GEOLOGIC RECONNAISSANCE OF THE WALLULA GAP, WASHINGTON - BLUE MOUNTAINS - LAGRANDE, OREGON REGION

prepared for

WASHINGTON PUBLIC POWER SUPPLY SYSTEM

under the direction of

UNITED ENGINEERS & CONSTRUCTORS INC.

December, 1979

SHANNON & WILSON, INC.

8007250396

GEOLOGIC RECONNAISSANCE OF THE WALLUALA GAP, WASHINGTON - BLUE MOUNTAINS - LAGRANDE, OREGON REGION

prepared for

WASHINGTON PUBLIC POWER SUPPLY SYSTEM

under the direction of

UNITED ENGINEERS & CONSTRUCTORS INC.

Contract No. 44013, C.O. No. 38

December, 1979

by

Clive F. Kienle, Jr.

Molly L. Hamill

Daniel N. Clayton

SHANNON & WILSON, INC.

2255 S.W. Canyon Road

Portland, Oregon 97201

TABLE OF CONTENTS

TABLE OF CONTENTS
(continued)

LIST OF TABLES

LIST OF FIGURES

TABLE OF CONTENTS
(continued)

LIST OF FIGURES
(continued)

1. INTRODUCTION

1.1 PURPOSE OF INVESTIGATION

The LaGrande graben and the Walla Walla syncline (Figure 1) are two areas of relatively young tectonic activity that have previously been considered as extensional basins or downwarps, bounded by normal faults (Hampton & Brown, 1964; Newcomb, 1970; WPPSS, 1977a). However, some recent regional tectonic models have postulated that both structures are related to the postulated Olympic-Wallowa lineament (OWL), or at least to that part of the lineament within the Columbia Plateau (e.g., Wise, 1963; Skehan, 1965; WPPSS, 1977b; Smith, 1977). These models have postulated that the crustal shortening, which occurred during formation of the Yakima fold belt of central Washington (Figure 1), may have been compensated for by crustal extension, possibly via a connection along the Olympic-Wallowa lineament southeast to the extensional Basin and Range province.

A reconnaissance was conducted in the south and east parts of the Walla Walla syncline and Blue Mountains of northeastern Oregon, therefore, to examine the fault relationships in these areas. The purpose of the reconnaissance was to examine the faulting in the area between the LaGrande graben, which represents the northernmost extension of the Basin and Range of Fenneman (1931), and the Rattlesnake-Wallula-Horse Heaven anticlines, which are the southeasternmost parts of the Yakima fold belt. Through this examination we hoped to address several related questions including:

1) Does the Walla Walla syncline represent a northern extension of the Basin and Range Province?
2) If so, does it directly connect, via through-going faults or systems of faults, with the main Basin and Range? (i.e., the LaGrande Graben)
3) What are the relationships between the north-northwest-trending LaGrande and the west-northwest-trending Wallula faults (and the OWL)?
4) What part does the north-northeast-trending Hite fault, which appears to separate the north-northwest and west-northwest faults, play in the regional tectonic scheme?

5) Finally, what are the ages of the various faults in the area; are any yet active?

These questions are significant to understanding the tectonic development of the Columbia Plateau, inasmuch as they all relate to the Olympic-Wallowa lineament (OWL) and its possible impact on the seismic design that should be considered for critical facilities in the area.

1.2 SCOPE OF INVESTIGATION

The investigation included a review of previous studies, an office evaluation and study of topographic maps and aerial photographs, and approximately 65-mandays of field studies. The field studies included reconnaissance of the area shown on Figure 1, a region approximately bounded on the north by the Walla Walla syncline, by the LaGrande graben - Grande Ronde syncline on the south, by longitude 118°00' on the east, and by a line extending approximately from Wallula Gap through Pendleton to the west end of the Grande Ronde syncline on the west.

The study was accomplished in two phases. The first phase involved a compilation of existing maps followed by reconnaissance studies, which delineated, as far as possible in the time available, the major structural features and the approximate distribution of major stratigraphic units in the area. The second phase involved a more detailed examination of the area between Tollgate, Adams, Milton-Freewater and Pikes Peak, Oregon. The purpose of this later work was, to the extent possible, to determine the sense and amount of offset of the more prominent faults in that area, and to determine the nature of their intersections. During and after field work, both the new and old data were evaluated for their relationship to the regional and local tectonics. A new reconnaissance tectonic map of the area was prepared, which incorporates our findings and those of previous investigations (Figure 2).

This report presents the results of these investigations along with a preliminary analysis of the new data on faulting in the region found during the investigation. The report is divided into four sections. Section 1 of the report is the Introduction. The Summary and Conclusions are presented in Section 2. Section 3 of the report presents a general

discussion of the major structural elements of the study area, while Section 4 discusses specifics of three major fault systems. Section 5 presents our interpretation of the tectonics of the area and conclusions as to their significance. The References Cited are given in Section 6.

1.3 PREVIOUS INVESTIGATIONS

Previous investigations in the study area include those of Hogenson (1964), Hampton and Brown (1964), and Newcomb (1965, 1967, 1970). Although these studies were primarily geohydrologic investigations, they delineated parts of many of the major structures and defined the master structures (e.g., Walla Walla syncline, Hite faults, Blue Mountain anticline, LaGrande graben, etc.) that influence the regional groundwater. Their mapping was accomplished using planimetric base maps, 30- and 15- minute quadrangles, and 1:24,000 black and white aerial photographs.

The increase in the detail and number of faults found during this study, as compared to earlier investigations, may be directly attributed to more sophisticated support materials available, and to having a reasonably accurate (though incomplete), picture of the regional tectonics from the aforementioned studies. In addition to these aforementioned studies, other small-scale geologic and tectonic maps were compiled by Walker (1973, 1977, 1979) at scales of 1:250,000 and 1:500,000. These compilations, which include the study area, were also evaluated for this study.

1.4 METHODS OF INVESTIGATION

Field studies involved both reconnaissance and local detailed mapping using U.S.G.S. 1:24,000 and 1:250,000 scale topographic base maps and U.S. Forest Service maps.

In addition, several different sets of aerial photographs were utilized in both field and photoanalytic studies. These included 1:80,000 black and white U-2 imagery of the entire area (Battelle, 1978), 1:31,000 false-color infrared (NASA, 1973) and 1:60,000 black and white imagery of the Umatilla National Forest (USDA, 1976). Because flight lines were oriented differently for each set of imagery (i.e., N-S, E-W and NE-SW) our evaluations of fault-controlled photo-linears should not be biased towards any particular orientation.

During field work, the basalt stratigraphy utilized by WPPSS (1977c) and Swanson and others (1979) was employed. Basalt units were identified, based on hand specimen petrology and magnetic polarities, as discussed in both of these stratigraphic compilations.

1.5 ACKNOWLEDGEMENTS

Field work for this project was conducted by C.F. Kienle, Jr., M.L. Hamill, and D.N. Clayton, assisted by R.J. Deacon. The authors were assisted in preparation of the report by W.H. Stuart, H.H. Waldron and R.J. Deacon. The geologic and tectonic maps were drawn by Chris Thoms and Chris Nastrom. Consultations and field conferences with H.C. Coombs, G.A. Davis, E.C. Simmons, and W.H. Taubeneck were of material assistance to us in our interpretation of the tectonics of the area.

Special thanks are due Paul Bouchard, Earl Malone and John Ware, of the U.S. Forest Service, who made 1:31,000 false color IR imagery available to us. We also wish to thank Dale Jenner of Harris Pine Company and Bob Weinburger of Boise Cascade Corporation for arranging access into the corporate properties in the Tollgate and Blalock Mountain area.

2. SUMMARY AND CONCLUSIONS

The study area contains three well-developed fault systems: 1) the Hite fault system which trends north-northeast diagonally across the area from Deadman's Pass to the northeast corner of the area; 2) the west-northwest-trending Wallula fault system in the north and northwest part of the area; and 3) the generally northwest-trending LaGrande fault system, which occupies the southeast one-third of the area. All three systems show evidence of post Miocene movement, and although relationships between the systems are not entirely clear, all three appear to have dextral (i.e. right lateral) strike-slip motions. Based on the available evidence, the Hite fault system is the oldest of the three, and appears to have undergone only local movement since development of the other two fault systems. The Wallula and LaGrande systems appear to be the youngest. Some faults in the Wallula system offset both colluvium and late Pleistocene Touchet deposits, while some in the LaGrande system cut late Pleistocene lake beds.

The Hite fault system consists of a north-northeast-trending main fault zone (Hite), which extends from near the Snake River to the South Fork of the Umatilla River (130 km), and several parallel faults west of the main fault. The main Hite fault zone consists of a complex, dextral shear zone, with an unknown amount of lateral offset, but at least 100 m of vertical offset of the Grande Ronde Basalt. Field data suggests two stages of movement: 1) dip-slip (west side down) prior to eruption of the flows of the Frenchman Springs member, and 2) dextral movement after about 14 mybp.

Other faults in the Hite fault system generally parallel the Hite fault zone and also have strike-slip (dextral) offsets. Some are major faults as long as 40 km. Strike-slip movement on these parallel faults could have been produced by dextral motion on a basement shear oriented about N20°-30°E.

The Hite fault system forms the boundary between the main parts of the Wallula and LaGrande fault systems. However, the Hite fault zone is also cut by faults parallel to and on trend with both the Wallula and LaGrande systems near Tollgate Chalet, although offset on these faults is small.

The Kooskooskie faults are north-striking, oblique-slip faults, with both west-side-down and dextral slip components. Orientation and

sense of motion are compatible with either the dip-slip or dextral motions on the Hite fault zone, thus these faults are included in the Hite system.

The Wallula fault system includes the west-northwest to northwest-striking faults between Wallula Gap and the Hite fault. Between Milton-Freewater and Wallula Gap, the northwest-striking faults (e.g., Vansycle and Warm Springs Canyon faults) form a pattern that suggests they are Riedel shears related to the Wallula fault. The pattern of the system suggests dextral motion. Exposures of the Milton-Freewater and Dry Creek faults also suggest dextral faulting of Frenchman Springs flows.

Faults of the Wallula system occur south of Walla Walla, Washington, and extend nearly continuously from the Columbia River south-eastward to the Hite fault. Some shears in the system cut the Hite fault near Tollgate Chalet.

The LaGrande fault system consists of north-northwest-to north-west-striking faults that extend from the LaGrande area to the Hite fault, where they are obscured by the complex faulting near the Hite fault. Most of the faults in this sytem appear to have a large normal component of movement (e.g., Phillips Creek). Those on the western side of the LaGrande graben are generally east-side-down, while those more than 2-3 km to the west are most often west-side-down. Large strike-slip components of motion have been documented both near the Hite fault and near the LaGrande graben on some of these faults. The overall geometry of the fault pattern suggests that the LaGrande graben is a pull-apart basin within a zone of dextral shear.

Some of the LaGrande faults cut and thus post-date the Sugarloaf Mountain volcanics (6.5 to 7.3 my) but do not appear to cut post-upper Pleistocene deposits. Maximum relief on these faults appears to be near the Grande Ronde syncline, suggesting genetic relationship between these features.

Analysis of the geometry of and interactions between the three fault systems suggests that the Hite system is the oldest, and that it influenced development of the two younger fault systems. This analysis also suggests that local reactivation of the westernmost faults in the Hite system has occurred through interaction with the Wallula fault system. Both the Wallula and LaGrande systems began to develop after the extrusion of

the Sugarloaf Mountain volcanice (6.5 mybp) and apparently both continued to move at least until late Pleistocene time.

Analysis of the fault patterns and motions suggests that both the LaGrande and Walla Walla basins are right-lateral pull-apart basins and that both could have been produced by a regional dextral shear transmitted through the Blue Mountains along the Wallula and LaGrande fault systems.

3. REGIONAL GEOLOGIC SETTING

3.1 STRATIGRAPHY

Geologic units exposed in the area range in age from the late Miocene Grande Ronde Basalt to Holocene alluvium (Figure 2a). For convenience in map compilation, we have grouped several minor geologic units (defined by previous investigation), and to some extent, further divided the Columbia River Basalt Group.

3.1.1 Columbia River Basalt Group (Tcr)

Within the area, at least 760 m of the Columbia River Basalt Group is present, including flows of the Grande Ronde, Wanapum and Saddle Mountains Formations. In addition, some olivine basalt, platy andesite, frothy andesite, and hornblende dacite shown on the map (Figure 2) in the southeast part of the area, are included in the Columbia River Basalt (see Walker, 1973, 1979).

Flows in the Grande Ronde Formation consist of fine-grained, glassy, tholeiitic basalt. Locally, an olivine bearing variant type, likely equivalent to a "High Magnesium" type of Beeson and Moran (1979) of the western plateau, is present near the top of the section, on the west flank of the Blue Mountains. Flow tops are most commonly of the "aa" type with thick (2-10m) blankets of scoraceous breccia. Flows and/or flow units are commonly thinner (10-20m) than the average of those in the western part of the Plateau (30m). Both the thickness of the flow-top breccias and the thinness of flow units is consistent with their proximity to the Chief Joseph dike swarm, the probable source for the flows (Taubeneck, 1969; Swanson and others, 1979).

Flows of both normal and reversed magnetic polarity are present within the Grande Ronde Basalt section (Swanson and others, 1979). In general, the upper part of the section exposed within the area is of normal polarity (N_2), where exposed in the drainages incised deeply into the Blue Mountains. The upper, normal part of the section ranges from about 200 m thick in the Walla Walla drainage to 300 m along the upper Umatilla River. Locally, a thin unit of reversed polarity is present near the top of the Grande Ronde Basalt. The variations in thickness of the upper, normal polarity unit and the local reversed flows within it suggest a magnetic

stratigraphy more complex than that defined by Swanson and others (1979). Unfortunately, however, the contact between the upper, normal polarity and the underlying reversed polarity flows, which is useful in defining the apparent dip-slip throw on some faults, is not extensively exposed in the area.

The Wanapum Formation is represented in the area only by flows assigned herein to the Frenchman Springs Member. These flows, which overlie the Grande Ronde Basalt, are olivine bearing, have a sub-diktytaxitic texture and contain distinctive embayed and rounded glomerocrysts of labradorite feldspar. Compared to the Grande Ronde flows, flows of the Frenchman Springs are generally coarser grained and have only minor flow top breccias. Presence of the distinctive feldspar glomerocrysts is diagnostic; they are present in virtually all Frenchman Springs flows in the area, although their abundance, size, and distribution are highly variable. Between flows, abundance ranges from 1 or 2 per square meter (m^2) of outcrop surface to more than $50/m^2$. Their size varies from less than 1/2 cm to over 5 cm, with an average range within a given flow unit of between 1 and 2 cm. All, however, have the distinctive internal complexitites of glomerocrysts, and commonly they are internally fractured and corroded or embayed by partial resorbtion. Assignment of these flows to the Frenchman Springs Member is based on: 1) their distinctive petrology, 2) their stratigraphic position, 3) their lateral continuity with Frenchman Springs flows in the Wallula Gap and Umatilla area, and 4) their chemical similarities to Frenchman Springs flows in other areas to the northwest (Wright and others, 1979).*

---

* Flows assigned herein to the Frenchman Springs Member may include some flows assigned by Swanson and others (1979) to the Eckler Mountain Member. These flows are chemically distinct from the Frenchman Springs (Wright and others, 1979) because of the petrographic, paleomagnetic and stratigraphic similarities of these flows to those of the Frenchman Springs Member, they are included with the Frenchman Springs flows for the purpose of this study.

Locally, the Frenchman Springs flows can be divided on the basis of the relative abundance of the glomerocrysts. For convenience, we divided the flows into sparsely glomeroporphyritic (less than approximately 1 feldspar/10m^2 of outcrop); moderately glomeroporphyritic (between about 1/10m^2 and 1/m^2); glomeroporphyritic (between about 1/m^2 and approximately 5/m^2); and abundantly glomeroporphyritic (greater than about 5/m^2). These differences in glomerocryst content persist over large distances in the western Columbia Plateau (Bentley, personal communication, 1979) and are very useful in establishing an intra-member stratigraphy for the Frenchman Springs flows.

Within the study area such differences are only useful locally, largely because of their proximity to a number of Frenchman Springs feeder dikes (Figure 2). Presence of the dikes, which also range from abundantly glomerophyric to sparsely glomerophyric in texture, resulted in a large number of local flow units. Many of these units probably were erupted simultaneously and mixed as they flowed away from the feeders, thus, accounting for some lateral variations observed within the flows. Others were apparently of minor extent and cannot be correlated throughout the area. Our observations indicate that no simple, consistent, internal stratigraphy is present throughout the area, and consequently, differences in glomerocryst abundance in the Frenchman Springs Basalt are only locally useful in establishing stratigraphic offsets across faults in the study area.

Dikes of Frenchman Springs Basalt were observed in several localities, particularly in the deeper drainages where their discordance with the older basalt flows is apparent. Several chemical analyses by Wright and others (1979) confirm the chemical identity of some of the dikes. However, west of the dikes are generally much coarser in texture than the Grande Ronde flows, which they intruded, and also considerably coarser than the Frenchman Springs flows and thus are readily identified in the field. All the dikes observed have the characteristic Frenchman Springs glomerocrysts, although as noted above, abundance of these glomerocrysts varies as widely in the dikes as in the flows.

Undoubtedly other, less well-exposed dikes are present in the area, but enough were observed to form some generalizations. First, all of the Frenchman Springs dikes observed are west of the Hite fault. Second, Frenchman Springs dikes near the Hite fault either dip at shallow angles westward (5°-20°) with respect to the host flows or are near vertical. Those

near vertical are located in or near fault zones and could have been emplaced either along a fault zone (e.g., Kooskooskie dike) or rotated by drag folding in the zone to a near vertical orientation (e.g., west Blalock Mountain dike). Those found in the western part of the area (e.g., Thorn Hollow, Couse Creek and Wildhorse Creek) appear to dip at shallow angles to the east. This pattern suggests that the dikes may intersect at depth along an arc extending approximately along the Ryan Creek fault to Bowlus Hill (T5N, R36E) and thence northeastward to Kooskooskie (T6N, R37E).

Although we did not find the type of linear vent systems reported by Swanson and others (1975), in several locations north of the Snake River, the Frenchman Springs dikes continue upwards into the Frenchman Springs flows, and clearly fed local flow units. Several dikes appear to become finer-grained and vesicular upwards, and to merge into individual flows. This relationship is apparent on the west side of Thorn Hollow (T3N, R35E), although partially obscured by the complexities of the Thorn Hollow fault.

The Saddle Mountains Basalt is represented in the area by the Umatilla Basalt flow. This flow appears to be largely confined to the Agency syncline (T2N, R33E through T4N, R35E) and areas to the west (e.g., T2N, R33E) and north (T5N, R35E). It appears to be contiguous with the type locality of the Umatilla flow at Silusi Butte, Benton County, Washington (Schminke, 1964). The flow is dark gray to black, generally fine-grained and has sparse, small plagioclose and pyroxene phenocrysts. In outcrop, it resembles many of the Grande Ronde flows; however, its stratigraphic position (above the Frenchman Springs flows), chemistry (Wright and others, 1979) and phenocryst content are diagnostic.

Only one area underlain by the Umatilla flow was found east of the Agency syncline (T3N, R34E). This is a tongue that extends east along Weston Mountain (SE 1/4, T4N, R35E) to near Tollgate Chalet (SE 1/4, T4N, R37E). In one locality on Weston Mountain, the Umatilla flow can be seen occupying a channel cut in an underlying, sparsely glomerophyric Frenchman Springs flow. At first glance, the outcrop (NE 1/4, SW 1/4, sec. 24, T4N, R35E) appears to be a Frenchman Springs dike cutting Grande Ronde Basalt. However, closer inspection shows that the overlying flow, which is Umatilla, clearly cooled against the Frenchman Springs flow, rather than vice versa, as one would expect with a dike. Thus the outcrops of Umatilla Basalt on Weston Mountain may represent filling of an ancestral drainage through the

Blue Mountains, which could possibly be the route by which the flow reached the Dalles-Umatilla syncline.

South of the Umatilla River (T2N, R36E) and east of Deadman Pass (T1N, R34E), the Grande Ronde Basalt is overlain by a sequence of olivine basalt flows, platy andesites and hornblende dacites. In addition, local eruptive centers of the andesites occur north and east of LaGrande (Figure 2). Work by Gehrels and others (1979) and Taubeneck (1979) suggests that these flows are lateral equivalents of similar rocks mapped in the Elgin, Oregon, area by Walker (1979). Our mapping largely confirms this, and also suggests that the olivine basalts occupy the same stratigraphic position as the Frenchman Springs flows to the west and north. Although these platy andesites and hornblende dacites probably should be separated from the other rocks in the area and given a formational rank, a reconnaissance study is insufficient to sustain such a revision, and therefore, we have included these rocks in the Columbia River Basalt Group.

However, we believe that the andesitic and dacitic centers, which overlie the olivine basalt and locally overlie the platy andesites, are sufficiently well defined to be mapped as a separate unit, as discussed below.

3.1.2 Sugarloaf Mountain Volcanics (Ta)

The upland buttes of Wilbur Mountain (sec. 6, T1S, R37E), Spring Mountain (sec. 19, T1S, R37E), Sugarloaf Mountain (sec. 32, T1S, R37E), Green Mountain (sec. 14 and 15, T1S, R37E), Black Mountain (sec. 6, T1N, R37E), and Huckleberry Mountain (sec. 28, T1N, R37E) consist of frothy, two-pyroxene andesite and dacite. Locally, platy andesites are exposed on these buttes, but their shieldlike form and high vesicularity suggest that the buttes are local volcanic centers. Indeed, frothy andesites were found only on or near these upland buttes. These rocks are quite distinctive from the underlying platy andesites and olivine basalts, and appear to be restricted in their distribution to the areas shown on Figure 2. We herein name these rocks the Sugarloaf Mountain volcanics, and define the south slopes of Sugarloaf Mountain (Drumhill Ridge Quadrangle, NW 1/4, and NW 1/4 SE 1/4, sec. 32, T1S, R37E, elevation 4,280 ft. to 4,467 ft.) as the type section. A detailed description of these volcanics and their type section will be forthcoming soon.

