

Saddle Mountains uplift was undergoing a vertical rate of uplift of ~250 m/m.y. in late Grande Ronde time but slowed to ~40 m/m.y. by Elephant Mountain time. Extrapolation of these rates to the present structural relief indicates a rate of ~40 m/m.y. for post-Columbia River Basalt Group time.

Reidel et al. (1980)

A minimum rate of uplift for the Saddle Mountains during Wanapum and Saddle Mountains time is ~39 m/m.y. A maximum rate of uplift for Rattlesnake Mountain during this same time interval is ~70 m/m.y.

Reidel et al. (1983a)

Between Rattlesnake Mountain and the Cold Creek syncline, the combined rate of uplift and subsidence was found not to exceed 150 m/m.y. over the time interval of 14.5 to 10.5 m.y.B.P. During this same time interval the combined uplift and subsidence of the Saddle Mountains and Wahluke syncline decreased to ~80 m/m.y. by 10.5 m.y.

Table F-3. Summary of Models for the Origin of Yakima Folds.
(sheet 1 of 4)

East-West Folds and Faults.

Bentley (1977)

"Brittle basalts can fold only under a combined horizontal compression and vertical movement along basement weakness zones. Each anticlinal structure has a weakness zone in basement rocks that has localized the horizontal stresses and caused the vertical uplift of the ridges at successive times. In gross character, anticlines are "drape" folds caused by vertical breakup of basement blocks."

"The "ridges" are faulted monoclinal anticlines formed as drape folds above rotated basement blocks. The narrow ridges were uplifted as adjacent broad synclinal basins subsided."

Bentley (1980a)

"These faulted anticlines (east-west folds) may be part of an extensive decollement system that has ~1% north-south horizontal shortening across the system."

Bentley (1982)

Yakima folds reflect drag on ramps from sub-basalt and interbasalt decollements.

Bentley et al. (1980b)

The Columbia Hills formed over "deep-seated left lateral strike-slip faulting (N.70° E.) localized mobile zone."

Bentley and Farooqui (1979)

"East-west Yakima folds mark the position of fundamental Reidel shears that formed in early Miocene time by left-lateral-strike-slip zones in later deformation, localizing most thrusting and folding, and subsequent, minor, left lateral movement.

Brown (1970)

"Anticlinal ridges, sometimes uplifted plateaus, are in part at least related to the vertical forces of basining. Evidence of major compression or tension with the formation of major thrust faults or normal faults respectively, appear absent."

Table F-3. Summary of Models for the Origin of Yakima Folds.
(sheet 2 of 4)

East-West Folds and Faults.

Bruhn (1981)

Long gentle limbs indicate fault ramp-flexure model with decollement of group of localized detachments at 3 to 5 km deep near the base of the basalts.

Davis (1981)

East-west trending fold-fault structures formed by buckling and local detachment.

Laubscher (1981)

East-west folds were formed over ramps that emanate from a decollement at the base of the crust.

Laval (1956)

"... two modes of structural genesis are suggested: folding free of the basement, or folding directly related to deformation of the basement. The first is suggested in the similarity of Snipes Mountain and Toppenish Ridge to some of the simpler Jura Mountains folds, and the second is suggested in the similarity of Saddle Mountains and the Horse Heaven Plateau to the Pryor Mountains of Montana. Neither type of folding can be proved because the base of the Yakima basalt is not exposed in the areas mapped."

Price (1982)

Major thrusts cannot underlie the Yakima anticlinal folds due to the lack of associated strain features. Folds probably overlie local detachments. Basalt was rotated clockwise into the folds from the southeast around the Palouse slope which acted as a rigid buttress.

Reidel et al. (1984)

East-west directed sinistral shear along the major anticlinal ridges is not supported by paleomagnetic data. There is a direct relationship between the amount of rotation and the amount of deformation and position of fold.

Table F-3. Summary of Models for the Origin of Yakima Folds.
(sheet 3 of 4)

East-West Folds and Faults.

Russel (1893)

"An example of the upturned edge of an orographic block is furnished by the northern escarpment of the sloping table land known as Horse-Heaven, which is well exposed in the neighborhood of Kiona and Prosser. This long line of cliffs is a fault scarp from which the strata slope gently southeast toward the Columbia."

"Narrow ridges were formed by an arching of the strata without breaking. The arches were raised by a force acting from below upward, and not by lateral pressure which forced the strata into ridges and troughs, as is common especially in the Appalachian Mountains."

Waitt (1979)

"An hypothesis consistent with regional relations is that the individual east-trending scarps in Kittitas Valley evince reverse faults caused by north-south compression ..."

Northwest-Trending Folds and Faults

Barrash et al. (1983)

"The Warps and folds may reflect local responses to rapid crustal loading over pre-existing northwest-trending structural grains. Alternately, or in addition, northwest compression may have induced limited dextral shear on pre-existing, northwest-trending basement structure(s) beneath the Olympic-Wallowa Topographic Lineament and thereby influenced the orientation of surface folds as in Reidel-type deformation."

"We suggest that a buttressing effect at depth across steeply dipping structures along the Rattlesnake Lineament (Bond and others, 1978; Davis, 1981) influenced the initial deformation pattern at the surface, and that the lateral continuity of the basalt flows allowed HHH area to respond as a continuous unit with similar volumes of rock displaced east and west of the symmetry plane."

Table F-3. Summary of Models for the Origin of Yakima Folds.
(sheet 4 of 4)

East-West Folds and Faults.

Bentley (1977)

The Olympic-Wallowa Topographic Lineament is a crustal weakness zone, old basement structures localized the later vertical movement along the line. "All structures are formed by vertical movement and are rooted in basement weakness zones and most structures are monoclinal faults at the surface.

Bentley (1980a)

The Olympic-Wallowa Topographic Lineament marks a Mesozoic Benioff zone formed from dextral translation abutted against a more rigid zone.

Bentley (1980b)

"The geometry of the Umtanum thrust fault zone is consistent with a model of north-south (horizontal) compression with decollement in several sedimentary interbeds within the Grande Ronde and Wanapum Basalt."

Bentley and Anderson (1979)

The Olympic-Wallowa Topographic Lineament formed as result of dextral shear along an incompetent compressive zone, as much of the translation abutted against the more rigid North American Plate."

Price (1982)

Rattlesnake Mountain and the northwest-trending portion of the Horse Heaven Hills are associated with dextral shear.

Waitt (1979)

In the Kittitas Valley "An hypothesis consistent with regional relations is that the ... southeast trend of dextral echelon pattern is due to right lateral couple across a southeast-trending structural zone that includes, but is not limited to the topographically defined Olympic-Wallowa Lineament ..."

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BEDROCK OUTCROP MAP OF A PORTION OF THE HORSE HEAVEN HILLS, SOUTH-CENTRAL WASHINGTON

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