Because the Sugarloaf Mountain volcanics appear to be significantly less weathered than the underlying flows of the Columbia River Basalt Group, we believe that they are likely much younger. Indeed, three K-Ar age determinations (Louis Hogan, written communication, 1979) from Spring Mountain, Wilbur Mountain, and a dacite plug that cuts the southeast flank of Sugarloaf Mountain, yielded ages between 6.5+/-.14 and 7.3+/-.15 my (Table 1). The youngest age is from the plug, as might be expected. Ages of the andesites from Wilbur and Spring Mountains were statistically identical (7.3+/-.15 and 7.26+/-.11 my, respectively). Although further work is planned on these vent rocks and their field relations, it is presently clear that they are significantly younger than flows of the Columbia River Basalt Group in the area.

3.1.3 Plio-Pleistocene Sedimentary Rocks (QTs)

All sedimentary units that postdate the Columbia River Basalt Group and predate the upper Pleistocene glaciofluvial deposits (Section 3.1.4) have been grouped together as QTs on Figure 2. The principle sediments included are the "fanglomerate of Pliocene age" of Hogenson (1964), and the "old gravel and clay" and the Ringold Formation of Newcomb (1965), in the Pendleton and Walla Walla areas, respectively. In the LaGrande area, units previously mapped as Tertiary fanglomerate and lacustrine deposits by Hampton and Brown (1964), and lake beds (QTl) by Gehrels and others (1979) have been grouped with these Plio-Pleistocene sediments.

In general, these sedimentary materials are correlative with, or contiguous with, the upper part of the Ellensberg and Ringold Formations in southeastern Washington, and The Dalles Formation in Oregon (Newcomb, 1979). They range from coarse - to fine-grained, dirty gravel fans shed from the rising Blue Mountains to fine-grained, silty-clayey lake beds deposited in basins that formed behind growing late Tertiary structures.

3.1.4 Glaciofluvial Deposits (Qgf)

Extensive deposits of upper Pleistocene, poorly-sorted gravel, sand, and silt deposited by the ice-age Columbia River, occur in the Walla Walla and Dalles-Umatilla synclines. In addition, fine-grained lake beds occur in areas away from the present main Columbia River drainage, which were deposited in the slack waters impounded behind the torrential glacial

floods (Newcomb, 1965). Both the coarse-grained, torrential flood deposits and the slack-water deposits are grouped on Figure 2 as glaciofluvial deposits (Qgf). They include Qgf of Newcomb (1965) and Hogenson (1964), the Touchet beds of Newcomb (1965) and glacial lake sediments (Qls of Hogenson, 1964). Of these deposits, the Touchet beds in the south part of the Walla Walla syncline are the most important to this investigation. Work by Waitt (1978) has shown the Touchet lake beds to range in age from about 13,000 years to about 10,000 years. Thus the evidence for faulting of Touchet beds (Sections 4.2.1 and 4.2.4) is indicative of young faulting on some of the structures in the area.

3.1.5 Loess (Ql)

Much of the area east of Pendleton, Wallula, and Walla Walla is underlain by extensive deposits of loess. Near Athena, Weston, and Helix, Oregon, cut slopes along the Union Pacific Railroad reveal the loess to be a sandy silt in excess of 20 m in thickness. Farther from the ancestral Columbia flood plain, the loess thins and becomes finer-grained.

At least two distinct ages of loess are included on Figure 2. These are the largely pre-glacial Palouse loess (Newcomb, 1951, 1965) and a younger, post-glacial loess derived principally from the Touchet beds (Figure 2b). The pre-Touchet (i.e. pre-13,000 year) age of much of the loess indicates that faulting of the loess is not prima facie evidence for very young faulting in the area (Section 4.2.4).

3.1.6 Quaternary and Holocene Alluvium (Qal)

Alluvial deposits of inferred late Pleistocene to Holocene age include fluvial sand, silt and gravel (Qya, Quv and Qoa of Newcomb, 1965; Qal of Hogenson, 1964) young alluvium and colluvium in the LaGrande area (Ql, Qaf and Qav of Hampton and Brown, 1964) and a variety of young stream deposits in the Blue Mountains.

3.2 REGIONAL TECTONIC SETTING

The area of investigation (Figures 1 and 2) includes several distinct structural terrains, notwithstanding the occurrence of Columbia River Basalt as bedrock throughout virtually the entire area. These structural terrains include the anticlinal Blue Mountains, the Walla Walla and LaGrande

structural basins, and the eastern ends of the southernmost Yakima Ridges - the Rattlesnake and Horse Heaven structures and the associated Dalles-Umatilla syncline.

3.2.1 Blue Mountains Anticlinorium

The main Blue Mountain uplift is a broad arcuate, generally gentle anticlinal fold. The highest uplands, which occur in a broad concave northwards arc between Balley Mountain (T3S, R33E) and Bald Mountain (T4N, R38E) coincide approximately with the anticlinal crest. South of the Wilbur Mountain area (T1S, R36E) the anticlinorium has a fairly symmetrical shape, as both flanks dip gently away from the crest at 2° to 5°. The axis and culmination both follow the axis shown on Figure 2. The north flank descends gently toward the McKay Creek drainage (T1S, R33E), interrupted only by the Cabbage Hill monocline. Southeast of this flexure, the dips approach horizontal, while to the north they abrubtly steepen to about 3° to 5° and locally approach 8° to 10°.

North of Wilbur Mountain, the Blue Mountains have a distinctly box-like structure. The crestal area is a broad flat upland from 6 to 10 km in width. The northwest flank dips gently 3° to 5° towards the Agency, Dalles-Umatilla and Walla Walla structural lows. The north hinge of the box fold lies along the Duncan monocline, the Hite fault and the Mill Creek monocline (Figure 2), from south to north, respectively, and thus, it roughly parallels the structural grain of the Hite fault system (Section 4.1). The southern hinge line of the box-shaped anticlinorium is less well defined than the northern. Indeed, our reconnaissance suggests that it is largely obscured by the intricate pattern of faults that comprise the LaGrande fault system. North of the Phillips Creek fault (T2N, R38E), the south hinge appears to be lost amongst north-striking faults paralleling the Bald Mountain fault.

The northern, box-shaped part of the Blue Mountains structure is paralleled by the Agency syncline and the Reith anticline. Although these two folds are of much lesser amplitude than the Blue Mountains, they appear to be similar in cross-section. Structural relief of the Blue Mountains is on the order of 1200 m (4,000 feet); i.e., the difference in elevation of the top of the Frenchman Springs Member between the axis of the Agency syncline near Mission (T3N, R34E) and the anticlinal crest east of Tollgate

(T4N, R38E). Total relief may increase south of the Tollgate area, but the detailed stratigraphic studies of the Grande Ronde flows needed to document this have not yet been done.

The Agency syncline, which bounds the north flank of the northern part of the Blue Mountains, begins as a low, or sag, in the north flank of the southern, northeast-trending part of the Blue Mountains at Pilot Rock and extends north-northeast to north of Athena. It appears to die out in the area of interference between the Horse Heaven anticline and the north flank of the Blue Mountains and the Walla Walla fault system.

The Reith anticline extends from the north flank of the Blue Mountains, west of the area of Figure 2, northeast to the Horse Heaven anticline. Maximum relief on this fold is about 230 m, west of Pendleton.

3.2.2 Horse Heaven Anticline

The Horse Heaven anticline is the largest anticlinal structure in the southern part of the Yakima Ridges (or Yakima Fold Belt; Shannon & Wilson, 1977b; WPPSS, 1977e). The fold rises from the Blue Mountains north flank, north of Athena, and continues north-northwest past Wallula Gap to near Benton City, Washington, where it turns to a generally westerly trend and continues westward to the Cascade Mountains (Newcomb, 1971; WPPSS, 1977a). Within the area of investigation, the Horse Heaven is an assymetrical anticline with a gentle $1/2^{\circ}$ to 1° south flank and a steeper 3° to 5° north flank. The north flank is interrupted by the secondary faults of the Wallula fault (Newcomb, 1965; Shannon & Wilson, 1979). Amplitude of the fold, which is about 400 m south of Umapine and Touchet (T5N, R33 and 34E), decreases to less than about 300 m at Wallula Gap; while west of Wallula Gap, the anticline becomes more complex and increases in amplitude to over 500 m. Presence of Wallula Gap at this sag in the Horse Heaven structure suggests structural control of the course of the Columbia River through the Horse Heaven anticline. However, the lowest structural elevation of the Horse Heaven occurs at its eastern end, north of the Agency syncline and southwest of Milton-Freewater. There, maximum elevation of the top of the Columbia River Basalt is about 500 m, as opposed to about 530 m at Wallula Gap. Perhaps this indicates subsidence of the east end of the structure since establishment of the present course of the Columbia through Wallula Gap. This would be consistent

with the apparent movements along young faults in the Wallula fault system, which trend west-northwest along the Horse Heaven's north flank.

4. REGIONAL FAULT SYSTEMS

Faults within the area between Pendleton, Walla Walla, and LaGrande all appear to be associated with three major fault systems. These fault systems are the north-northeast-trending Hite system, the west-northwest-trending Wallula system, and the north-northwest-to northwest-trending LaGrande fault system. The Hite fault system parallels, and is largely confined to, the northwest flank of the north-northeast-trending portion of the Blue Mountains anticlinorium, north of the Umatilla River. As discussed later (Section 4.1), the latest motion on faults within the Hite system appears to be largely right-lateral (i.e., dextral strike-slip). Because these faults transect the regional dip, their effect is to extend the Blue Mountains northern slope.

The Wallula fault system parallels the Rattlesnake-Wallula lineament, located along the north flank of the Horse Heaven anticline. Although these faults appear to be dominantly dextral strike-slip, some also have a down-to-the-north dip component which drops the Columbia River Basalt down into the Walla Walla syncline. Faults of the system appear to extend from near the postulated Olympic-Wallowa lineament on the south, northwards across the Walla Walla syncline. Along trend, it extends east-southeastward from Wallula Gap to the Hite fault.

The LaGrande fault system occupies the southeast part of the area. It extends from the Mill Creek-Hite fault-Duncan hinge line south-southeast into the LaGrande graben. The movements on the north part of the system appear to be, in part, dextral strike-slip, and in part, dip-slip. Near LaGrande, two periods of movement -- early dextral strike-slip and later dip-slip -- are documented (Gehrels and others, 1979).

No unequivocable age relationship between the three fault systems has been documented. In the Milton-Freewater and Tollgate area, where the three systems intersect, the junctures between the faults, in some places, suggest conflicting relative ages. This evidence may be indicative of reactivation along parts of the Hite fault system or at least partially concurrent development of the systems. The preponderance of the evidence however, does not indicate that the Wallula and LaGrande systems are younger than the Hite system and that they have moved since late Pleistocene time.

4.1 HITE FAULT SYSTEM

The Hite fault system is a series of north-northeast-to north-striking, strike-slip faults, which parallel the Blue Mountain trend from the McKay Creek drainage north to the Mill Creek drainage (Figure 2). These faults are largely confined to the north flank of the Blue Mountains, between the Agency syncline and the Mill Creek-Hite fault-Duncan structures. They form an en echelon pattern with an overall trend of N20° to 30°E. From west to east the major faults in the system include the Thorn Hollow, Saddle Hollow, Ryan Creek, Peterson Ridge, Blalock Mountain and Hite faults. The Thimbleberry Mountain fault strikes parallel to the Hite fault about 10 km to the east. Several lesser faults with similar north to north-northeast trends occur in the Deadman Pass-Emigrant Springs area and south of Bingham Springs along the southern projection of the Hite fault. The Hite fault, which is a much more prominent and complex structure than others in the system, extends northeast of the study area for at least 60 km. However, within the area, all faults within the Hite system appear to have similar orientations, and are interpreted to have similar motions, as discussed below.

4.1.1 Hite Fault

The Hite fault is the easternmost and longest of the faults within the Hite system. It extends from near the northeast corner of the study area (Figure 2) along a gently sinuous trend south-southwest about 40 km to the South Fork of the Umatilla River (T3N, R37E). North of the map area, the fault crosses the Touchet, Tucannon and Pataha Creek drainages and extends to near the Snake River, about 50 km north of the study area (Shannon & Wilson, 1973). Within the study area, the Hite fault is an extremely complex zone of faulting that ranges in width from a few tens of meters to more than 1-1/2 km.

Portions of the Hite fault zone exhibit at least three generations of gouge; and rock units of different ages appear to have different amounts of displacement across the zone. Both of these phenomena suggest episodic movement of the fault. Although the fault is shown on Figure 2 as a discrete trace, it actually consists of from one to several sub-parallel shear zones, as well as drag folds and associated riedel shears (Tchalenko, 1970). North of The Horseshoe (T5N, R38E), the fault bifurcates into a major and minor

strand. Similar patterns are suspected for other portions of the fault, but have not been documented.

At its southern end, the Hite fault zone appears to dissipate into a number of smaller faults. However, because this area is quite complex and poorly exposed, the southern terminus of the zone has not been definitely located. Several, east-dipping, dip-slip faults appear to take up some of the motion south of Graves Butte (T3N, R37E). In addition, some of the motion may be translated into the northwest-trending faults between Black Mountain and Buck Mountain (T2N, R37E) and northeast-trending faults which extend from Duncan (T1N, R36E) to Graves Butte.

The Hite fault zone is best exposed in the upper Walla Walla River and Mill Creek drainages. Logging roads and natural exposures north of Tollgate Chalet (SE 1/4, T4N, R37E) and on Indian Ridge (T6N, R38E) reveal a broad 80 to 200 m zone of crushed, brecciated, and sheared basalt. Much of the zone is cemented by chalcedony and stands in positive topographic relief as a "china wall". Other areas within the zone consist of angular, crushed, uncemented basalt with variable amounts of clay matrix. Well defined zones of yellow, orange or red-brown silty clay, which appear to be finely commutated basalt, cross-cut both the cemented and uncemented gouge.

In the South Fork of the Walla Walla River drainage, north of Tollgate Chalet, few structural indicators of the sense of faulting are evident. Those observed indicate oblique-slip; however, some small shears within the main fault zone show sub-horizontal striae.

On Indian Ridge (T6N, R38E), the Hite fault consists of two principal zones. The eastern zone, which appears to be the main zone, is about 75 m in width and contains all three generations of gouge. The western zone parallels the main zone, but it contains no cemented gouge where exposed. Both zones contain three well-developed sets of shears, which are generally expressed as silty-clay or finely-brecciated basalt gouge. The best developed set trends N10° to 15°E, parallel to the Hite zone. These shears, which are vertical or near vertical, form the main boundaries of the gouge zone and also occur within the gouge. The second set is also near vertical, but trends N5° to 15°W. Shears on this trend originate within the gouge, and in some places, extend over 1 km from the Hite fault (Figure 2). The

third set is poorly developed. It trends N45° to 60°E and dips 65° to 70°W. These shears appear to extend as far as 100 m, or so, beyond the main zone.

Orientation of these three shear sets is consistent with the interpretation that the most recent movement on the Hite fault was dextral strike-slip. The N10° to 15°E shears represent both the main shear and possibly some P shears (Tchalenko, 1970), the N5° to 15°W shears are reidel shears, while the N45° to 60°E shears are conjugate reidel shears, or tension gashes (Hills, 1963).

Striae are well developed on all three sets of shears on Indian Ridge along Tiger Creek Road (SE 1/4, T6N, R38E). Striae on the main shears (N10° to 15°E) are generally near horizontal, with a few inclined as much as 15°N from horizontal, where the shears dip west about 85°. Our interpretation of paleomagnetic data from Indian Ridge (Weston Geophysical Research, Inc., 1978; Shannon & Wilson, 1977c) shows the west side of the Hite fault zone to be down. Thus the dip of the shears, the rake of striae, and the sense of vertical offset are all consistent with nearly pure dextral motion along the zone.

Striae on the N5° to 15°W (reidel) shears are also near horizontal (0°-8°N) consistent with dextral motion on the Hite fault zone. The conjugate reidels or tension gashes (N45° to 60°E-trending shears) exhibit striae which rake more steeply, generally from 25° to 45°NW. This is consistent with a large normal component of movement, as would be expected on these shears for dextral motion on the Hite zone.

The geometry of the three sets of shears favor nearly horizontal dextral slip on the Hite fault zone. However, the large vertical offset of Grande Ronde flows suggests a large component of dip-slip movement. On both Indian Ridge (T6N, R38E), and in the South Fork of the Walla Walla River, north of Tollgate Chalet (T4N, R38E), N-2 polarity flows are juxtaposed with R-2 polarity flows, indicating vertical offset of over 100 m of the Grande Ronde flows. However, the Frenchman Springs and Saddle Mountains flows, which overlie the Grande Ronde flows in the uplands of the Tollgate Chalet (T4N, R38E) area appear to have only a few tens of meters of vertical offset across the Hite zone. Thus, the small amount of stratigraphic data available near the Hite fault zone suggests larger vertical offset of the older Grande Ronde flows (15my) than of the younger flows. Such age variation

in the amount of offset could be explained by either: 1) continued strike-slip movement of the Hite zone from post-Grande Ronde time to shortly after Saddle Mountain time; or 2) normal, dip-slip movement in post-Grande Ronde time, and post-Saddle Mountains dextral strike-slip motion. The first alternative requires a relatively large amount of strike-slip, sufficient to produce more than 100 m of apparent vertical offset. The inclinations of striae measured suggest that at least 0.7 to 1.0 km of lateral motion would be required. The second alternative requires no strike-slip motion in post-Grande Ronde, pre-Saddle Mountains time, and a much smaller amount of strike-slip in post-Frenchman Springs time. In addition, rejuvenation of the Hite fault is consistent with the multiple generations of gouge present along the zone. The favored interpretation is that the cemented "china wall" breccia likely developed during an initial phase of predominantly dip-slip movement which occurred in pre-Frenchman Springs time. The younger, uncemented gouges, which cut the older breccia, were developed during dextral movement of post-Saddle Mountains age.

4.1.2 Blalock Mountain Fault

The Blalock Mountain fault, as defined herein, extends from the South Fork of the Walla Walla River north-northeast to the Kooskooskie fault (sec. 29, T6N, R38E), a distance of about 13 km. The fault is best expressed on the south side of Blalock Mountain (Figure 2) where it offsets Grande Ronde flows (NE 1/4, sec. 10, T4N, R37E). Little is known about the fault. In the South Fork Walla Walla River, the Grande Ronde flows appear to be down on the east, suggesting dextral dip. No shear zone directly observed; however, on the color infrared air photos, the fault appears as a series of sub-parallel to en echelon shears, each from one-half to about 3 km in length and apparently striking slightly to the west of the overall trend of the zone. Such a pattern would imply sinistral slip, at odds with that suggested by the apparent stratigraphic offset.

The Blalock Mountain fault appears to die out south of the west-northwest-striking Lincton Mountain faults. Its inferred juncture with Kooskooskie faults is not exposed; however, the oblique sense of motion measured (Figure 2; SW 1/4 sec. 9, T6N, R38E) on the eastern Kooskooskie fault (right-later, west-side-down) is consistent with and compatible with

the right-lateral motion inferred for the rest of the Hite fault system. Thus, right-lateral strike-slip on the Blalock Mountain fault could produce the observed slip on the Kooskooskie faults, if the two are connected.

4.1.3 Peterson Ridge Fault

The Peterson Ridge fault, named herein, is inferred to extend from west of Bingham Springs near the Umatilla River, north-northeast near Peterson Ridge, a distance of at least 24 km. The fault may extend south of the Umatilla drainage; however, more detailed mapping would be required to establish this extension. The fault is expressed as a series of saddles and notches in the ridge and spur crests, as a linear depression on flat area, and as aligned side drainages near the main streams.

On the south flank of Blalock Mountain (sec. 4, T4N, R37E, and sec. 33, T3N, R37E) the Peterson Ridge fault appears to juxtapose colluvium and Grande Ronde Basalt. However, detailed mapping of this area would be necessary to confirm this apparent relationship. Attitudes of the basalt change measurably across the fault. For example on Blalock Mountain (SE 1/4, T5N, R36E) the basalt east of the fault dips 15°E and strikes about N15°E, while west of the fault it dips 5°W and strikes about N45°E. This dip reversal occurs over a distance of about 150 m, and flows within this reach are frequently highly jointed or shattered. This relationship suggests a significant amount of compression across the fault. In the North Fork of Cottonwood Creek (NW 1/4 sec. 10, T4N, R37E) and on Blalock Mountain (NW 1/4 sec. 9, T4N, R37E), Grande Ronde Basalt has an apparent east-side-down offset across the Peterson Ridge fault. On Blalock Mountain this offset is less than about 20 m, based on elevation of the N_2-R_2 contact. In the Umatilla drainage, the Grande Ronde Basalt appears to be down on the west side of the fault. Our reconnaissance did not establish directly the sense of motion of the Peterson Ridge fault. However, the apparent east-side-down offset of the northwesterly regional dip suggests right-lateral slip. In addition, the changes in attitude of the basalt, apparent change in vertical offset along trend, the extremely linear topographic expression, and the similarities in both orientation and expression to the Hite, Thorn Hollow and Saddle Hollow faults suggests that strike-slip was the principal component of movement.

4.1.4 Ryan Creek Fault

The south end of the Ryan Creek fault, south of the Umatilla River, was partially mapped by Hogenson (1964) along Ryan Creek. Our reconnaissance documents that the fault extends north from Ryan Creek along a N5°W trend to Weston Mountain (T4N, R36E), where it turns to a N5° to 10°E trend, nearly parallel to the other faults in the Hite system northwest of Black Mountain (SE 1/4, T2N, R36E).

From Weston Mountain, the Ryan Creek fault extends at least 6 km northwards into the Dry Creek drainage, where it appears to either intersect, or terminate the eastward projection of the Dry Creek fault (Section 4.2.3). South of Ryan Creek, the fault can be followed into the Meacham Creek drainage (SE cor. T2N, R36E) where it appears to connect with the south extension of the Hite fault trend.

Apparent offset of the fault north of Dry Creek is down to the east by almost 30 m. This is based on the occurrence of a prominent Grande Ronde flow at different elevation on opposite sides of the zone.

During the July 16, 1936, Milton-Freewater earthquake, a large spring began to flow near the inferred juncture of the Ryan Creek and Dry Creek faults. Figure 2 shows the spring as "Earthquake Springs" (sec. 16, T4N, R36E). Flow of the springs, which was about 230 liters/min. before the earthquake, increased to about 11,400 liters/min. at the time of the earthquake, and then diminished rapidly to 3,800 liters/min. by August 14, 1936 (Newcomb, 1965). In 1960, the flow from this spring was 4 liters/min. (Newcomb, 1965). The flow pattern and spring location suggest rapid, partial draining of one of the basalt acquifers, where it was cut by the Ryan Creek or Dry Creek faults. Such draining might have been a result of movement of either of the faults, tilting of the strata up-structure of the faults, or dilatency within the fault gouge allowing increased flow.

Although the Ryan Creek fault appears to terminate the inferred projection of the Dry Creek fault (Figure 2) at their juncture, as discussed below (Section 4.2.3), the Dry Creek fault appears to be young and more likely related to current tectonic activity than is the Ryan Creek fault.

4.1.5 Saddle Hollow Fault

The Saddle Hollow fault is perhaps the best expressed (other than

the Hite fault) of the north-northeast-striking strike-slip faults in the area. It was traced during our reconnaissance from 3 km south of Highway I-80 (NE 1/4, T1N, R35E) north-northeast to near Milton-Freewater. Throughout this 42 km extent the fault is either a prominent topographic or vegetation linear, which cuts diagonally across the general northwest-trending topographic grain of the area. Locally it forms a major groundwater barrier, as evidenced by numerous seeps and small springs that originate in, or just up-dip of, the gouge zone. Water-loving vegetation, such as ferns, elderberry, and aspen, which are normally sparse in the area, are more common along much of the zone, particularly south of the Umatilla River.

The Saddle Hollow fault zone is well-exposed in the north bank of the Umatilla River (SE cor., T3N, R35E) just west of Saddle Hollow. There, the fault consists of at least three, nearly parallel shear zones, which trend between N15° and 26°E. The largest zone is the easternmost, which trends N18°E, dips 66° to 72° northwest, and ranges between 10 and 12 m in width. Apparent offset of several distinctively jointed flows within the Grande Ronde Basalt is east-side down; however, well developed sub-horizontal (0°-10°N) grooves and striae in the zone show nearly pure strike-slip motion (Figure 3).

The westernmost zone, which is exposed about 200 m west of the main zone, trends N15°E and is more than 10 m in width. As with the easternmost zone, striae are near horizontal, with a slight northwards (5°-10°) rake. Between these two zones, several small shears occur, and the basalts are crushed and shattered. One of these larger secondary shears exposed about 120 m west of the main shear, trends N26°E, dips 45°SE, and the striae on it rake 40° to 70°SW. The pattern of the two main strike-slip shears, and of secondary oblique-slip shears at a low angle to them, is indicative of dextral motion on the zone as a whole.

A similar picture emerges about 6 km north of Saddle Hollow, where the fault crosses Reed and Hawley Mountain (SE 1/4 sec. 1, T3N, R35E). There a complex zone, 120-150 m in width, contains shears trending from N15°E to N35°E. Those shears most divergent from the main N10°E trend of the fault show the most steeply raking striae (up to 45°S). Striae on those shears parallel to the main trend are near horizontal. The contact between the Frenchman Springs and the underlying Grande Ronde flows is about 25 m

lower east of the fault than it is to the west. Since the regional dip is to the northwest, this apparent offset suggests dextral slip.

North of Reed and Hawley Mountain the Saddle Hollow fault is topographically expressed as an alignment of saddles and notches in the ridge crests, and structurally expressed by a 2^{o} to 4^{o} change in dip, with steeper dips generally to the west. Little or no vertical offset is apparent across the fault north of Pine Creek.

Age and total offset of the Saddle Hollow fault are not known; more detailed stratigraphic work would be necessary to establish these parameters. What data is available is somewhat ambiguous. For example, the Saddle Hollow fault appears to terminate or offset the eastward topographic extension of the Milton-Freewater and Little Dry Creek faults, both of which show late Pleistocene movement (Sections 4.2.3 and 4.2.4). Thus, one could argue that the Saddle Hollow fault appears to be quite young. Other evidence of relative youth is provided by the apparent topographic offset of northwest-striking faults by the Saddle Hollow fault south of Deadman Pass (T1N, R34E). These northwest-striking faults are thought to be part of the LaGrande fault system, which, in part, is at least younger than 6.5 my (Section 4.3).

The topographic expression of the Saddle Hollow fault, however, does not suggest young movement. Ridges and spurs crossed by the fault are not systematically offset, nor are drainages offset by the fault. In addition, the upland pediment is not offset, and alluvial deposits in stream valleys appear to cross the fault undisturbed. More detailed work would be necessary to resolve the apparent conflict between those data that suggest a young age and those that suggest a much older age.

4.1.6 Thorn Hollow Fault

Thorn Hollow is a linear stream valley, tributary to the Umatilla River (T2 and 3N, R35E), which has been excavated along part of the fault herein named the Thorn Hollow fault. The fault is inferred to be a zone of faulting extending from the Bade fault (NW sec. 23, T5N, R35E), near Milton-Freewater south and south-southwest to near Deadman Pass, where it joins a number of other north-northeast-and northwest-striking faults. From Deadman Pass it appears to continue about 13 km farther to the south-southwest as

shown on Figure 2, for a total length of at least 43 km. Over this extent, the fault has an expression quite similar to the Saddle Hollow fault. It is expressed as an alignment of linear streams, saddles and notches in ridges north of the Umatilla River, and as a shallow, linear depression associated with moisture-loving vegetation south of the Umatilla River. It differs from other faults in the Hite system by turning to a N5°W strike at its north end.

Only the margins of the fault zone are exposed along the slope of Thorn Hollow. On the east side of the hollow (NW 1/4, SW 1/4, sec. 33, T3N, R35E) near vertical to 80°W-dipping secondary shears are exposed in the roadcut striking N10°W through Grande Ronde Basalt. In a borrow pit on the west side of the hollow (NW cor. SW 1/4, sec. 33), a nearly horizontal thrust fault cuts flows and a dike of the Frenchman Springs and juxtaposes the flows with the dike (Figure 4A). Striae on the N10°W shears rake 10°N, while those on the thrust zone trend between N10°W and N20°E. The thrust appears to be part of the faulting related to the Thorn Hollow zone, perhaps similar to the "Palm Tree" structure on the Forks fault discussed in Section 4.2.5.

Frenchman Springs flows occur on the west side of the hollow at the same elevation as Grande Ronde flows occur on the east side, suggesting west-side-down component of motion, as does offset of the Frenchman Springs dike (Figure 2). However, the thrust and N10°W shears, together with the striae, demonstrate that the major movement was strike-slip. As with the Saddle Hollow fault, the fault pattern at Thorn Hollow is consistent with dextral motion. However, the slight northward rake of striae, the regional dip, together with the apparent vertical component of offset, would appear to require dextral movement to produce the observed offset.

Several smaller, but still impressive faults, which parallel the Thorn Hollow fault, cross Highway I-80 at Deadman Pass (Figure 2). These faults also have some component of vertical motion; however, striae developed on them demonstrate largely strike-slip motion. These small faults are well exposed in roadcuts in sections 1, 2 and 3, T1N, R34E, along I-80 north and Old U.S. 30, west of Deadman Pass. In addition, several other fault zones are inferred to be concealed beneath colluvium in small swales. Figure 4B shows the largest zone exposed, near the center of sec. 2, about 1.8 km west of Deadman Pass. This zone juxtaposes glomerophyric Frenchman Springs

Basalt against high-Magnesium Grande Ronde Basalt along both the old highway and I-80 north. The zone trends N15°E, dips 87°E, and has striae which rake 13°-15°S. The gouge shown in the photo is uncemented, crushed basalt with a clay-silt matrix. About 10 m of gouge is exposed in the cut, but the zone is likely at least twice that width. Vertical offset of the Frenchman Springs flows is estimated to be more than 85 m, down to the west, on this fault. The rake of striae and the regional dip, which is to the northwest (Figure 2), suggests that at least 450 m of dextral slip would be required to produce the apparent vertical offset.

South of the Bade fault (Figure 2), the Thorn Hollow fault is well defined by a topographic lineation. The lineation consists largely of the aligned, straight, N-S drainage of Dry Creek, through sections 2 and 11, T4N, R35E, and sections 23, 26 and 35, T5N, R35E. Extension of the fault into the Dry Creek drainage is based on continuation of topographic and magnetic linears, and on steepening of dips near the zone to the southwest of Weston. Road cuts in Highway 11 reveal the fault to be a complex zone of brown, crushed and altered basalt gouge. The most recent and most intensely faulted zone exposed is located on Highway 11 between Dry Creek and Little Dry Creek, about 0.3 km south of Dry Creek (SW 1/4 NE 1/4, sec. 2, T4N, R35E). This zone, which is about 20 m in width, trends about N15° to 5°W and dips 85°W. Striae within the zone are near horizontal on shears parallel to the N5°W trend. Several shears within the zone strike near the trend of the Little Dry Creek fault (N30° to 40°W). A small fluvial channel overlies part of the Thorn Hollow fault zone, and in turn, is overlain by loessial material (Palouse Formation). Abundant fractures filled with caliche occur in the gouge zone. A few of these fractures, which are parallel to the main gouge zone, can be traced through the fluvial silt, sand and gravel, and into the loess to near the ground surface. Because of poor stratification, the relationships are not entirely unequivocal; however, it appears that along some of the fractures basaltic gouge is juxtaposed against loess and the fluvial deposits. If this is correct, and it appears to be so, it is strong evidence for post-late Pleistocene movement of the Thorn Hollow fault. Other, circumstantial evidence for young movement is the "Earthquake Spring", which is located to the southeast on the connecting Dry Creek fault, and faulting of the Palouse Formation along the Little Dry Creek fault (discussed in Section 4.2.4).

4.1.7 Kooskooskie Faults

The Kooskooskie faults are three north-striking faults which extend from the northeast corner of the area (Figure 2) south into the Mill Creek drainage and thence south to the Mill Creek monocline. All three faults have prominent topographic expressions as linear depressions which cut across the topographic grain.

The westernmost of the Kooskooskie faults extends from north of the study area, southwards along the west boundary of Tps. 6 and 7N, R38E, south to the Mill Creek monocline (NW 1/4, T5N, R38E). South of Mill Creek this fault appears to connect with the north-northeast-trending Blalock Mountain fault. Dips on both sides of the fault increase to 5° to 10°NW away from the 2° to 3°NW regional dip, suggesting gentle, west-facing drag folds. The fault is near vertical, but it has a tendency to deviate slightly to the east on highlands, suggesting a slight westward dip. On the east end of Blacksnake Ridge (sec. 18, T7N, R38E), the fault drops the Frenchman Springs Basalt about 100 m down to the west. On the north side of Mill Creek (NE 1/4 sec. 6, T6N, R38E), a vertical Frenchman Springs dike, about 12 m in width, occurs in the fault zone. Exposures do not permit evaluation of the relationship, so it is not clear if the dike intrudes the fault, or the fault parallels or cuts the dike. Because of the offset of Frenchman Springs Basalt by the Kooskooskie fault to the north on Blacksnake Ridge, it is most likely that the fault follows or cuts the dike. However, dike emplacement and faulting could have been contemporaneous.

The eastern Kooskooskie fault extends from north of the area (Figure 2) across the west ends of Biscuit and Blacksnake Ridges (near the center of Tps. 7 and 6N, R38E) south to Mill Creek near the west end of Indian Ridge. An air photo linear south of Mill Creek suggests that the fault may continue south to a north-striking fault on the east side of Government Mountain (secs. 4, 9 and 16, T5N, R38E) to the Hite fault. The eastern Kooskooskie fault is apparently joined by the central Kooskooskie fault about 1 km north of Mill Creek, near the Oregon-Washington State Line. Both the central and eastern faults have strong topographic expressions, similar to the western Kooskooskie faults although the central fault appears to be a narrower zone with less offset. Offset of the western zone is down to the west, and dips about 85°W, where exposed.

On Blacksnake Ridge (sec. 21, T7N, R38E) a distinctive glomeroporphyritic Frenchman Springs flow (possibly the Eckler Mountain Member of Swanson and others, 1979) is dropped about 160 m down to the west by the fault. Striae on the zone at Biscuit Ridge (about 3 km to the north) rake 48°NW. The offset of flows, together with the striae, indicate dextral, oblique-slip motion. Total throw is likely only about 230 m. The sense of throw on the fault is compatible with the dextral motion of the nearby faults of the Hite fault system. Together with their apparent proximity to, or connection with the Hite system, the offset suggests a genetic relationship; therefore, the Kooskooskie faults are included in the Hite fault system for the purposes of this study.

4.1.8 Other Faults in the Hite Fault System

Interpretation of the Hite fault system is critical to the understanding of the tectonic history of the area, and also, to an understanding of the neotectonics. Consequently, it is important to understand the limits of this study, which has only briefly examined a very complex area. Several other faults, not discussed above, which appear to be part of the Hite system, have not been examined on the ground. Their traces and apparent offsets, shown on Figure 2, were estimated largely from aerial reconnaissance, and from aerial photographs and topographic maps. For the purposes of this evaluation, it is assumed that these faults are, indeed, similar to the more prominent faults in the Hite system. In addition, there are literally dozens of small faults, which are probably also part of the Hite system, but which we have not shown on Figure 2. Most of these small faults form prominent one-half to 1 km long photo lineations on the Blue Mountain's summit and slopes. Detailed mapping on air photo interpretation of some areas would undoubtably double or triple the density of faults shown on Figure 2 west of the Hite fault. East of the Hite fault, there are also several zones which may be part of the Hite system. Trends of several of these zones are parallel to or slightly divergent to the Hite fault. However, the complexities of the LaGrande fault system obscure these faults and their relation to the Hite system.

The most prominent of the faults east of the Hite fault are the Meacham Creek (sec. 30, T1N, R37E through sec. 8, T2N, R38E) and Thimbleberry

Mountain fault zones (sec. 17, T1S, R37E through sec. 14, T2N, R37E) (Figure 2). These two fault zones are similar in their expression to the Hite faults, in that they consist of 50-200 m zones of poorly exposed, crushed and shattered basalt, with several discrete zones of gouge, that generally form topographic lows or saddles.

Where part of the Meacham Creek fault zone is exposed near Phillips Creek (T2N, R38E), the youngest-appearing shear within the fault zone is about 10 m in width and consists of brown pulverized basalt in a silt-clay matrix. This shear zone strikes about N25°E, dips 65°NW, and the striae in it rake 45°W. Lack of stratigraphic control west of Phillips Creek prevents an interpretation of the sense of motion; however, offset of the Shimmiehorn (SE 1/4 sec. 2, T1N, R37E) and Ruckel Ridge faults (SE 1/4 sec. 36, T2N, R37E) suggest sinistral (i.e. left-lateral) down-to-the-west, oblique-slip on the zone to the southwest.

The apparent age of the Meacham Creek and Thimbleberry Mountain faults is perplexing. Both appear to offset or truncate faults in the LaGrande system, suggesting that they are younger. However, the LaGrande faults have much more prominent topographic expression, and thus, appear geomorphically younger. Perhaps the north-northeast-striking Meacham and Thimbleberry Mountain faults are older, and the development of faults in the LaGrande system were distorted by their presence; or perhaps, several episodes of movement occurred on the north-northeast-striking faults.

4.2 WALLULA FAULT SYSTEM

The Wallula fault system (Bingham and others, 1970) approximately parallels part of the postulated Olympic-Wallowa lineament (Figure 1; Raisz, 1945). This system is defined here to extend from about 3 km west of Wallula Gap (Figure 2) east-southeast at least 55 km to Milton-Freewater, and based on the results of this study, it is inferred to extend an additional 22 km along the South Fork of the Walla Walla River to the Hite fault. In addition to this main fault trend, several parallel faults occur in and east of the Walla Walla syncline, and are herein included in the Wallula fault system (Figure 2). These faults occur as far north as Walla Walla, Washington and Pikes Peak, Oregon (T6N, R37E). Most appear geomorphically youthful and many appear to offset the youngest geologic units in the area (upper Pleistocene or possibly even Holocene).

4.2.1 Wallula Fault

The Wallula fault appears to be the most extensively developed zone in the system. It has been mapped by Shannon & Wilson, Inc. (1979) from west of Wallula Gap east-southeast to near the Oregon State Line (T5N, R33E); the reader is referred to that report for more details. The fault appears to continue beyond the state line to the Pine Creek fault, along a strong east-southeast-trending magnetic linear (Weston Geophysical Research, Inc., 1979). The fault consists of a broad 100 m to 300 m wide zone, with abundant evidence of strike-slip motion. Farooqui (Shannon & Wilson, Inc., 1979) reports faulted colluvium and inferred faulted Touchet deposits along the fault trace. Faulting of the Touchet appears to have occurred along the "Bingham linear" (Bingham and others, 1970). Faulting of the Touchet also occurs south of Umapine, as discussed in Section 4.2.4. Faulting of colluvium near "The Slide" (sec. 12, T6N, R32E) has been described by Farooqui (Shannon & Wilson, Inc., 1979). However, we believe the exposure reported by Farooqui may represent an outcrop of refaulted gouge and that more detailed work would be needed to fully evaluate "The Slide" and nearby faults.

4.2.2 Pine Creek Faults

Five short, en echelon faults occur along the north flank of the Horse Heaven anticline. Three of these faults were mapped by Newcomb (1965) near Pine Creek (SE cor., T6N, R34E). These faults parallel the Vansycle - Warm Springs set of faults south of the Wallula fault zone (Shannon & Wilson, Inc., 1979). Both this reconnaissance and the investigation by Farooqui (Shannon & Wilson, Inc., 1979) suggest that the three faults mapped by Newcomb (1965) and several other newly mapped, associated faults, are best interpreted as reidel shears related to the main Wallula fault zone. This interpretation is based primarily on similarities in trend and in apparent motion, and in the similarity of topographic expression of these faults with the Vansycle Canyon - Warm Springs faults to the west, and their geometric relation to the Wallula fault zone (Figure 2).

The Pine Creek fault is inferred to be about 3 km in length. It has a well developed topographic expression east and south of Pine Creek (NW 1/4 sec. 35, T6N, R34E), and is inferred to follow a prominent magnetic linear west-northwest to the Wallula fault. The fault zone described by

Newcomb (1965) is no longer exposed, as it is now covered by debris from a borrow pit, just east of Pine Creek, and by extensive plowing of the hillside along the trace east of Pine Creek. Four other faults in the set, vary in length from 2 to 4-1/2 km. They occur near the Pine Creek fault, and are mapped on the basis of apparent offset of stratigraphic units (glomerophyric and sparsely glomerophyric Frenchman Springs flows) and topographic expression.

The area between the Pine Creek fault and the north end of the Little Dry Creek fault, which is nearly on trend, is largely loess-covered. Thus, although it was not possible to evaluate a connection between these faults, a well-developed magnetic linear (Weston Geophysical Research, Inc., 1979), which parallels both of these faults, continues between the two.

4.2.3 Little Dry Creek and Dry Creek Faults

The Little Dry Creek fault is inferred to extend along a topographic and vegetation lineation from the NW 1/4, T4N, R35E, southeast along Pine Creek to the Thorn Hollow fault, and thence, southeast along Little Dry Creek east of Weston, Oregon (Figure 2). From there, the fault strikes southeast along a topographic linear towards a fault of similar strike (Figure 2) in the SW cor., T4N, R36E; however, a connection between the two faults has not been documented.

Two strands of the Little Dry Creek fault, which cut glomerophyric Frenchman Springs flows, are exposed in roadcuts on the west side of Highway 11 north of Weston (SE 1/4 SW 1/4, sec. 2, T4N, R35E) about 600 m south-southwest of the exposure of the Thorn Hollow fault discussed in Section 4.1.6. The two strands are about 1 1/2 - 2 m in width and strike N20° to 35°W, on trend with Little Dry Creek. Both exhibit striae indicative of oblique-slip motion, which appears to be consistent with the strike-slip on the nearby N5°W-striking Thorn Hollow fault. The westernmost of these zones dips 75°NE and has striae which rake 40° to 80°E. Movement on the fault appears to be up to the east. It is inferred to join the main fault in Little Dry Creek, where it is exposed in a cut along the Winn road (in NE 1/4 sec. 11) about 500 m from Highway 11. In Little Dry Creek, this zone is about 2 m wide, and has dropped a Frenchman Springs flow and Palouse Formation down to the east about 0.5 m. A small graben within the zone is filled with loess, which appears to be in fault contact with the basalt.

The northeastern strand of the Little Dry Creek fault is exposed about 200 m north-northeast of the western strand discussed above. The fault strikes N50°W at a very low angle (dips 8°SW), but it has horizontal striae that are subparallel to the trend of the Little Dry Creek fault. This somewhat anomalous zone could be related to interference between the Little Dry Creek fault and the nearby Thorn Hollow fault.

The apparent faulting of young loess and the Palouse Formation indicate young activity on the Little Dry Creek fault. A minimum age for this activity likely could be established by a more detailed study to evaluate the age of the loess and the Palouse Formation at this locality.

The Dry Creek fault was not observed in outcrop. It is inferred to extend along Dry Creek between the Thorn Hollow and Saddle Hollow faults. The basis for the location of a fault along Dry Creek is an apparent difference in elevation of both the top and bottom flows of the Frenchman Springs Basalt across the creek, with the east side lower by 15 to 20 m. This offset would be consistent with offset of the northwest-dipping flows in a dextral sense along Dry Creek.

East of the Saddle Hollow fault, the Dry Creek fault appears to continue to the Ryan Creek fault, albeit to the north of its inferred location on the west. Offset, which here appears to be down to the north, is based on the difference in elevation of the top of the Frenchman Springs flows along strike (they strike N30°E and dip 2°-3°NW) across Dry Creek. North of the creek they appear to be about 30 m lower than to the south, consistent with the apparent offset along the fault to the east.

If the fault continues farther to the east (past the Ryan Creek fault) is is not expressed as an obvious mismatch of flows across Dry Creek. At present, therefore, we believe the fault terminates at the Ryan Creek fault.

4.2.4 Milton-Freewater Faults

Four northwest-striking faults, which appear to be part of the Wallula fault system, are present south of Milton-Freewater. The southernmost is herein named the Bade fault. It is inferred to extend along Dry Creek from near Highway 11 (center sec. 23, T5N, R35E) past Bade (NW 1/4 sec. 15) to near Barrett (NW sec. 4, T5N, R35E). No exposure of this fault

was found during our reconnaissance, however, several small, N50°W shears occur at Bade, and the Frenchman Springs flows cannot be matched across the trend, which follows a prominent northwest-trending linear portion of the Dry Creek drainage. Brown (1937) reported ground cracking parallel to the inferred trace of the fault. At its south end, the Bade fault is inferred to connect with the N5°W-trending Thorn Hollow fault, while the north end is inferred to connect with the eastward projection of the Wallula fault along a prominent west-northwest-trending aeromagnetic lineation.

About 0.4 km north of Barrett, a prominent topographic linear trends N50°W for about 4 km. At a landfill on Dry Creek Road, 0.4 km north of Barrett, the linear can be seen to consist of a scarp-like lineation in the Touchet deposits. Anomalously steep (15°-30°) dips to the northeast, and an intraformational angular unconformity occur within the Touchet at the landfill. Height of the scarp-like feature is about 12 m to 15 m. West of the NW cor. sec. 32, T5N, R35E, the "scarp" turns to a more westerly trend. About 2.5 km farther to the west, Touchet beds are exposed along the Pine Creek Road (NW cor. SW 1/4 SE 1/4, sec. 25, T6N, R34E), and several faults, which parallel the "scarp", are exposed (Figure 5). These faults dip north, and cut both Touchet and clastic dikes within the Touchet. The faults strike about N70° to 75°W and generally dip either 30° or 60°N. Offsets vary from about 2 cm to 0.5 m, with the north side down. Most of the larger displacements occur on the 30°N-dipping faults. Individual fault zones are 1 to 4 cm in thickness. Striae are well developed on both sets of faults. Those on the 30°N-dipping faults rake N30°E, while striae on the 60°N faults rake due north. Orientation of the striae, and the apparent down-to-the-north offset, are consistent with dextral oblique-slip. These small faults are believed to be related to a larger fault, which is inferred to extend between the Pine Creek Road and Barrett along the base of the N50°W-trending "scarp". This fault is herein named the Barrett fault.

The Milton-Freewater fault was mapped by Newcomb (1965) along the steep, northwest-trending bluffs southwest of Milton. Although the fault is not exposed in Milton-Freewater, Newcomb (1965) inferred its existence based on the fault scarp-like appearance of the bluff, and on water well data, which suggest the presence of both gouge and a groundwater barrier along the bluff.

Recent work east of the Walla Walla River, along the southeast projection of the fault, has exposed the fault. It is well-exposed in the wall of the borrow pit, is located on the Walla Walla River Road about 1.5 km south of Milton-Freewater (NW cor. sec. 18, T5N, R36E). Here, two shear zones, which cut glomerophyric flows of Frenchman Springs Basalt, trend N50°W and are near vertical. They can be traced from the lower face of the pit across the hillside until they disappear beneath slopewash, colluvium, and plowed fields on the upland above the river. Both zones consist of sheared and pulverized Frenchman Springs Basalt, in an orange to yellow matrix of clayey silt. Striae on the two shear zones are near horizontal. Vertical offset of a flowtop across the northern, 1 m-wide zone is down to the south, indicating sinistral motion. Offset on the larger, 2 m-wide southern shear zone, juxtaposes abundantly glomerophyric Frenchman Springs flows on the north with sparsely glomerophyric flows on the south (Figure 6). The 12 m, down-to-the-north, vertical component of offset on this zone indicates dextral offset of these northwest-dipping flows. If one assumes that the horizontal striae on the main (south) zone of the Milton-Freewater fault zone represent the true slip on the fault, and that the apparent vertical offset of the Frenchman Springs flowtop is strictly due to horizontal slip, it would require about 130 m of dextral slip to produce the measured 12 m vertical offset.

The Milton-Freewater fault zone is believed to continue to the southeast through an apparent 2-4 m offset of Frenchman Springs flows about 2 km southeast of the borrow pit (SE cor. sec. 18). Age of the fault is inferred to be young, based on Brown's (1937) report of ground disturbance near its inferred trace, and on its similarity in strike and motion (dextral strike-slip) to the nearby Dry Creek, Little Dry Creek and Barrett faults. In addition, abundant angular basaltic debris is incorporated in the loess along the trend of the fault. This suggests that a nearby source of Frenchman Springs Basalt fragments, such as a fault scarp, could have supplied the fragments mixed with the loess.

4.2.5 Walla Walla River Faults

The South Fork of the Walla Walla River appears to be one of the key elements of the physiographic linear known as the Olympic-Wallowa

Lineament (Raisz, 1945). Previous work in the area (e.g., Newcomb, 1965), however, has not found any structural justification for the straight northwest trend of the South Fork between its confluence with the North Fork (sec. 22, T5N, R36E) and Elbow Bend. The course of the South Fork is at a slight (10° to 20°) angle to the regional dip (Figure 2) and its side drainages are arranged in a remarkably trellis-like pattern, with streams, gullies and spurs oriented near parallel or perpendicular to the South Fork. A similar geometry is observed for the North Fork, from about 2 km above its confluence with the South Fork to Blalock Mountain (sec. 29, T5N, R37E).

Evidence found during this investigation strongly suggests structural control for the west-northwest-trending South Fork drainage. The evidence consists of newly discovered fault zones on both sides of, and parallel to, the South Fork Valley. These faults, herein named the Forks fault and the Lincton Mountain faults, parallel the Milton-Freewater fault to the northwest and constitute a nearly continuous N55° to 60°W - trending zone from Umapine to the Hite fault (Figure 2).

The Forks fault is named for Forks School, which is located about 1.5 km west of the northwesternmost exposure of the zone. The fault appears to extend along Blalock Mountain, from near the forks of the Walla Walla River (NW 1/4 sec. 23, T5N, R36E) south-southeast to near Flume Canyon (SW 1/4 sec. 32, T5N, R37E). The fault is best exposed in roadcuts along the north bank of the North Fork above the USGS gaging station in the NW 1/4 sec. 23, T5N, R36E. There, the fault is exposed for about 230 m along the road. The southwest margin of the fault zone consists of gray cemented breccia cut by seams of uncemented yellow-brown breccia with a clay matrix. Shears within both breccias range in strike from east-west (90°) to west-northwest (140°) with the west-northwest shears dominant. Those striking east-west dip about 45°SE, while those striking west-northwest are near vertical and have horizontal striae. The fault zone grades into shattered basalt towards its northeast margin, with local areas of both cemented and uncemented gouge. Total width of the zone appears to be about 100 m.

This fault cannot be traced directly from roadcuts on the North Fork; however, from our examination of aeromagnetic maps (Weston, 1979), we infer that it extends east-southeast along a prominent aeromagnetic linear on a diagonal across Blalock Mountain to a near-vertical fault of similar

strike (west-northwest) in the SE cor. sec. 23, T5N, R37E. The fault was traced from sec. 23, on the basis of stratigraphic mismatch, southeast into the NW 1/4 sec. 25, where the zone is exposed in a side canyon on the south flank of Blalock Mountain (Figure 2). There, the Forks fault is a near-vertical, N45° to 50°W-trending structure. The fault zone is at least 12 m wide and consists of sheared and brecciated basalt healed by chalcedony cement (Figure 7). The fault appears to have a south-side-down offset, although the amount of displacement has not been determined. Striae plunging 15°SE suggest a significant component of strike-slip motion. The fault merges upslope to the northeast with a low-angle, south-dipping thrust fault with unknown, but apparently minor, displacement (Figure 7). This thrust zone can be traced for only a few hundred meters, whereas the deeper-seated, high-angle zone can be traced east-southeastward along the south flank of Blalock Mountain to Flume Canyon. This structural style, associated with the postulated strike-slip movement of the Forks fault is characteristic of "palm tree structures" developed by near-surface contraction and uplift along strike-slip faults (Sylvester and Smith, 1976). We interpret the contraction and uplift to have resulted, here, from a change in trend of the fault from N45° to 50°W, to the northwest of the thrust, to N60°W, southeast of the thrust.

The Lincton Mountain faults are exposed south of the South Fork on the north slope of Lincton Mountain west of Tollgate Chalet (secs. 5 to 26, T4N, R37E). These faults form an en echelon set of structures that extend from near the north-northeast-striking Peterson Ridge fault east-southeast past the north-northeast-trending Hite fault zone (Figure 2). Because of the steep topography in the South Fork drainage, the traces of the non-vertical members of the set appear to diverge from an en echelon pattern. However, our mapping shows that the individual faults generally parallel or strike slightly to the north of the overall trend of the set.

The two largest faults in the set have strong topographic expressions (Figure 8) as 5 to 15 m deep linear depressions, 50-100 m in width, which cut across the spurs south of the river. The gouge zones are covered by colluvial deposits in these depressions. However, the fault control is quite evident because of the visible mismatch of Grande Ronde flows and a Frenchman Springs dike across the depressions (Figures 2 and 8).

In Elbow Creek (NE 1/4, sec. 23, T4N, R37E), one of the lesser Lincton Mountain faults is exposed in a road cut along the south side of the creek. The fault zone consists of brecciated basalt in a matrix of orange-brown clayey silt. Only the northwest side of the zone is exposed; the southeast side is covered by colluvium and Mt. Mazama ash. About 4 m of the total width of the gouge, which cuts a Grande Ronde flow top breccia, are exposed. The zone strikes N60° to 50°W, dips 65°N, and has well-developed striae which rake 30°E. The fault appears to continue east-southeast of Elbow Creek for about 0.5 km, and to the west-northwest for about 0.8 km, with an overall strike of N60°W. About 0.5 km west of Elbow Creek it offsets a Frenchman Springs feeder dike. The dike strikes about N10°E and dips between 12° and 30° W. Although the zone is covered, the top of the dike is at different elevations on either side and appears to be dropped about 30 m south-side-down, across the fault. Together, the dip of the dike, rake of the striae, and apparent offset suggest sinistral oblique-slip on this fault.

A left-lateral offset is in the opposite sense of that suggested by the north-side-down apparent offset of the Grande Ronde flows across the main Lincton Mountain faults. It is also at odds with the apparent offset of the Frenchman Springs dike by the main (SE) Lincton Mountain fault.

The faulting of the dike by the main faults is concealed, as is the dike, for several tens of meters on either side of the fault. South of the fault the top of the dike occurs at an elevation of more than 3250' (approximately 986m), whereas it is no higher than 3140' (approximately 953m) along strike north of the fault. Thus, if the dike maintains a westward dip south of the Lincton Mountain fault, it must be dropped down on the north by about 30 to 50 m. Because this dike, which averages more than 30 m in thickness, has a dip which varies consistently between 12° and 30°W, vertical throw cannot be estimated more accurately.

Although there is no direct evidence of strike-slip motion on the main Lincton Mountain faults, two facts convince us that they do have major strike-slip components. First, is the en echelon pattern, and second is the presence of horizontal or shallowly-dipping striae on smaller faults that have strikes close to, or the same as, the main faults. (Two such zones cut the Hite fault gouge zone in the NE 1/4 sec. 26, T4N, R37E).

Another factor consistent with dextral slip on the Lincton Mountain faults is the apparent dextral offset of the main Hite fault by one of the Lincton Mountain faults across Elbow Creek. Although breccia of the Hite zone can be traced north-northeast through the SE 1/4 sec. 23, T4N, R37E, to Elbow Creek, the nearest exposure of breccia found north of the creek is almost 0.5 km to the east. If this observation is true, it would imply about 0.5 km of dextral offset of the near-vertical Hite zone across the Lincton Mountain fault. However, because the juncture of these faults is very complex, with numerous shears striking in a variety of orientations, we have only moderate confidence in this interpretation.

The Lincton Mountain faults appear to be younger than the Hite fault. However, another fault of the Hite system, the Peterson Ridge fault, appears to terminate the Lincton Mountain faults on the west, so that evaluation of their relative ages is problematic in terms of the data presently available. The youngest rocks cut by the faults are apparently those of the Frenchman Springs dike and the cemented gouge of the Hite zone near Tollgate Chalet.

4.2.6 Other Wallula Faults

Several other faults with strikes similar to the Wallula fault (N70° to 80°W), and its related faults (N40° to 70°W), or with inferred or mapped connections to the Wallula fault, are shown on Figure 2. The most significant of these, the Promontory Point fault, occurs between Walla Walla, Washington, and Pikes Peak, Oregon (T6N, R37E). The Promontory Point fault appears to extend southeast from Newcomb's (1965) inferred fault trace onto slopes of the Blue Mountains. The trace of the fault beneath the fill of the Walla Walla syncline is based on differences of water levels and temperatures (Figure 2) in several nearby wells (Newcomb, 1965). In secs. 10 and 11, along a linear ditch that trends straight down the regional slope, the Promontory Point fault appears to offset the Palouse Formation, but the sense, amount, and age of offset is not known.

South of Pikes Peak, a short (1.5 km), strike-slip fault is present on the south side of Saddle Mountain (T6N, R37E), and herein named the Saddle Mountain fault. It is expressed as a strong N50°W linear on all sets of air photos available to us. On the ground it is expressed as

a linear, with dextral offset of spurs on the south side of Saddle Mountain (in sec. 34, T6N, R37E). Its age was not determined.

In addition, several other N50°W-trending faults are inferred to transect Government Mountain, east of the Saddle Mountain fault. These faults, shown on Figure 2 near the southeast part of T6N, R37E, exhibit small vertical displacements of the Frenchman Springs flows, and in turn, appear to be offset by the N15°E-trending Blalock Mountain fault and an unnamed fault parallel to the Blalock Mountain fault. Because of poor exposures on Government Mountain, however, the apparent relationship between these faults is based largely on topographic interpretation.

4.3 THE LAGRANDE FAULT SYSTEM

The LaGrande fault system extends from southeast of the study area (Figures 1 & 2) on a north-northwest trend into the southeastern part of the area. The system is defined to include the generally north-northwest-striking faults that bound the LaGrande graben and extend on northward to the Hite fault. The system also includes parallel and slightly more westerly-striking faults to the west and northwest of LaGrande in the vicinity of Meacham (NE 1/4, T1S, R35E) and Kamela (SE 1/4, T1S, R35E). Near LaGrande, the dominant offset on most of these faults is normal, with the sides nearest the graben down (Gehrels and others, 1979; Hampton & Brown, 1964). However, west of LaGrande, the dip-slip on most of the faults in the system is down to the west (Walker, 1979; Taubeneck oral comm., 1979). Our investigations are in substantial agreement with these observations; however, some of our data (discussed below), together with those of Gehrels and others (1979), suggest a more complex picture of the LaGrande system, one which involves substantial amounts of strike-slip movement on some of the faults. Faulting of the Sugarloaf volcanics by the LaGrande system faults indicates an age of less than 6.5 my for the latest activity of the system.

The major faults comprising the LaGrande fault system are, from northeast to southwest, the Bald Mountain, Nine Mile, Phillips Creek, Ruckel Ridge, Shimmiehorn, Indian Rock, Drumhill Ridge, Wilbur Mountain - Horseshoe, Perry, Peach Canyon, Hilgard and Spring Creek-Coleman Ridge faults. Many other smaller faults are also present within the system (Figure 2). However, our reconnaissance suggests that the aforenamed are

the most significant elements of the LaGrande system within the area studied. Most of these faults occur south and east of the Hite fault zone. Several additional faults, with NNW strikes similar to the faults of the LaGrande system, occur north of the Hite fault. As discussed below, these faults, which include the South Fork, Elbow Bend and Pikes Peak faults, are considered as part of the LaGrande fault system, for purposes of this study.

4.3.1 Bald Mountain Fault

The Bald Mountain fault trends N2° to 5°W for about 22km, from near Highway 204 (T3N, R38E) to near the Hite fault. The southern part of the fault forms the west-facing escarpment of Bald Mountain. Here, it drops the Blue Mountain summit area from a general elevation of about 5,300 feet down to about 4,800 to 5,000 feet on the Tollgate plateau (Hogenson, 1964).

Throughout its southern part, colluvium from the escarpment covers the fault zone, but north of the Tollgate plateau, the fault is exposed where it crosses the ridges and spurs that descend into the drainage of the South Fork of the Walla Walla River (sec. 10, 15 and 22, T4N, R38E). There, the fault is a zone 10 to 30 m in width of uncemented, orange to brown basaltic gouge. The zone dips 55° to 60° west. No striae were observed, but drag near the fault, and the apparent offset of the Frenchman Springs flows on Tollgate plateau, suggest predominantly dip-slip motion.

The north end of the Bald Mountain fault is inferred to approach to within about 3 km of the Hite fault zone. There, its trace becomes lost in the complex shearing of the Hite zone. Detailed mapping would be required to evaluate the intersection, if any, between the Bald Mountain and Hite faults.

4.3.2 Ninemile Fault

The Ninemile fault extends north-northwest along the west flank of Ninemile Ridge to the North Fork of Umatilla River, then along Coyote Ridge, and thence north into the South Fork of the Walla Walla drainage, a distance of about 17 km. The fault appears to be near vertical, or slightly westward dipping along most of its extent. Although the fault can be readily traced by topographic expression and stratigraphic offset, no

exposures of the fault zone were observed. Additional field work in the relatively inaccessable English Spring area (sec. 18, T3N, R38E) likely would find exposures of the fault zone. Aerial reconnaissance of that area suggests about 70 m of apparent dip-slip on the Ninemile fault, with the west side down. This offset is in good agreement with the apparent offset of about 70 m at the north end of Ninemile Ridge (secs. 30 and 29, T3N, R38E).

At its north end, the Ninemile fault appears to continue into Tamarak Basin (secs. 24 and 13, T4N, R37E), and to terminate at the Hite fault zone (SE 1/4 sec. 13), as shown by Newcomb (1970). Detailed mapping of this relatively inaccessable area would be required to evaluate the intersection of these two major faults.

4.3.3 Phillips Creek Faults

The Phillips Creek faults trend north-northwest along Phillips Creek from near Highway 204, 16 km west of Elgin (NE 1/4, T1N, R38E) to the Hite fault zone near Grouse Mountain (NE 1/4, T3N, R37E), a distance of approximately 25 km (Figure 2). The Ninemile fault, discussed above, may represent a branch of the Phillips Creek fault zone; however, it appears to be separated by a structual ramp east of Phillips Creek (SE 1/4 sec. 8, T2N, R38E) at its south end.

Both the north and south ends of the Phillips Creek structure appear to consist of single, west-dipping, normal faults. However, the central 11 km, where the fault cuts the summit of the Blue Mountains anticlinorium, is more complex, as it consists of two or more parallel faults along the same trend. South of the Meacham Creek fault, both main strands appear to be west-dipping normal faults. North of the Meacham Creek fault (Section 4.1.7), the Phillips Creek faults bound the narrow, north-northwest-trending horst (NW 1/4, T2N, R38E and SW 1/4, T3N, R38E), which forms High Ridge.

The bounding faults of the horst are exposed in cuts along Skyline Road (W 1/2 sec. 7, and E 1/2 sec. 8, T2N, R38E). The western branch of the fault is a zone of uncemented, fresh-appearing gouge about 25 m wide, which contains several slivers of relatively intact, but shattered basalt. This zone dips 85°W, has well-developed west-facing drag folds, and an apparent offset of about 200 m of Frenchman Springs flows, down to the west. The eastern branch is less well developed, consisting of an uncemented gouge zone about 5 to 8 m wide. In roadcuts, shears within the zone appear near vertical, but the fault trace across the south end of High Ridge suggests an east dip (approximately 80°E). Striae within this zone rake 10°S, suggesting a substantial component of strike-slip. The apparent dip-slip offset of Frenchman Springs flows on the east branch is about 60 m.

Both the east and west branches exposed along High Ridge appear to either terminate against, or to be offset by, the northeast-trending Meacham Creek fault. The Phillips Creek faults, south of the Meacham Creek fault, do not align with those to the north (Figure 2). Our reconnaissance was not able to determine whether or not the Meacham Creek fault offsets the Phillips Creek faults, largely because of colluvial cover in the area of juncture. However, the change in sense of offset of the Grande Ronde and Frenchman Springs flows on the east branch across the Meacham Creek fault (Figure 2) suggests that the Phillips Creek faults were influenced by pre-existing trend parallel to the Hite fault system (Meacham Creek fault), rather than offset by a younger trend.

4.3.4 Ruckel Ridge Faults

The Ruckel Ridge faults extend from near Mt. Emily (SW 1/4, T1S, R38E) north-northwest to the Hite fault zone near Graves Butte (center, T3N, R37E). The south parts of the Ruckel structures were mapped by Hampton & Brown (1964) as the major, west boundary fault of the LaGrande graben along the east flank of Mt. Emily (Figure 2, T1S, R38E). Our reconnaissance confirms the interpretation of Hampton and Brown (1964), as does the recent work of Gehrels and others (1979).

South of the Meacham Creek fault, two main branches of the Ruckel Ridge fault exist; an east-facing normal fault, which forms the main graben boundary, and a west-facing normal fault of lesser offset, which forms a narrow, minor graben along the flank of the main graben (Figure 2).

Vertical offset on the main, east-facing branch is in excess of 1,500 m. Gehrels and others (1979) infer dextral strike-slip on this branch of the Ruckel Ridge fault; however, we were not able to document such

motion because of the blanket of extensive debris that has been shed from the scarp. The sinuous trend of the scarp seems to argue against significant horizontal offset.

Apparent offset of the west-facing, east branch of the Ruckel Ridge fault, south of the Meacham Creek structure, is also normal. The Grande Ronde and platy andesite flows appear to be downdropped at least 100 m to the west along Dry Creek (sec. 31, T2N, R38E).

Neither of these two branches of the Ruckel structure can be traced directly north of the northeast-trending Meacham Creek fault. The pattern of intersection appears to be similar to that of the Phillips Creek faults where they cross the Meacham Creek fault; i.e. an apparent change in offset and location of the faults. Several branches of the Ruckel Ridge faults occur north of the Meacham Creek fault. The best expressed of these branches trends along the west side of Ruckel Ridge (sec. 24, T2N, R37E). There, the fault appears to be near vertical with about 110 m of west-side-down, dip-slip offset. A similar apparent offset was observed on this fault north of Thomas Creek (NW 1/4, sec. 11, T2N, R37E).

Topographically less well-expressed faults, which parallel the main Ruckel Ridge fault, but are about 1 and 2 km west, occur on either side of Round Mountain (Figure 2, secs. 22 & 23, T2N, R37E). The fault on the east side of Round Mountain has an apparent dip-slip offset of about 100 m, down to the east, while the fault to the west side has at least 30 m of west-side-down, dip-slip motion.

Both of these faults are exposed in road cuts along the Thomas Creek Road (SW 1/4 sec. 10, and NW 1/4 sec. 14, T2N, R37E). Both are wide zones (65-70m) of mixed gray cemented and yellow-brown uncemented gouge. The western of the two zones strikes N10°W and has well-developed striae, which, on the average, are horizontal, both in the cemented and the uncemented gouge. Few striae were observed in the east gouge zone, but those parallel to the main N10°W trend were sub-horizontal.

The traces of both the main Ruckel Ridge fault and the zone west of Round Mountain appear to continue north-northwest to near the Hite fault zone at Graves Butte; however, the nature of any juncture was not determined. No continuation of the Ruckel Ridge fault could be found north of the Hite zone.

4.3.5 Shimmiehorn Fault

The Shimmiehorn fault extends along Shimmiehorn Creek, for which it is herein named, between the South Fork Umatilla River (SW cor. sec. 5, T2N, R37E) south to Dusty Saddle Canyon (NE 1/4 sec. 3, T1N, R37E) where it appears to be offset by bothe the northeast-trending Meacham Creek and the north-to-north-northeast-trending Thimbleberry Mountain fault. To the south, the Shimmiehorn fault appears to continue south-southeast to the margin of the LaGrande graben (NE 1/4, T1N, R37E), west of Thimbleberry Mountain.

Our evaluation of the Shimmiehorn fault is based entirely on aerial reconnaissance and air photo analysis; no outcrops of the zone were found in the field. However, the fault trace is readily identifiable on air photos, and thus, it is well located on Figure 2. Apparent offset by the Meacham Creek fault is consistent with the northwest-side-down, sinistral, oblique-slip observed on the Meacham Creek fault near Phillips Creek (Section 4.1.7). Offset of the trace of the Shimmiehorn fault across the Thimbleberry Mountain fault is apparently the same sense.

In Shimmiehorn Creek, the fault appears to dip west (secs. 20 & 21, T1N, R37E). It truncates an east-dipping, 4 km-long dike, previously mapped by Hogenson (1964) on the west side of the creek. The dike was not found east of the creek, implying a significant offset across the fault.

4.3.6 Indian Rock Fault

The Indian Rock fault forms the east-facing Mt. Emily escarpment. Its dominant motion appears to have been dip-slip; possibly as much as 500 m near Mt. Emily (T1S, R38E) (Figure 2). The northern part of the fault trends north-northwest, while the southern part swings around to a southwest trend. Gehrels and others (1979) observed strike-slip striae on the northern segment of the fault, and hence, inferred that part to be en echelon with the Phillips Creek and other north-northwest-trending, graben-bounding faults.

4.3.7 Drumhill Ridge and Wilbur Mountain Faults

The Drumhill Ridge fault extends from the Grande Ronde syncline, 3 km east of Perry (SE cor., T2S, R38E), north-northwest to the east of Sugarloaf Mountain, and thence along the east flank of Drumhill Ridge. The fault is an east-dipping normal fault. Near the Grande Ronde River it drops an olivine basalt overlying the Grande Ronde flows down about 60 m to the east (Gehrels and others, 1979). East of Spring and Wilbur Mountains (T1S, R37E), the fault has a similar down-to-the-east offset of about 100 m of the olivine basalt.

Between Smith Ridge (sec. 11, T2S, R37E) and Wilbur Mountain (Figure 2), the Drumhill Ridge fault is parallelled on the west by a series of west-facing normal faults, herein named the Wilbur Mountain faults. Thus Drumnill and Smith Ridges appear to be horsts, similar to Round Mountain and High Ridge to the northeast. Offset on the Wilbur Mountain fault, at Wilbur Mountain, appears to be about 30 m, down to the west. This estimate is based on the apparent offset of the frothy andesite of the Sugarloaf Mountain volcanics, which forms the Wilbur Mountain shield volcano. The fault appears to dip west (75° to 80°) south of Wilbur Mountain (SE 1/4 sec. 18, T1S, R37E), as does a branch of the fault expose on Mt. Emily Road (SW cor. sec. 28, T1S, R37E). No evidence of strike-slip was observed on any of the small branch faults associated with either the Drumhill Ridge or the Wilbur Mountain faults. Although the main fault zones are not well exposed, the faults are near vertical, and their traces quite straight, so strike-slip motion is not unlikely on these faults. Faulting of the Sugarloaf Mountain volcanics by the Wilbur Mountain faults indicates an age of less than 6.5 my for these structures.

4.3.8 South Fork, Elbow Bend and Pikes Peak Faults.

Although most faults with trends similar to those in the LaGrande fault system occur south and east of the Hite fault system, a few north-northwest-to north-striking faults extend into or occur within the area of the Hite system. The best expressed of these faults are those north of Tollgate Chalet in Tps. 4, 5 and 6N, R37E. The Elbow Bend, South Fork, and Pikes Peak faults are the most prominent, although several shorter faults also appear to have significant offsets.

The Elbow Bend fault was mapped by Newcomb (1965) from the Hite fault (SW 1/4 sec. 24, T4N, R37E) north-northeast across Blalock Mountain, the North Fork of the Walla Walla River, and onto the south flank of Peterson Ridge (NE 1/4 sec. 21, T5N, R37E). West-facing drag folds east of the fault, and offset of Grande Ronde flows and two Frenchman Springs dikes (Figure 2) clearly show the fault to have an apparent down-to-the-west vertical offset. Such an offset of the 2° to 5°NW-dipping flows and 12° to 30°W-dipping dikes could also be a result of sinistral strike-slip. North of Elbow Creek, vertical offset of the larger of the two dikes appears to be about 20 m, while that of the host Grande Ronde flows is slightly more (25-30m). Because the dike dips more steeply than the flows, it should be offset more than the flows by pure strike-slip faulting. Since the opposite is apparently the case, however, motion on the fault must have had a reasonably large down-to-the-west, vertical component. Any horizontal component could have been either dextral or sinistral.

We were not able to trace the fault across Blalock Mountain north of the Blalock Mountain fault. However, we did find a fault on strike with the Elbow Bend fault in the North Fork Walla Walla River drainage, which corresponds with the north end of the fault as shown by Newcomb (1965).

The South Fork fault is named herein for its prominent exposure in the South Fork Walla Walla River (W 1/2 sec. 10, T4N, R37E). The fault has a markedly straight N17°, to 20°W trace from the Hite fault zone (NW 1/4 SE 1/4 sec. 26, T4N, R37E) to the Peterson Ridge fault northwest of Blalock Mountain (SE 1/4 SW 1/4 sec. 28, T5N, R37E). There, it appears to cross the Peterson Ridge fault and die out about 1.5 km.to the north-northwest on the south side of Peterson Ridge. About 2.5 km further north-northwest, however, a short, 1 km long fault is on strike with the South Fork fault.

Vertical offset on the South Fork fault appears to be down to the south, based on the offset of several prominent Grande Ronde flow units on spurs north of the South Fork Walla Walla River and in Flume Canyon. Given the gentle northwesterly regional dip, the south-side-down-offset could have been produced by: 1) normal faulting, 2) pure sinistral slip, or 3) dextral slip with a large vertical (south-side-down) component. Because

the apparent offset of the fault is greater near the South Fork, where dips are relatively steep (7° to 8° WNW), than to the north, where dips are shallower, we favor the latter possibility. Dextral slip on this north-northwest-striking fault would also be more consistent with the dextral slip observed on the nearly north-northeast-striking Hite fault and inferred for the west-northwest-trending Lincton Mountain faults.

The Pikes Peak fault is inferred to extend from south of Pikes Peak (SW 1/4 sec. 26, T6N, R37E) north-northeast to Mill Creek. Although the fault is not exposed, it can be identified by a prominent topographic lineation and a groundwater barrier.

Several other short faults, with small offsets and strikes similar to the Elbow Bend and South Fork faults, occur in Tps. 5N and 6N, R37E (Figure 2). These faults are inferred both on apparent offset of the basalts and on their distinct topographic expression.

The South Fork, Elbow Bend, Pikes Peak, and the other smaller faults of similar strike discussed above, are the only significant structures west of the Hite fault zone with strikes and apparent offsets consistent with those of the LaGrande fault system. The Elbow Bend fault appears to cross the Hite zone, while the South Fork extends into the Hite zone, albeit no significant offset of the Hite was observed in either instance.

5. INTERPRETATION AND CONCLUSIONS

The discovery of several previously unknown major faults within the Wallula, Washington - Blue Mountains - LaGrande, Oregon, areas, along with the discovery of an apparently genetic grouping of these and numerous lesser faults into three major systems (described in Section 4), requires a major reinterpretation of the structural geology of the area. Previous interpretations, which have envisioned this part of the Blue Mountains as a symmetrical anticlinal upwarp (e.g., Walker, 1973, 1979) or as a gentle anticlinorium with only moderate and infrequent faulting (e.g., Newcomb, 1965, 1970; Hogenson, 1964; WPPSS, 1977b), are inadequate to explain the degree, complexity and sense of faulting in the area.

The new data on faulting presented herein document extensive strike-slip movements on several faults. Indeed, our observations suggest that strike-slip and oblique-slip motions have been the dominant mode of deformation between the LaGrande and Walla Walla structural basins, with significant dip-slip motions confined to these basins.

Several studies of focal mechanisms and tectonics have postulated a generally north-south maximum compressive stress for southeastern Washington and northeastern Oregon (Smith, 1977, 1978; Kienle & Newcomb, 1974; Bingham and others, 1970; WPPSS, 1977a) for late Cenozoic and the present time. In such a regime, normal faults would be expected to trend generally north, while dextral and sinistral faults should strike northwest and northeast, respectively, and thrust faults should strike eastwards. Fault trends between these orientation should exhibit appropriate combinations of these motions. Perplexingly, however, the strike-slip motions observed, or inferred, are dextral for all three fault systems. Dextral motion on the northwest- to north-northwest-striking LaGrande system is compatible with a north-south maximum compressive stress, as are the dextral motions observed on several of the west-northwest-striking Wallula system faults. However, dextral motion on the Hite system is not compatible with any simple model involving north-south compression.

Two hypotheses could explain the anomalous dextral motion on the Hite fault system. First, the Hite system may be of a different age than the other two fault systems in the area, and consequently, it may

have formed largely in response to a stress field of quite different orientation. Second, it is possible that all three of the fault systems are approximately the same age, and are a result of a relatively uniform compressive stress. If so, then the maximum stress must have been oriented at a relatively low angle to all three systems; i.e., nearly parallel to the Hite fault (approximately N20E). If the first alternative is correct, then one would expect to find evidence of different ages or episodes or faulting, while, if the second is correct, one should find evidence of compatible interactions between the systems.

But, in fact, the data are conflicting, as different relationships appear in different parts of the area. For example, in the Milton-Freewater-Umapine area, the Wallula fault system appears to be quite young, with several instances of offset of upper Pleistocene strata. In this system the Little Dry Creek fault appears to offset the Thorn Hollow fault (Hite fault system) but young movement on the Thorn Hollow fault is also present between Little Dry Creek and Bade faults. However, this young movement can easily be interpreted as reactivation of part of the Thorn Hollow fault between the two younger faults of the Wallula system, particularly in light of the marked absence of evidence for young movement on the Thorn Hollow fault to the south. Thus, in the Milton-Freewater area, the Wallula system appears to be younger than the Hite system.

Farther east, however, faults of the Wallula system appear to be truncated or offset by faults of the Hite system. Here, the Dry Creek fault appears to be offset by the Thorn Hollow fault although in an opposite sense from that required by the motion determined for the Thorn Hollow fault elsewhere (Section 4.1.6). Here, also, the westernmost of the Lincton Mountain faults (Wallula system) appears to terminate against the Peterson Ridge fault (Hite system). On the other hand, the Forks fault (Wallula system) appears to terminate an unnamed fault of the Hite system (SE 1/4, T5N, R36E), and the Lincton Mountain faults cut the Hite fault and may offset it as much as 0.5 km (Section 4.2.5).

Unfortunately not all of these apparently conflicting relationships are equally well documented. Those which are best documented obviously should be given the most weight in an analysis of relative ages, providing that the analysis also can explain other apparent conflicting relationships. Thus, despite some conflicting evidence, those areas which show offset of the Hite system faults by the Wallula system faults are the more definitive.

The areas of intersection of the Thorn Hollow and Little Dry Creek faults and the Hite and Lincton Mountain faults are relatively well exposed, so that the relationships shown on Figure 2, which indicate a younger age for the Wallula faults, are based on interpretations of considerable data. Those junctures which show the opposite, such as the intersection of the Ryan Creek and Dry Creek faults, or of the Saddle Hollow and Dry Creek faults, are much less well constrained by field observations. Thus, the best evidence now available indicates that faults in the Wallula fault system are younger than those in the Hite fault system. This interpretation also is consistent with the geomorphically younger character of the Wallula system faults compared with the Hite system faults.

The relative ages of the LaGrande and the Hite fault systems are not as well defined as those between the Hite and Wallula fault systems. The available evidence suggests that either the Hite system is the older, or that both may be about the same age. An older age for the Hite system is suggested by the observation that northeast of the Ryan Creek fault most of the LaGrande system faults appear to stop at the Hite fault. Faults that cross the Hite fault (Elbow Creek and South Fork faults) or occur to the north of it (Pikes Peak) have vertical offsets that are apparently much less than those of the LaGrande system faults east of the Hite. A similar relationship likely exists for the juncture of the Meacham Creek fault (Hite system) and the Phillips Creek faults (Figure 2, T2N, R38E) as discussed in Section 4.3.3. There, branches of the Phillips Creek fault appear to change in sense and amount of offset across the Meacham Creek fault. These observations suggest that the Hite fault either obstructed or limited northwestward propagation of much of the LaGrande system. The Ryan Creek fault itself turns progressively north-northeastward as it extends into the area of the Hite fault system (Section 4.1.4)

Southwest of the Ryan Creek fault, the LaGrande and Hite fault systems seem to interfere with each other. In most places, northwest-striking faults appear to be terminated by north-or north-northeast-striking faults. However, in a few places north-or north-northeast-striking faults

are terminated by northwest-striking faults, or like the Gibbon Ridge fault (Tps. 1 and 2N, R35E), bend from a north-northeast strike to a northwest strike. Where northwest-striking faults appear to be offset by the north-northeast-striking faults, apparent offsets are frequently opposite (sinistral) to the dextral sense of the fault motion determined from other criteria. Consequently the relationships southwest of the Ryan Creek fault could be a result either of contemporaneous movement on the two systems, or of disruption of the propagation of the northwest-trending LaGrande system by a pre-existing grain of the Hite fault system.

In summary, therefore, the available data is best interpreted that the Hite fault system is older than the LaGrande fault system north and east of the Ryan Creek fault, whereas south and west of the Ryan Creek fault the data suggest that the Hite system could be either older or contemporaneous with the LaGrande faulting. Our more favored interpretation is that the Hite fault system is the older of the two. This interpretation is influenced by the contrasting geomorphic expression of the two fault systems. Those of the LaGrande system appear younger -- fault scarps have not receded significantly from the fault traces, and, in most localities, little difference exists between the amount of stratigraphic offset and the vertical topographic offset of the faults. These conditions are in contrast to the generally pronounced erosion of the upthrown side of the Hite faults, which, in most instances, have been stripped to the level of the upland pediment of the Blue Mountains' slope. Although the Hite faults are expressed topographically, they do not exhibit the primary control on topography that generally characterizes the LaGrande faults. Instead, the Hite faults are expressed largely by areas of differential erosion -- aligned drainages, notches in ridges and spurs, or locally, as fault line scarps, or "china walls" of cemented breccia. These contrasting geomorphic expressions strongly favor a younger age for the LaGrande fault system, as do many of the structural relationships discussed above.

Based on these observations, it is apparent that most of the evidence is consistent with an age for the Hite fault system older than the ages of either the LaGrande or Wallula fault systems. The conflicting evidence can be attributed either to re-activation of local parts of the Hite fault system (i.e., Thorn Hollow) or to the possible interaction of

the southeastern part of the Hite system with the western part of the LaGrande system. Such interaction could have also been a result of reactivation of parts of the Hite system during the dextral slip of the LaGrande system.

What then can be said about the relative ages of the LaGrande and Wallula systems? Intersection of the two systems is minimal, chiefly confined to a few LaGrande faults that extend north and west of the Hite fault north of Tollgate Chalet, such as the Elbow Creek, South Fork, Pikes Peak and related faults discussed in Section 4.3.8. As shown on Figure 2, these faults cross, or are crossed by, faults of the Wallula system with no apparent offset of either set. Such a lack of offset could be a result of either purely dip-slip motion on one set of faults, or constructive interference of the two sets through contemporaneous motion. However, our observations suggest at least some strike-slip motion on both the Wallula and LaGrande fault systems. Also, north of Tollgate Chalet the west-northwest-striking Lincton Mountain faults (Wallula system) and the northwest-striking Elbow Creek and South Fork faults (LaGrande system) have the geometry of a complementary set of fractures, suggesting contemporaneous motion on the two systems in that area.

In conclusion, the favored interpretation of the age relationships between the three regional fault systems is that the Hite fault system is the oldest. The limited available evidence suggests a common, or overlapping age, of faulting for the LaGrande and Wallula fault systems. Thus, it is not necessary to postulate -- or to account for -- contemporaneous dextral motion of all three fault systems. The dextral motion on the Hite fault system can be related to an older episode of deformation, while the dextral-slip of the LaGrande and Wallula systems can be related to north-south compressive stresses thought to be typical of the area from late Cenozoic time until the present.

Once age and offset relationships for the Wallula, LaGrande and Hite fault systems are established, the specific questions noted in Section 1.1 can be addressed in more detail.

1) "Does the Walla Walla syncline represent a northern extension of the Basin and Range Province?" The answer is probably not. Indeed, we question the association of the Basin and Range with either the Walla Walla

or LaGrande basins. The evidence for dextral strike-slip and pull-apart (Crowell, 1974) origin of the LaGrande "graben" (Gehrels and others, 1979) seems to preclude classification of the LaGrande basin as a typical Basin and Range extensional basin -- unless the view is taken that the Basin and Range is comprised of a series of pull-apart basins. If the origin of the LaGrande graben is accepted as a pull-apart in a zone of dextral shear, then a similar origin can be hypothesized for the Walla Walla syncline. A pull-apart origin would be consistent with the documented dextral-slip on the south boundary of the basin (Wallula fault) and on other faults in, and southeast of, the basin which connect to the Wallula fault. Some of these faults such as the Warm Springs fault southeast of Wallula (SW 1/4 T6N, R33E) (Shannon & Wilson, 1979) show evidence for both dextral strike-slip and a basinward normal component of faulting required for a pull-apart basin. If one accepts the hypothesis that both the LaGrande and Walla Walla Basins are pull-apart basins in zones of dextral shear, the relationship between the two becomes significant, particularly in light of the second question (Section 1.1).

2) "Does the Walla Walla basin connect, via through-going faults or systems of faults with the LaGrande graben?" The apparent similarity of age, the dextral slip common to the Wallula and LaGrande fault systems and the small difference in strike between the two systems suggest that they could have moved in response to the same regional stresses. The apparent complementary interaction in the small area of overlap between the two systems (i.e., neither offsets the other) also strongly suggests that the two systems moved together.

The main objection to a through-going dextral fault, or system of dextral faults, is the lack of major dextral offset of the north-northeast-striking Hite fault and other faults in the Hite system by any such zone. A previous study speculated that as much as 5 km of crustal shortening has occurred in the anticlinal Yakima Ridges of the Columbia Plateau (e.g., Laubscher, 1977); others have proposed that dextral shear through the Blue Mountains to the LaGrande graben is necessary to compensate for the difference between this amount of shortening and the relatively much lesser amounts east of the Yakima Ridges (for a more complete discussion refer to Laubscher, 1977; and Shannon and Wilson, 1977b). The magnitude of dextral shear

proposed along this hypothetical fault approaches the difference in crustal shortening on either side of it in central Washington, probably on the order of 3 km or more.

In the Yakima Ridges, the boundary between areas of different amounts of crustal shortening is the Cle Elum-Wallula deformed belt or CLEW (Shannon & Wilson, 1977b). The CLEW coincides with the central one-third of the postulated Olympic-Wallowa lineament (Skehan, 1965; Raisz, 1945). Because the CLEW appears to be a major structural boundary, other recent studies have resurrected the hypothesis that the entire Olympic-Wallowa lineament (OWL) is a fundamental structure (e.g., Wise, 1963, Smith, 1977, 1978; Shannon & Wilson, 1977b). Consequently, the OWL, which corresponds approximately with the Wallula, Milton-Freewater, Forks, and Lincton Mountain faults, is a logical location for the continuation of hypothetical dextral shear to the southeast.

Our observations, while suggesting that the LaGrande and Wallula fault systems do connect, also demonstrate a lack of major offset across this connection. However, the extensional, and hence, the dextral shear required to form a pull-apart basin is small (Crowell, 1974) relative to the shear proposed for the OWL. Thus, if these basins are pull-aparts, the lack of significant offset of the Hite fault system does not preclude a connection between the LaGrande and Walla Walla basins.

Finally, the most important question of all -- "What are the ages of the various faults in the area; are any yet active?" As discussed above, the available data indicate that the Hite fault system is older than the other two systems in the area, and that it has been essentially inactive since inception of the LaGrande and Wallula fault systems. Only two notable exceptions to this interpretation are evident. One suggests local re-activation of the north end of the Thorn Hollow fault, where it has been caught between two faults of the Wallula system. The other exception -- the occurrence of the "Earthquake Springs" (Figure 2) near the north end of the Ryan Creek fault -- has no straightforward explanation. However, it should be noted that re-activation, or initiation of springs during earthquakes can be attributed to a variety of causes other than proximity to an active fault.

The age of the LaGrande fault system is constrained by the 6.5 my minimum age of the Sugarloaf Mountain volcanics (Section 3.1.2) and by the young alluvial Holocene fill of the Grande Ronde Valley. Faults of the LaGrande system cut the Sugarloaf Mountain volcanics, and thus began to move after 6.5 my ago. Fault contacts between colluvial terrace gravels and Holocene (?) alluvium in the city of LaGrande suggest Holocene or at least late Pleistocene movement on some of the LaGrande faults (Gehrels and others, 1979).

Data for the age of movement on faults of the Wallula system indicate that they began to move sometime after extrusion of the Frenchman Springs Basalt, or about 13 to 14 mybp (Holmgren, 1979). If one accepts the apparent contemporaneous motion of the LaGrande and Wallula fault systems discussed above, then the Wallula system must also postdate the Sugarloaf Mountain volcanics (i.e., less than 6.5 my). In the Milton-Freewater to Umapine area, Wallula faults cut Touchet beds (upper Pleistocene) and may cut post-Touchet loess (along the Little Dry Creek fault), indicating that the Wallula system continued to move through late Pleistocene, and probably into Holocene time.

TABLE ONE

Age of the Sugarloaf Mountain Volcanics

Sample	MEM-3	MEM-4	MEM-5
Sample Location	Sugarloaf Mtn.	Spring Mtn.	Wilbur Mtn.
% Potassium	1.7625 %	1.642 %	1.2657 %
% Radiogenic Argon	34.14906 %	53.33278 %	37.14261 %
Age (10^6 years)	6.5370	7.2583	7.3165
Precision (10^6 years)	0.1408	0.1078	0.1458

Age determination by Louis Hogan, School of Oceanography, Oregon State University, on October 2, 1979.

6. REFERENCES CITED

Battelle, 1978, Aerial photographs of the Columbia Plateau: NASA-Aimes Research Center, Moffat Field, California, flight lines 78-092, 78-093, 78-100, 78-101, 78-103, 78-106, scale 1:80,000, July, 1978, black and white.

Beeson, M.H. and Moran, M.R., 1979, Columbia River Basalt Group Stratigraphy in Western Oregon: Oregon Geology, v. 41, no. 1, p. 11-14.

Bentley, R.D., 1979, personal communication: Central Washington University, Ellensburg, Washington.

Bingham, J.W., Longquist, C.T., and Baltz, E.H., 1970, Geologic investigation of faulting in the Hanford region, Washington (with a section on the occurrence of micro-earthquakes by A.M. Pitts): U.S. Geol. Survey Open File Report, 104 p.

Brown, B.H., 1937, The State-line earthquake at Milton and Walla Walla: Seismol. Soc. America Bull., v. 41, no. 3, p. 205-209.

Crowell, J.C., 1974, Origin of Late Cenezoic basins in southern California: Dickenson, W.R. ed., Soc. Econ. Paleont. & Min. Special Pub. 22, 204 p.

Fenneman, N.M., 1931, Physiography of Western United States: New York, McGray-Hill Book Company, Inc., 534 p.

Gehrels, G., White, R., and Davis, G., 1979, The LaGrande pull-apart basin, northeastern Oregon: Letter report prepared for Washington Public Power Supply System.

Hampton, E.R., and Brown, S.G., 1964, Geology and groundwater resources of the upper Grande Ronde River basin, Union County, Oregon: U.S. Geol. Survey Water Supply Paper 1597, 99 p.

Hills, E.S., 1963, Elements of structural geology: New York, John Wiley & Sons, Inc.

Hogan, L., 1979, written communication: School of Oceanography, Oregon State University, Corvallis, Oregon.

Hogenson, G.M., 1964, Geology and groundwater of the Umatilla River basin, Oregon: U.S. Geol. Survey Water Supply Paper 1620, 162 p.

Holmgren, D.A., 1970, K/Ar dates and paleomagnetics of the type Yakima Basalt, central Washington: Proceedings of the second Columbia River Basalt Symposium, Eastern Washington State College, Cheney, Wash., p. 189-199.

REFERENCES CITED
(continued)

Kienle, C.F., Jr., and Newcomb, R.C., 1974, Age of Cascadian tectonic structures, north central Oregon and south central Washington: Oregon Academy of Science Proceedings, v. X, p. 69.

Laubscher, H.P., 1977, Structural analysis of post-Yakima deformation Columbia Plateau, Washington: Draft report prepared for Washington Public Power Supply System.

NASA, 1973, Aerial photographs of the Umatilla National Forest: Eros Data Center, Sioux Falls, South Dakota, Scene No. 5730014180000 through 5730014180152, scale 1:31,000, September 1973, false color infrared.

Newcomb, R.C., 1961, Storage of groundwater behind surface dams in the Columbia River Basalt, Washington, Oregon and Idaho: U.S. Geol. Survey Prof. Paper 383-A, p. 1-15.

Newcomb, R.C., 1965, Geology and groundwater resources of the Walla Walla River basin, Washington-Oregon: Washington Div. Water Resources Water Supply Bull. 21, 151 p.

Newcomb, R.C., 1967, The Dalles-Umatilla syncline, Oregon and Washington: U.S. Geol. Survey Prof. Paper 575-B, p. 88-93.

Newcomb, R.C., 1970, Tectonic structure of the main part of the basalt of the Columbia River Group, Washington, Oregon and Idaho: U.S. Geol. Survey Misc. Geol. Inv. Map I-587, 1:500,000.

Newcomb, R.C., 1971, Relation of the Ellensburg Formation to extensions of The Dalles Formation in the area of Arlington and Shutler Flat, north-central Oregon: The Ore. Bin., v. 33, p. 133-142.

Raisz, E., 1945, The Olympic-Wallowa lineament: Am. Jour. Sci., vol. 243-A, p. 479-85.

Schmincke, Hans-Ulrich, 1964, Petrology, paleocurrents and stratigraphy of the Ellensburg Formation and interbedded Yakima Basalt flows, south-central Washington: The John Hopkins University, Ph.D. Thesis.

Shannon & Wilson, Inc., 1973, Geologic studies of Columbia River Basalt structures and age of deformation: Report prepared for Portland General Electric Company, by C.F. Kienle, Jr., and R.C. Newcomb.

Shannon & Wilson, Inc., 1977a, Additional information on the seismicity and tectonics of the Columbia Plateau: Report prepared for Portland General Electric Company, by C.F. Kienle, Jr., and R.W. Couch.

REFERENCES CITED
(continued)

Shannon & Wilson, Inc.,1977b, Geologic reconnaissance of CleElum-Wallula lineament and related structures: Report prepared for Washington Public Power Supply System, under direction of United Engineers & Constructors, Inc., by C.F. Kienle, Jr., R.D. Bentley, and J.L. Anderson, Oct. 1977.

Shannon & Wilson, Inc., 1977c, Oriented rock sampling for geomagnetic evaluations of structures in the Columbia Plateau 1872 earthquake study: Report prepared for Washington Public Power Supply System, under direction of United Engineers & Constructors, Inc., by J. Gorans.

Shannon & Wilson, Inc., 1979, Evaluation of faulting in the Warm Springs Canyon area southeast Washington: Report prepared for Washington Public Power Supply System under direction of United Engineers & Constructors, Inc., by S.M. Farooqui, Dec. 1979.

Skehan, 1965, A continental crustal boundary in the Pacific Northwest: Prepared by Boston College, Chestnut Hill, Mass., for Air Force Cambridge Research Laboratories, Office of Aerospace Research, Bedford, Mass., AFCRL-65-904.

Smith, R.B., 1977, Intraplate tectonics of the Western North American Plate: Tectonophysics, v. 37, p. 323-336.

Smith, R.B., 1978, Seismicity, crustal structure, and intraplate tectonics of the interior of the western Cordillera, "in" Smith, R.B. and Eaton, G.P., eds., Cenozoic tectonics and regional geophysics of the western Cordillera: Geol. Soc. America Memoir 152, p. 111 - 144.

Swanson, D.A., Wright, T.L., and Helz, R.T., 1975, Linear vent systems and estimated rates of magma production and eruption for the Yakima Basalt on the Columbia Plateau: Am. Jour. Sci., v. 275, p. 877-905.

Swanson, D.A., Wright, T.L., Hooper, P.R., and Bentley, R.D., 1979, Revision in stratigraphic nomenclature of the Columbia River Basalt Group: U.S. Geol. Survey Bull. 1457-G, 59 p.

Sylvester, A.G., and Smith, R.R., 1976, Tectonic transgression and basement-controlled deformation in the San Andreas fault zone, Salton Trough, California: Am. Assoc. Petroleum Geologists Bull., v. 60, p. 2081-2102.

Taubeneck, W.H., 1969, Dikes of Columbia River Basalt in northeastern Oregon, western Idaho and southeastern Washington: Proceedings of the second Columbia River Basalt Symposium, Eastern Washington State College, Cheney, Wash., p. 73-96.

Taubeneck, W.H. 1979, personal communication: Dept. of Geology, Oregon State University, Corvallis, Oregon.

Tchalenko, J.S., 1970, Similarities between shear zones of different magnitudes: Geol. Soc. America Bull., v. 81, no. 6, p. 1625-1640, 12 fig.

U.S.D.A., 1976, Aerial photography of Wallowa-Whitman and Umatilla National Forests: USFS project No. 41061, Scale 1:80,000, black and white.

Waitt, R.B., 1978, Post-Miocene stratigraphy and tectonism of parts of the Great Columbia Plain and adjacent Cascades, Washington: Tectonics and Seismicity of the Columbia Plateau Workshop (symposium), Rockwell International.

Walker, G.W., 1973, Reconnaissance geologic map of the Pendleton Quadrangle, Oregon and Washington: U.S. Geol. Survey Misc. Inv. Ser. Map I-727, 1:250,000.

Walker, G.W., 1977, Geologic Map of Oregon east of the 121st meridian: U.S. Geol. Survey Misc. Inv. Ser. Map I-902, 1:500,000.

Walker, G.W., 1979, Reconnaissance geologic map of the Oregon part of the Grangeville Quadrangle, Baker, Union, Umatilla, and Wallowa Counties, Oregon: U.S. Geol. Survey Misc. Inv. Ser. Map I-1116, 1:250,000.

Washington Public Power Supply System, 1977a, WNP - 1/4 PSAR, Amendment 23, Subappendix 2R D, "Geological studies in the 1872 earthquake epicentral region", by Shannon and Wilson, Inc., Oct. 1977.

Washington Public Power Supply System, 1977b, WNP - 1/4 PSAR, Amendment 23, Subappendix 2R C, "Tectonic evolution of the Pacific Northwest Precambrian to Present", by G.A. Davis, Oct. 1977.

Washington Public Power Supply System, 1977c, WNP - 1/4 PSAR, Amendment 23, Subappendix 2R H, "Geologic evaluations of structures in the Columbia Plateau", by Shannon & Wilson, Inc., Chapter 2R H-a, "Stratigraphy of the Columbia River Basalt Group and Ellensburg Formation", by R.D. Bentley and Shannon & Wilson, Inc., Oct. 1977.

Washington Public Power Supply System, 1977d, WNP - 1/4 PSAR, Amendment 23, Subappendix 2R H, "Geologic evaluation of structures in the Columbia Plateau", by Shannon & Wilson, Inc., Chapter 5.0, "Geologic studies - Wallula Gap to Badger Coulee", by S. M. Farooqui, Oct. 1977.

REFERENCES CITED
(continued)

Washington Public Power Supply System, 1977e, WNP - 1/4 PSAR, Amendment 23, Subappendix 2R I, "Geophysical evaluation of structures in the Columbia Plateau", by Weston Geophysical Research, Inc., Oct. 1977.

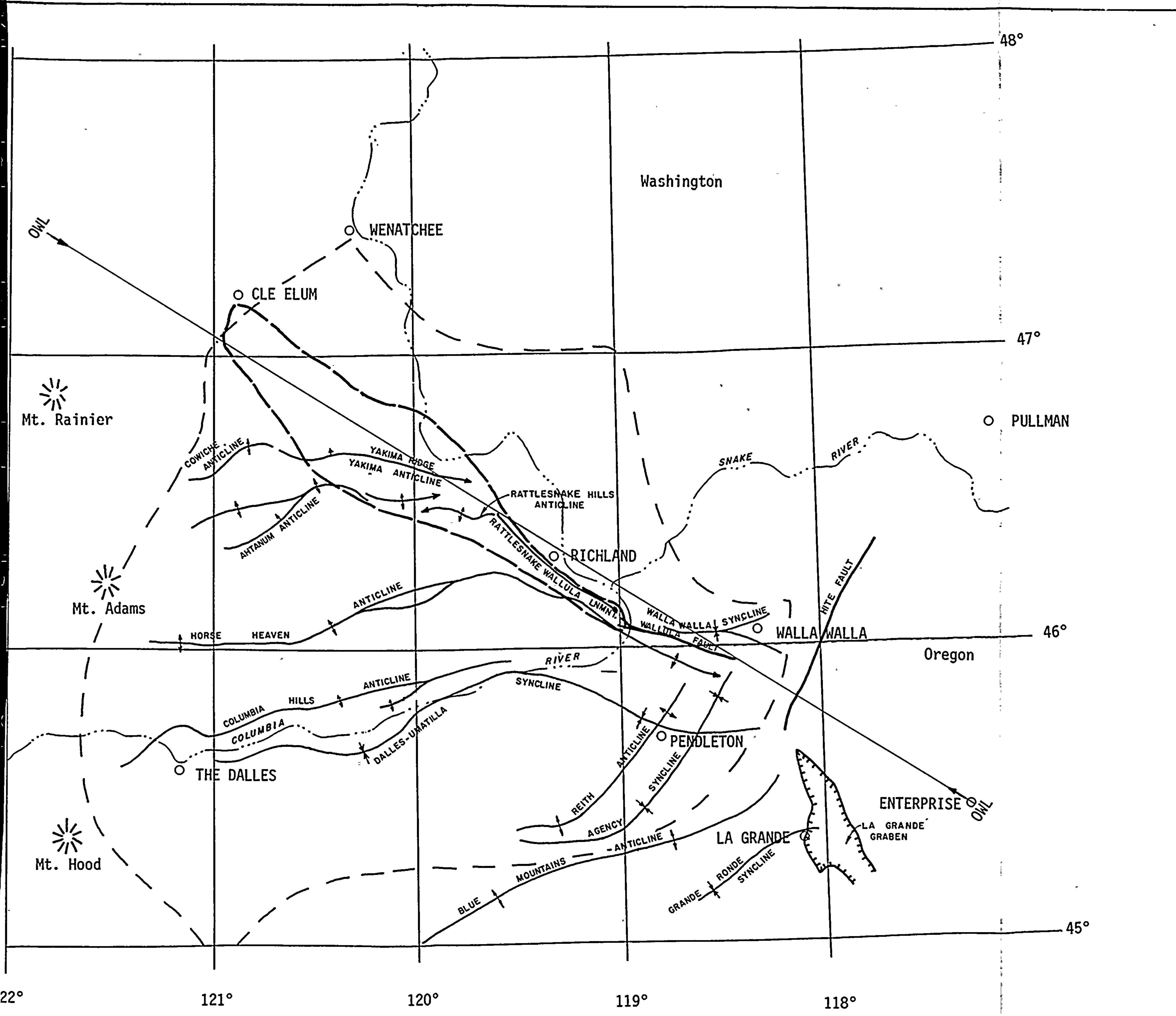
Washington Public Power Supply System, 1977f, WNP - 1/4 PSAR, Amendment 23, Subappendix 2R H, "Geologic evaluation of structures in the Columbia Plateau", by Shannon & Wilson, Inc., Chapter 7.0, "Reconnaissance mapping of the Rattlesnake-Wallula Lineament, eastern Rattlesnake Hills, and Yakima Ridges", by Clive F. Kienle, Jr., Oct. 1977.

Weston Geophysical Research, Inc., 1978, Magnetic properties of basalts from the Columbia Plateau, Part I and II: Report prepared for Washington Public Power Supply System under direction of United Engineers & Constructors, Inc., March 1978.

Weston Geophysical Research, Inc., 1979, Magnetic modeling, Columbia Plateau area Washington and Oregon: Report prepared for Washington Public Power Supply System under direction of United Engineers & Constructors, Inc., Aug. 1979.

Wise, D.U., 1963, An outrageous hypothesis for the tectonic pattern of the North American cordillera: Geol. Soc. America Bull., v. 74, p. 357-362.

Wright, T.L., Swanson, D.A., Helz, R.T., and Byerly, G.R., 1979, Major oxides trace elements, and glass chemistry of Columbia River Basalt samples collected between 1971 and 1977: U.S. Geol. Survey Open-File Report 79-711.



LEGEND

BOUNDARY OF THE CLEW

BOUNDARY OF THE YAKIMA FOLD BELT

OWL

OLYMPIC-WALLOWA LINEAMENT

0 50 100

APPROXIMATE SCALE IN KILOMETERS

WASHINGTON PUBLIC POWER SUPPLY SYSTEM
NUCLEAR PROJECT NOS. 1 & 4

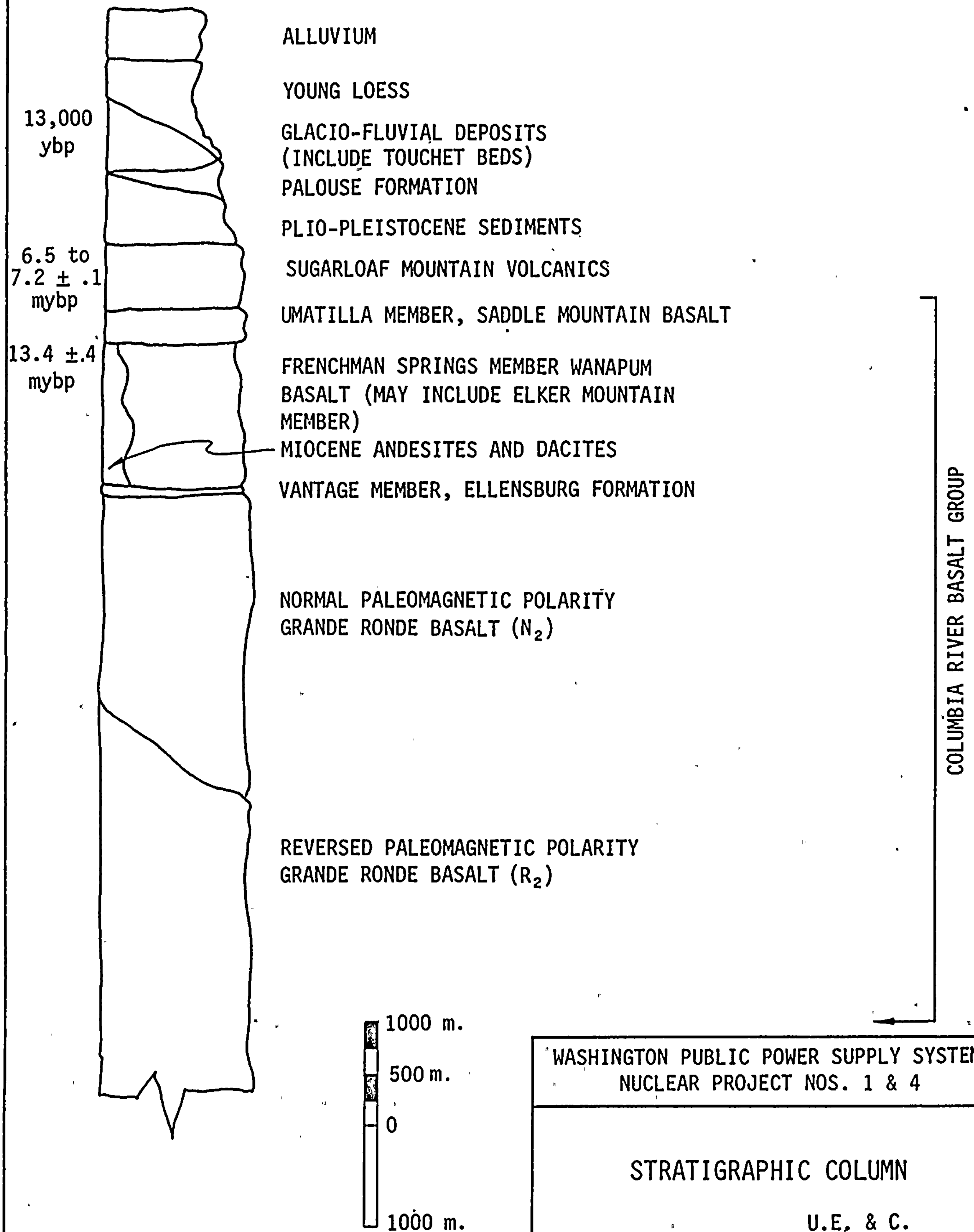
GENERALIZED REGIONAL TECTONIC MAP

DECEMBER, 1979

U.E. & C
CONTRACT #44103

SHANNON & WILSON, INC.
Geotechnical Consultants
Portland, Oregon

FIG. 1



WASHINGTON PUBLIC POWER SUPPLY SYSTEM
NUCLEAR PROJECT NOS. 1 & 4

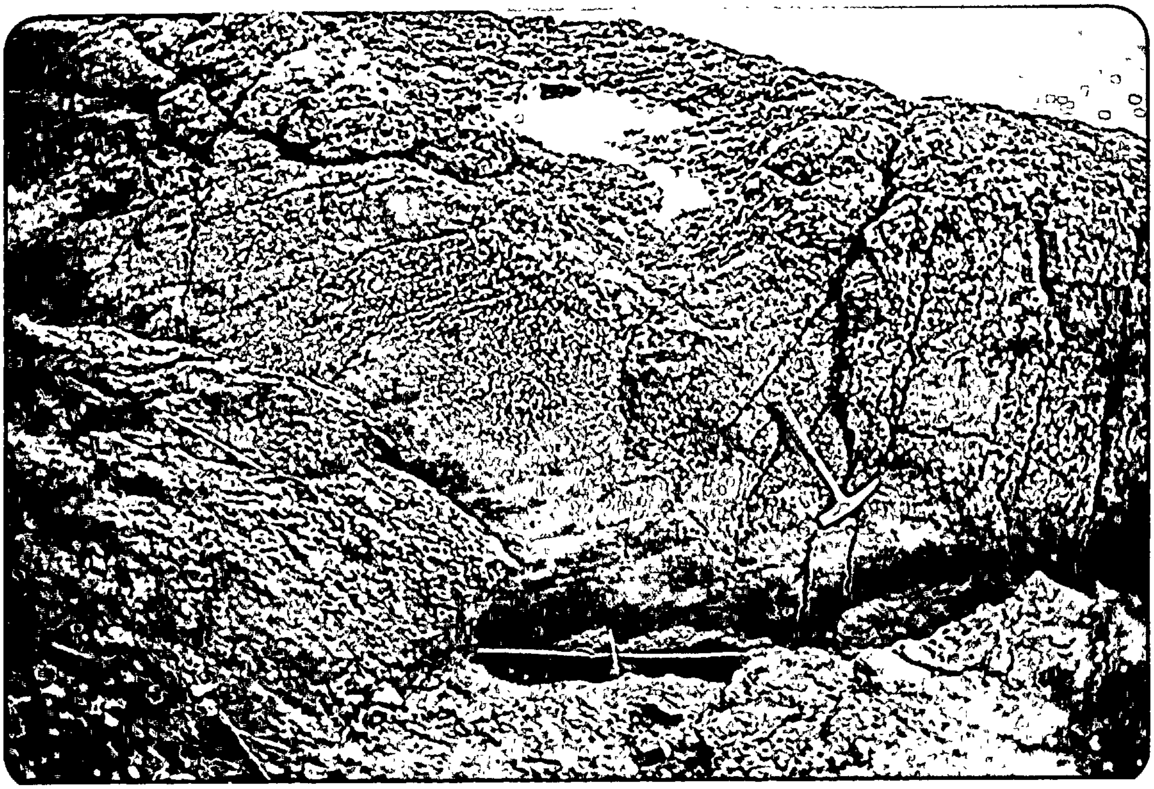
STRATIGRAPHIC COLUMN

DECEMBER, 1979

U.E. & C.
CONTRACT #44103

SHANNON & WILSON, INC.
Geotechnical Consultants
Portland, Oregon

FIG.2A



STRIKE-SLIP STRIAE ON SADDLE HOLLOW FAULT; LOOKING EAST ON NORTH BANK OF UMATILLA RIVER AT MOUTH OF SADDLE HOLLOW.

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NOS. 1 & 4	
SADDLE HOLLOW FAULT	
DECEMBER, 1979	U.E. & C. CONTRACT #44013
SHANNON & WILSON, INC. Geotechnical Consultants Portland, Oregon	FIG. 3

THRUST FAULTING OF FRENCHMAN SPRINGS FLOWS AND DIKE AT THORN HOLLOW. NOTE TRUNCATION OF DIKE SELVEDGE BY FAULT. THRUST FAULT APPEARS TO BE COMPRESSIONAL "PALM TREE" STRUCTURE ASSOCIATED WITH MAIN RIGHT-LATERAL STRIKE-SLIP THORN HOLLOW FAULT.

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NOS. 1 & 4	
THORN HOLLOW FAULT	
DECEMBER, 1979	U.E. & C. CONTRACT #44013
SHANNON & WILSON, INC. Geotechnical Consultants Portland, Oregon	FIG. 4A

FAULT ON DEADMAN PASS - STRIKE-SLIP ZONE ASSOCIATED WITH THORN HOLLOW FAULT. GOUGE (ON RIGHT) HAS NEAR HORIZONTAL STRIAE.

WASHINGTON PUBLIC POWER SUPPLY SYSTEM
NUCLEAR PROJECT NOS. 1 & 4

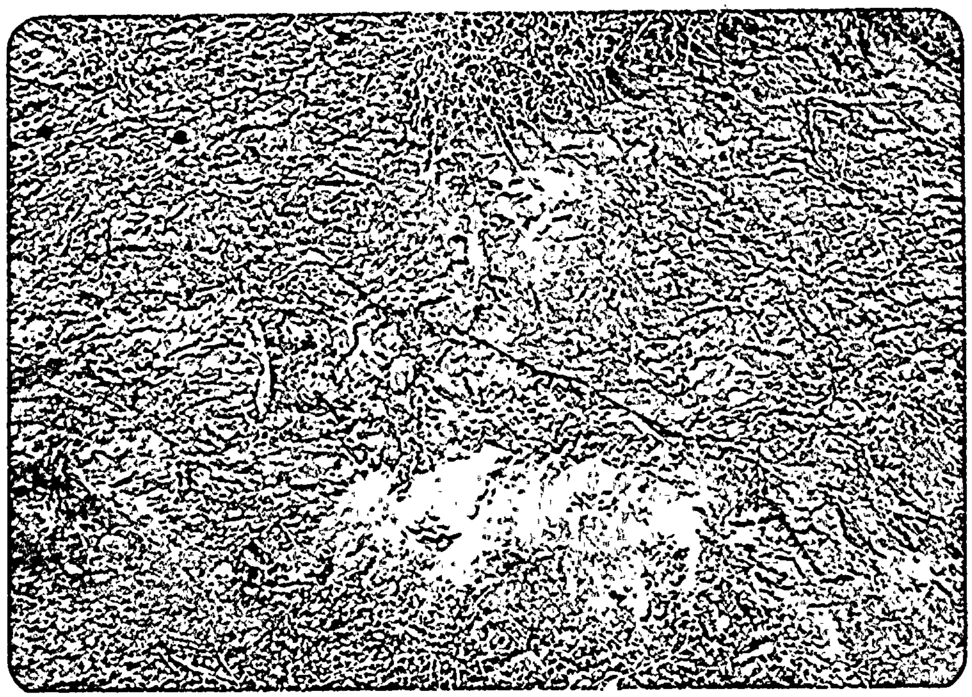
THORN HOLLOW FAULT

DECEMBER, 1979

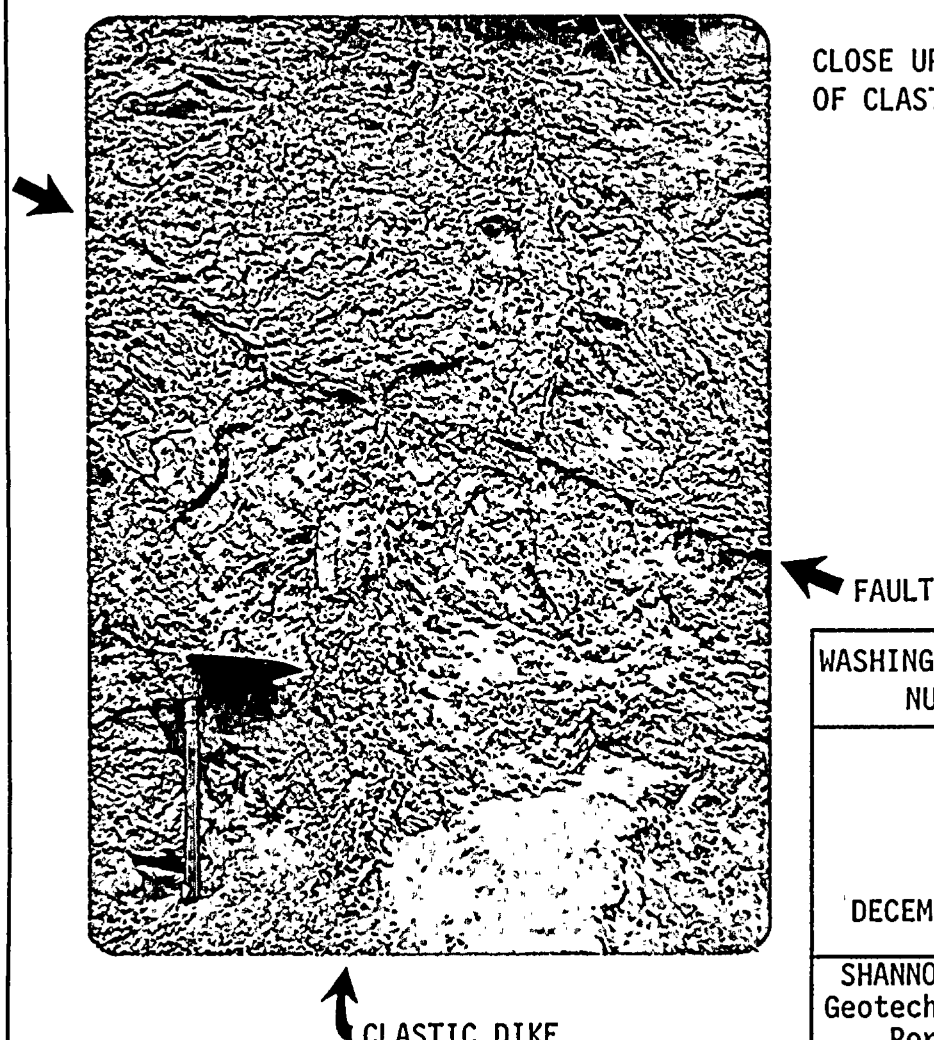
U.E. & C.
CONTRACT #44013

SHANNON & WILSON, INC.
Geotechnical Consultants
Portland, Oregon

FIG. 4B



FAULTING OF TOUCHET BEDS SOUTH OF UMAPINE. OFFSET APPEARS ASSOCIATED WITH BARRETT FAULT (SW¼ SE¼ SEC. 25, T6N R34E)



CLOSE UP VIEW OF ABOVE; NOTE OFFSET OF CLASTIC DIKE IN TOUCHET BEDS.

WASHINGTON PUBLIC POWER SUPPLY SYSTEM
NUCLEAR PROJECT NOS. 1 & 4

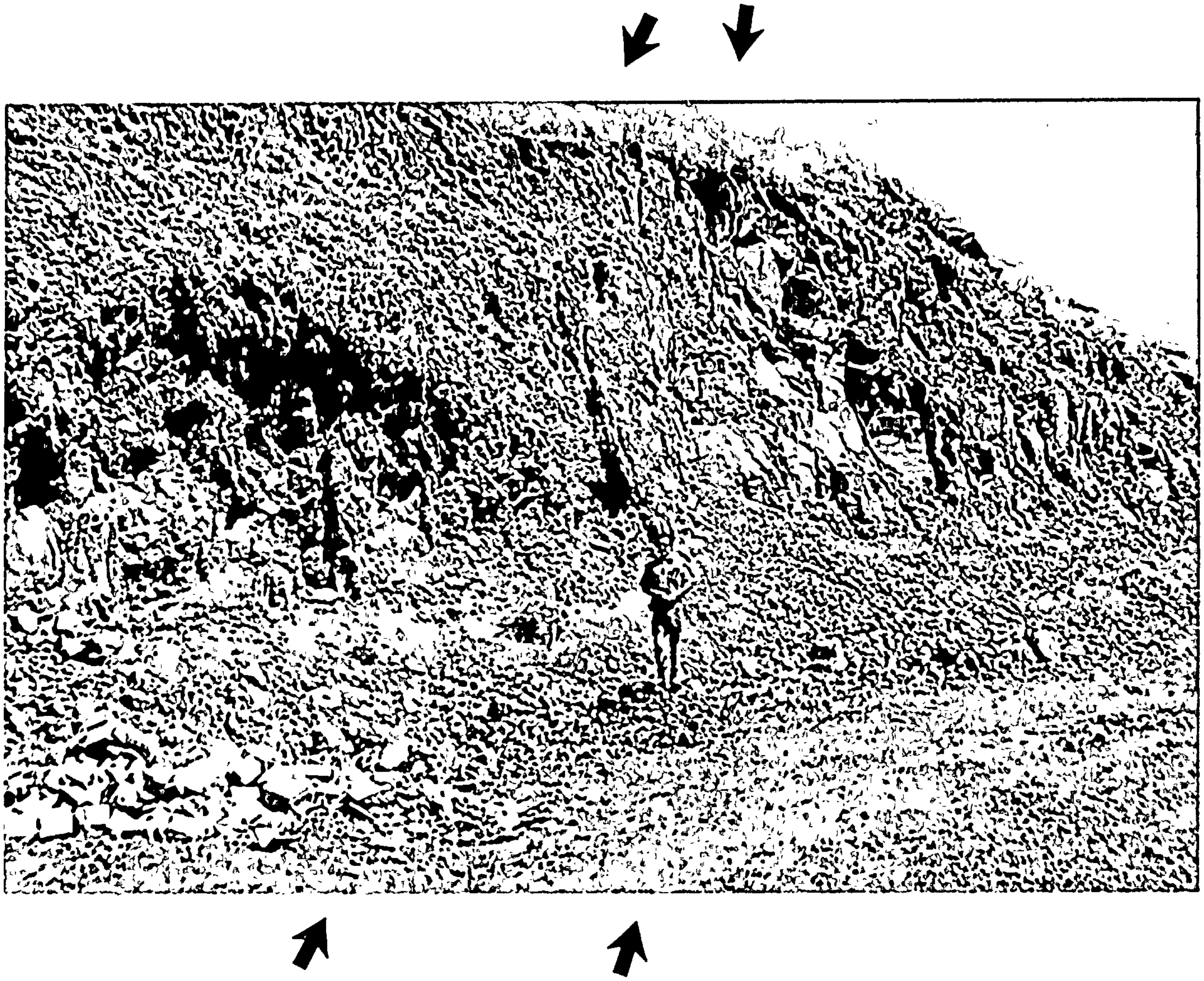
BARRETT FAULT

DECEMBER, 1979

U.E. & C. CONTRACT #44013

SHANNON & WILSON, INC.
Geotechnical Consultants
Portland, Oregon

FIG. 5



MILTON-FREEWATER QUARRY FAULT, BOWLUS HILL QUADRANGLE, NW¼ SW¼ SEC. 18, T5N R36E, TRENDS 130°-140°, DIPS 85°SE, WITH HORIZONTAL STRIAE. FRENCHMAN SPRINGS BASALT FLOWS EXPOSED ON EACH SIDE OF THE GOUGE ZONE. ARROWS MARK TOP AND BOTTOM OF GOUGE.

WASHINGTON PUBLIC POWER SUPPLY SYSTEM
NUCLEAR PROJECT NOS. 1 & 4

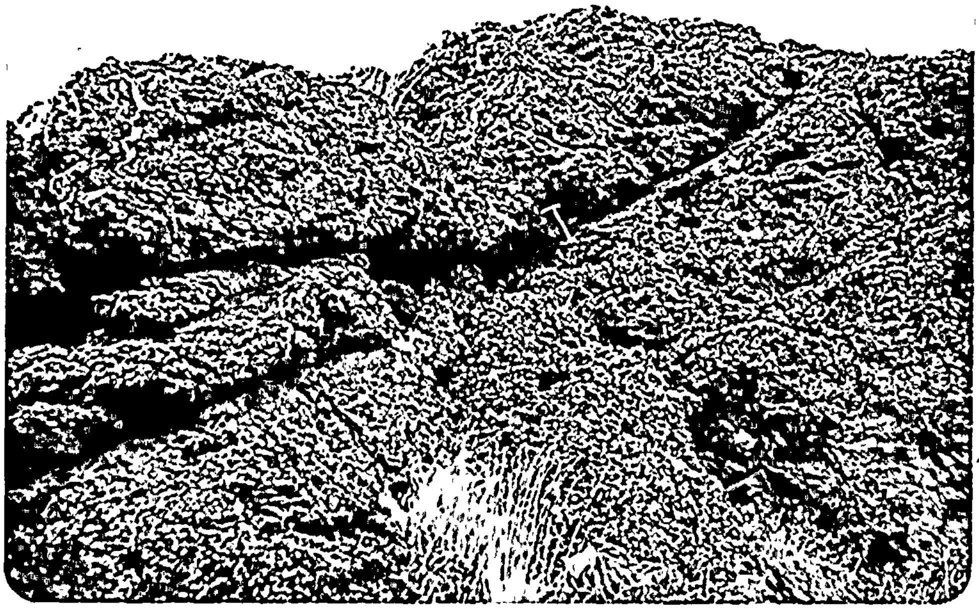
MILTON-FREEWATER FAULT

DECEMBER, 1979

U.E. & C.
CONTRACT #44013

SHANNON & WILSON, INC.
Geotechnical Consultants
Portland, Oregon

FIG. 6

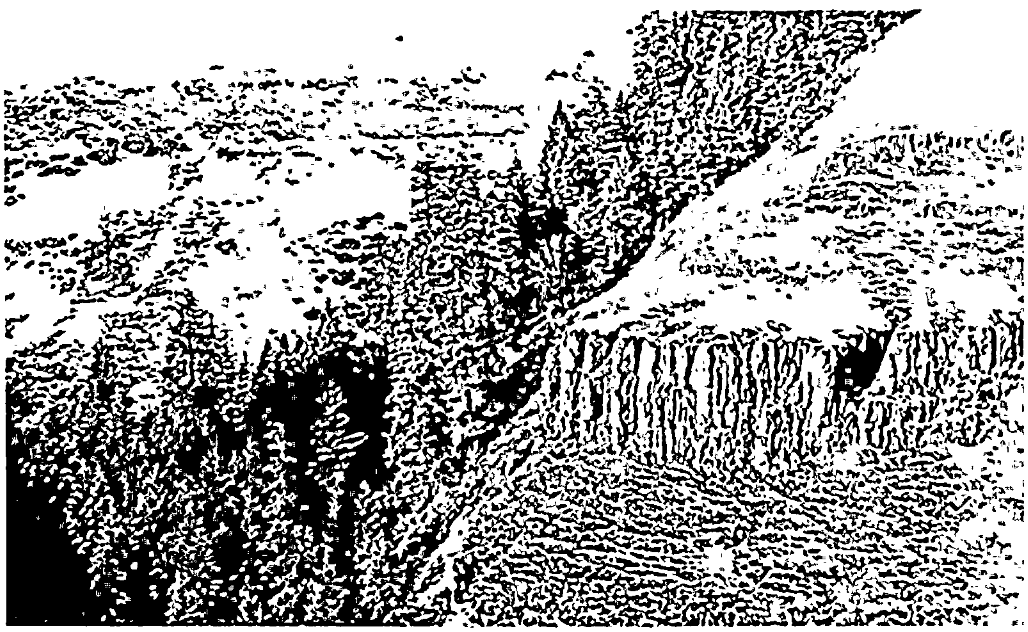


VIEW OF LOW-ANGLE SOUTH DIPPING THRUST ZONE ON THE NORTH FLANK OF THE FORKS FAULT (NW¼ SEC. 25, T5N R36E)

VIEW OF THE FORKS FAULT IN NW¼ SEC. 25, T5N R36E LOOKING N50°W. NEAR-VERTICAL FAULT ZONE IS SHEARED, BRECCIATED, AND CHALCEDONY CEMENTED WITH SUB-HORIZONTAL STRIAE.

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NOS. 1 & 4	
FORKS FAULT	
DECEMBER, 1979	U.E. & C. CONTRACT #44013
SHANNON & WILSON, INC. Geotechnical Consultants Portland, Oregon	FIG. 7

VIEW WNW PARALLEL TO SOUTH FORK OF WALLA WALLA RIVER. LINCTON MOUNTAIN FAULT FOLLOWS NOTCHES IN SPURS. NOTE MISMATCH OF FLOWS ACROSS FAULT ZONE (COVERED BY DIAGONAL LINE OF TREES). LOWER PHOTO SHOWS TRUNCATION OF MASSIVE GRANDE RONDE FLOW BY FAULT (CLOSE UP OF CENTER OF AREA OF UPPER PHOTOGRAPH) SEC.15, T4N R37E.



WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NOS. 1 & 4	
LINCTON MOUNTAIN FAULTS	
DECEMBER, 1979	U.E. & C. CONTRACT #44013
SHANNON & WILSON, INC. Geotechnical Consultants Portland, Oregon	FIG. 8

APPENDIX A

Task 2 - Supplemental Report

TABLE OF CONTENTS

APPENDIX A

Task 2 - Supplemental Report

A-1. INTRODUCTION

A-1.1. PURPOSE AND SCOPE OF INVESTIGATION

This report presents the results of additional geologic field studies of the area between Adams, Milton-Freewater, Tollgate Chalet, and Pikes Peak in northeastern Oregon, that were conducted to supplement our previous field studies reported in the main body of this report. The purpose of the studies was to provide additional information on the relative age of motion between the north-northeast structures of the Hite fault system and the northwest-southwest structures of the Wallula and LaGrande fault systems. Particular emphasis was placed on determination of the sense of motion on the faults of the Hite system. This area was identified during earlier reconnaissance mapping as the area most likely to provide data critical to the interpretation of the motion, amount of offset, and relative ages of the Wallula and the Hite fault systems. Field mapping was directed toward refining the stratigraphy of the Grande Ronde Basalt and the Frenchman Springs Member of the Wanapum Basalt in order to evaluate the age and the amount and sense of offset on the more prominent faults in the two systems.

This report summarizes these supplemental field investigations. The data contained in this report, together with our interpretation of the significance of the data are more fully discussed in the main body of the report, which combines the results of this work and our earlier reconnaissance of the Blue Mountains.

A-1.2. ACKNOWLEDGEMENTS

Field work for these investigations was conducted by C.F. Kienle, Jr., and D.N. Clayton, under the direction of R.J. Deacon. The authors were assisted in preparation of the report by M.L. Hamill and H.H. Waldron.

Special thanks are due Paul Bouchard, Earl Malone and John Ware, of the U.S. Forest Service, who made 1:31,000 false color infrared imagery available to us. We also wish to thank Dale Jenner of Harris Pine Company and Bob Weinburger of Boise Cascade Corporation for arranging access into the corporate properties in the Tollgate and Blalock Mountain areas.

A-2. FIELD INVESTIGATIONS

A-2.1 STRATIGRAPHIC STUDIES

The stratigraphic studies consisted of measuring and evaluating several sections of the Grande Ronde Basalt and the Frenchman Springs Member of the Wanapum Basalt. Although subtle interflow variations occur in the Columbia River Basalt Group, specific flows or groups of flows within the study area are fairly uniform in their chemistry, petrology, and magnetic polarities. Thus, major basalt units generally can be readily distinguished in the study area by their petrologic characteristics, while magnetic polarity changes can be used to determine the internal stratigraphy of the Grande Ronde Basalt. Although chemical analyses are also useful in differentiating the basalt flows, none were made for this brief study.

The following stratigraphic sections were studied: 1) the Grande Ronde Basalt on the south side of Blalock Mountain, and along the north bank of the Umatilla River between Thorn Hollow and Ryan Creek; and 2) the Frenchman Springs Member along the Walla Walla River between Milton-Freewater and Forks, and on Reed and Hawley Mountain, between Weston and Tollgate Chalet.

A-2.2 FAULT STUDIES

Faults in the area can be grouped into three major systems: the west-northwest-trending Wallula, the north-northeast-trending Hite, and the north-northwest-trending LaGrande fault systems. Faults examined in the study area included the Milton-Freewater, Bade, Barrett, Forks, Little Dry Creek, Dry Creek, and Lincton Mountain faults in the Wallula fault system; the Peterson Ridge, Saddle Hollow, and Thorn Hollow faults in the Hite fault system; and the South Fork and Elbow Bend faults in the LaGrande fault system. The three major systems and the faults examined within them are discussed briefly in the following sections. The faults are shown on Figure 2 of the main report.

A-2.2.1 Wallula Fault System

The Wallula fault system is a series of en echelon faults that approximately parallel the Rattlesnake-Wallula lineament along the north flank of the Horse Heaven anticline in southwestern Washington and northeastern Oregon. The system extends east-southeastward from west of Wallula Gap to the Hite fault, and includes faults as far north as Walla Walla,

Washington, and Pikes Peak, Oregon, and as far south as the vicinity of Weston, Oregon.

A-2.2.1.1 Milton-Freewater Fault

The Milton-Freewater fault was first mapped by Newcomb (1965). It is exposed in a borrow pit east of the Walla Walla River (NW cor. sec. 18, T5N, R36E), where two, nearly vertical, N50°W-striking shear zones cut glomerophyric flows of the gently, northwest-dipping Frenchman Springs Member basalt. Both zones consist of sheared and brecciated basalt in an orange to yellow clayey silt matrix of finely comminuated basalt fragments. If the nearly horizontal striae in the two zones are assumed to represent the true slip on the fault, then approximately 130 m of dextral slip could account for the 12 m of north-side-down vertical component of movement that can be measured on the 2 m-wide southern shear zone.

A-2.2.1.2 Bade Fault

The Bade fault is inferred to extend along a prominent northwest-trending linear portion of Dry Creek from near Highway 11 (center sec. 23, T5N, R35E) past Bade (NW1/4 sec. 4). Although the fault is not exposed it is inferred from Frenchman Springs basalt flows that cannot be matched across the trend, and the presence of several small N50°W-trending Thorn Hollow fault, and at its north end with the eastward projection of the Wallula fault. The Bade fault is not exposed; thus, no estimate could be made of the amount of offset on the fault.

A-2.2.1.3 Barrett Fault

A prominent, 12- to 15 m-high topographic lineation extends from near Barrett (sec. 4, T5N, R35E) N50°W for about 4 km. Along this escarpment, at a landfill on the Dry Creek Road, anomalously steep dips (15°-30° to the northeast) and an intraformational angular unconformity occur within the Touchet beds. Paralleling the scarp to the west, along Pine Creek Road (NW cor, SW1/4 SE1/4 sec. 25, T6N, R34E), several faults in Touchet beds are exposed. These small faults are inferred to extend between Pine Creek Road and Barrett along the base of the escarpment. The faults, which cut both Touchet beds and clastic dikes in the Touchet, strike about N70° to 75°W and generally dip either 30° or 60°N. Striae are well developed on both

sets of faults. Orientation of the striae, and the apparent down-to-the-north offsets are consistent with dextral oblique-slip.

A-2.2.1.4 Forks Fault

The Forks fault extends for several miles along the south flank of Blalock Mountain (T5N, R36E). It is best exposed in roadcuts along the north bank of the North Fork of the Walla Walla River, where it consists of a zone about 100 m wide. Although the fault cannot be traced directly from the North Fork, it is inferred to extend east-southeast along a prominent magnetic linear (Weston, 1979) for approximately two miles to Blalock Mountain where it is exposed as a near-vertical fault that can be traced east-southeastward to Flume Canyon. On Blalock Mountain the fault appears to have a south-side-down offset, but the amount of displacement could not be determined. Striae plunging 15° SE on the Forks fault suggest a significant component of strike-slip motion. Near its center, the fault appears to merge upslope with a low-angle, south-dipping thrust fault. This structural style, which is characteristic of "palm tree structures" developed by near-surface contraction and uplift along strike-slip faults (Sylvester and Smith, 1976), is interpreted here to have resulted from a change in trend of the Forks fault from N45° to 50°W, northwest of the thrust, to N60°W, southeast of the thrust.

A-2.2.1.5 Lincton Mountain Faults

The Lincton Mountain faults comprise an en echelon set of faults that extend along the north flank of Lincton Mountain from near the Peterson Ridge fault east-southeast to about a mile east of the Hite fault. The individual faults generally parallel or strike slightly north of the overall trend of the zone. Grande Ronde Basalt flows and a Frenchman Springs feeder dike are offset by the faults, with apparent north-side-down displacement. One of the lesser faults exposed along the south side of Elbow Creek, however, shows an apparent south-side-down offset with well-developed striae that rake 30°E. The faults appear to be terminated on the northwest by the Peterson Ridge fault. Near Tollgate Chalet, however, small faults paralleling the Lincton Mountain fault cut cemented gouge of the Hite fault and display horizontal or shallow dipping striae (NE1/4 sec. 26, T4N, R37E). An apparent offset of the western part of the near-vertical Hite fault zone, where it intersects the Lincton Mountain fault, near Tollgate Chalet suggests

dextral slip of about 0.5 km on the fault. The en echelon pattern of the Lincton Mountain faults, the presence of shallow-dipping striae on smaller faults with strikes parallel to the main faults, and the apparent offset of the Hite fault zone, all suggest that the Lincton Mountain faults may have a major component of strike-slip motion.

A-2.2.1.6 Little Dry Creek Fault

Little Dry Creek fault is inferred to extend along a topographic and vegetation lineation from west of Milton-Freewater southeast along Pine and Little Dry Creeks to east of Weston. Two strands of the fault cut glomerophyric Frenchman Springs basalt flows about 500 m south-southwest of the Thorn Hollow fault. The two zones are about 1.5 to 2 m wide, strike N20° to 35°W, and exhibit striae indicative of oblique-slip motion. Movement on the steeply-dipping, westernmost strand appears to be up-to-the-east. In Little Dry Creek, the main fault has dropped both basalt and Palouse Formation down-to-the-east about 0.5 m.

A-2.2.1.7 Dry Creek Fault

The Dry Creek fault was not observed in outcrop, but is inferred to extend along Dry Creek between the Thorn Hollow and Saddle Hollow faults, based on the apparent elevation differences across the creek of both the top and bottom of a Frenchman Springs flow, with the east side lower by 15 to 20 m. This offset would be consistent with a dextral offset of the northwest-dipping flows along Dry Creek. The fault may continue east of the Saddle Hollow fault, but if so, it has been offset to the north. Because no obvious stratigraphic mismatch occurs across the creek east of the Ryan Creek fault, it appears that the Dry Creek fault terminates at the Ryan Creek fault.

A-2.2.1.8 Tectonics of the Wallula Fault System

The Wallula fault system consists of a series of subparallel, generally left-stepping, en echelon faults -- a pattern that suggests the faults were formed by overall dextral shear motion of the system. Individual fault relations support this concept. Shallow-dipping striae occur on several of the faults, and the apparent fault offsets observed are compatible with dextral slip. Dextral motion is demonstrable on the Milton-Freewater fault, and evidence suggests that the Lincton Mountain fault off-

sets the Hite fault zone in a dextral sense. The cumulative amount of dextral displacement along the Wallula fault system has not been determined, owing to inadequate stratigraphic control, poor exposures, and the vertical component of motion. Faults within the Wallula system cut upper Pleistocene strata in several locations, and all the faults exhibit a youthful geomorphic expression.

The Wallula fault system is interpreted to be younger than the Hite system on the basis of the relative age of strata affected, geomorphic expression, and cross-cutting relationships of the two systems. However, in a few places the Hite system faults appear to terminate and possibly offset faults of the Wallula system.

The tectonic relationship of the Wallula and LaGrande systems could not be resolved from this supplemental study. Only two significant northwest-trending faults of the LaGrande system occur in the study area, both of which cross the Lincton Mountain fault without displaying any definitive cross-cutting relationships. As discussed in Section A-2.2.3.3, contemporaneous motion on these two systems seems likely based on their cross-cutting relationships.

A-2.2.2 Hite Fault System

The Hite fault system consists of a series of north-northeast-to north-striking faults that parallel and are largely confined to the northwest flank of the north-northeast-trending part of the Blue Mountains anticlinorium. These faults occur in a broad belt between the Agency syncline and the Mill Creek-Hite fault-Duncan structures. The Hite fault, which is the easternmost and longest of the faults in the system, extends northeast of the study area for at least 60 km.

A-2.2.2.1 Peterson Ridge Fault

The Peterson Ridge fault is inferred to extend from the vicinity of the Umatilla River north-northeast through Peterson Ridge to the vicinity of the Middle Fork of Cottonwood Creek. At one locality on Blalock Mountain, the attitudes of the basalt flows change measurably from northwest to southwest across the fault, suggesting significant compression along the fault. At two other localities in the vicinity of the Walla Walla River, elevations of the Grande Ronde Basalt N_2-R_2 magnetic polarity contact across the fault suggest an east-side-down vertical displacement of less that 20 m.

In the Umatilla drainage, however, the fault appears to have an opposite sense of displacement. The combination of these features, plus the very strong linear topographic expression of the fault and its similarities in both orientation and expression to other faults in the Hite system, suggest that strike-slip was the principal component of movement on the Peterson Ridge fault.

A-2.2.2.2 Saddle Hollow Fault

The Saddle Hollow fault is a long north-northeast-striking fault that can be traced by its strong topographic expression of aligned valleys and notches. It extends from south of Highway I-80 north-northeast to near Milton-Freewater. It is well-exposed in the north bank of the Umatilla River, where it forms a 200 m-wide zone consisting of at least three nearly parallel shear zones that trend N15° to 26°E. Apparent offset of the Grande Ronde Basalt here is east-side-down, but the presence of well-developed, sub-horizontal grooves and striae in two of the main shear zones indicate strike-slip motion on the fault. The pattern of the two main strike-slip shears, and of secondary oblique-slip shears at low angles to them, is indicative of dextral slip on the Saddle Hollow fault. Farther north, apparent offset of about 25 m down-to-the-east of the northwesterly-dipping basalt flows, also suggests dextral slip on the fault.

A-2.2.2.3 Thorn Hollow Fault

The Thorn Hollow fault is inferred to extend from the Bade fault near Milton-Freewater, south and south-southwest through Thorn Hollow to several miles south-southwest of Deadman's Pass. Unlike other faults in the Hite system, the Thorn Hollow fault swings to a N5°W strike at its north end. Where secondary shears are exposed on the east side of Thorn Hollow, dips range from near vertical to 80°W. On the west side of the Hollow, a nearly horizontal thrust fault cuts Frenchman Springs flows and a dike. This thrust appears to be related to the Thorn Hollow fault, and perhaps is similar to the "palm tree" structures previously noted on the Forks fault. The presence of Frenchman Springs flows on the west side of the Hollow at the same elevation as the Grande Ronde flows on the east side indicates a west-side-down component of motion. However, the thrust fault and the secondary shears, together with the striae, suggest that the major component of move-

ment was strike-slip. The apparent vertical offset, together with the regional dip and the rake of the striae, is consistent with dextral movement on the fault.

A-2.2.2.4 Tectonics of the Hite Fault System

The Hite fault system is a broad north-northeast-trending zone with several long, parallel faults. These faults show evidence of strike-slip displacement, and all are interpreted to have a primary component of dextral motion (Shannon & Wilson, 1979). The faults examined in this study support this interpretation. These long, relatively straight faults locally show horizontal striae, minimal vertical displacement, and apparent vertical offsets consistent with dextral-slip movement.

A minimum age of faulting was not established for the system. As discussed in Sections A-2.2.1.8, A-2.2.2.4, and A-2.2.3.3 the Hite fault system is interpreted to be older than either the Wallula and LaGrande fault systems, based on cross-cutting relationships between the systems and on the age of strata observed to be cut by the fault systems. This interpretation is also consistent with the geomorphically older character of the Hite system faults compared with those of the Wallula and LaGrande systems.

A-2.2.3 LaGrande Fault System

The LaGrande fault system consists of a series of generally north-northwest-striking faults that bound the LaGrande graben and extend northward to the vicinity of the Hite fault. The system also includes parallel and slightly more westerly-striking faults to the west and northwest to LaGrande.

A-2.2.3.1 Elbow Bend Fault

The Elbow Bend fault was mapped by Newcomb (1965) from the Hite fault, north-northeast across Blalock Mountain to the south flank of Peterson Ridge (NE1/4 sec. 21, T5N, R37E). On Blalock Mountain, the Elbow Bend fault offsets both gently-dipping Grande Ronde Basalt flows and two steeply-dipping Frenchman Springs dikes vertically down-to-the-west. The larger of the dikes is offset about 20 m, whereas the Grande Ronde flows are offset about 25 to 30 m. This relationship suggests that fault movement was predominantly vertical, but does not preclude lesser amounts of horizontal

slip in either a dextral or sinistral direction. Although the fault intersects the Hite, Lincton Mountain, and Blalock Mountain faults, cross-cutting relationships between these structures were not apparent.

A-2.2.3.2 South Fork Fault

The South Fork fault trends N17°-20°W from the west side of the Hite fault at Tollgate Chalet to Blalock Mountain, where it crosses the Peterson Ridge fault. It appears to die out on Peterson Ridge. Down-to-the-west vertical offset appears to have been produced by dextral slip on the fault. Apparent offset of the fault, however, is greater near the South Fork, where the Grande Ronde flows dip relatively steeply, than farther north, where dips are shallower.

A-2.2.3.3 Tectonics of the LaGrande System

Both the Elbow Bend and South Fork faults display west-side-down offsets, with some dextral slip occurring on the South Fork fault, and possibly on the Elbow Bend fault. These motions are consistent with the overall dextral-oblique slip on many of the faults within the LaGrande system. The age of youngest motion on the LaGrande system faults in the study area was not determined, but faults in the system locally cut Holocene or at least late Pleistocene deposits on the west side of the Grande Ronde Valley (Gehrels and others, 1979).

The relationship of the LaGrande faults to either the Hite or Wallula systems is unclear. In the Tollgate Chalet area, faults within the Wallula and LaGrande systems intersect with no apparent offset of each other, which could be attributed to purely dip-slip motion on the two sets, or to constructive interference from contemporaneous motion.

Based on the available evidence, contemporaneous motion on the Wallula and LaGrande systems in this area seems more likely. Although the Hite fault appears to terminate at the South Fork fault, the Elbow Bend fault extends across the Hite with no apparent offset of either fault. This relationship might best be explained by later, predominantly dip-slip motion on the Elbow Bend fault. If the Wallula and LaGrande fault systems are indeed contemporaneous, this relationship is consistent with evidence presented in Section A-2.2.1.8, which suggests the Wallula system is younger than the Hite system.

A-3 CONCLUSIONS

Three major fault systems, the west-northwest-trending Wallula, the north-northeast-trending Hite, and the northwest-trending LaGrande systems, are recognized on the basis of their principal structural trends. Faults within all three systems have a major component of dextral-slip motion, as evidenced by a combination of apparent stratigraphic offsets, shallow-dipping striae, and their regional structural pattern. The exact amount of offset has not been determined because of a lack of observed piercing points along the faults.

Available evidence, particularly the apparent offset of the Hite fault by the Lincton Mountain fault, suggests that the Hite system is the oldest of the three fault systems. This evidence is not conclusive, however, as only one of two branches of the Hite fault has been shown to be offset. In addition, age relationships elsewhere at intersections of the Hite, Wallula, and LaGrande systems are ambiguous. The relatively younger Wallula and LaGrande fault systems appear to be contemporaneous, at least in the vicinity of Tollgate Chalet, based on cross-cutting relationships. These two systems also have a younger geomorphologic expression that the Hite fault system. Further resolution of the relative ages of these fault systems will require more detailed mapping near Tollgate Chalet and elsewhere at intersections of the fault systems.

Faults within the Wallula fault system cut upper Pleistocene strata in several locations. Quaternary deformation, possibly Holocene, has also been recognized on faults of the LaGrande system outside the study area. Quaternary offset was not observed on any faults within the Hite fault system, except for the Thorn Hollow fault north of Weston.

A-4. REFERENCES

Gehrels, G., White, R., and Davis, G., 1979, The LaGrande pull-apart basin, northeastern Oregon: Letter Report prepared for Washington Public Power Supply System.

Newcomb, R.C., 1965, Geology and groundwater resources of the Walla Walla River basin, Washington-Oregon: Washington Division of Water Resources Water Supply Bulletin 21, p. 151.

Sylvester, A.G., and Smith, R.R., 1976, Tectonic transpression and basement-controlled deformation in San Andreas fault zone, Salton Trough, California: American Association of Petroleum Geologists Bulletin, v. 60, p. 2081-2102.

Weston Geophysical Research, Inc., 1979, Magnetic Modeling, Columbia Plateau area, Washington and Oregon: Report prepared for Washington Public Power Supply System under direction of United Engineers & Constructors, Inc., Aug. 1979.