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UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

GEOLOGIC INVESTIGATION OF FAULTING IN THE HANFORD REGION, WASHINGTON

By

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with a section on the

OCCURRENCE OF MICROEARTHQUAKES

By

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Prepared on behalf of the
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SUMMARY OF CONCLUSIONS

The U. S. Geological Survey conducted geologic investigations at the request of the U. S. Atomic Energy Commission in three principal areas of southcentral Washington -- the Saddle Mountains and Smyrna Bench area north of the Hanford Reservation; Gable Mountain and Gable Butte on the reservation; and the Rattlesnake Hills - Wallula Gap area south and southeast of the reservation. These areas were selected for study to resolve differing interpretations of previous investigators concerning the existence of faults and the recency or antiquity of tectonic movements on some of these geologic structures. Although the investigations confirmed the presence of faults in each area, most of the faults are relatively old -- the latest surface displacements on all but one apparently occurred more than 12,000 years ago and probably before late Pleistocene time (probably more than 100,000 years ago).

Geologic mapping and trenching on and near Smyrna Bench was done to investigate the Saddle Mountains fault -- a high-angle fault that cuts the flows of the Yakima Basalt and extends along the north side of the Saddle Mountains anticline from Smyrna Bench westward across the Columbia River. The faulting appears to be younger than the sediments of the Ringold Formation (Pliocene and Pleistocene age), and it is probably older than the glacial flooding which is thought to have begun in this region about

100,000 years ago. However, the faulting can be dated clearly only as older than Pinedale age (12,000 to 25,000 years ago). Grabenlike, topographically closed depressions and minor scarps in the Ringold Formation, which occur on the southern margin of Smyrna Bench north of the Saddle Mountains rault, were believed by some previous investigators to indicate geologically young, or even historic, tectonic faulting. However, the present investigation found evidence that these are not tectonic features but are the results of a mass movement of the Ringold Formation that underlies the Smyrna Bench. Part of the Ringold moved northward as a large block-glide landslide toward the Crab Creek valley, and the grabenlike depressions and scarps were produced by tensional separation of slices and small blocks on the back (south) side of the mass as the gliding continued. Landslide blocks of basalt and Ringold sediments that slumped northward from the Saddle Mountains scarp into the depressions conceal the Saddle Mountains fault throughout the length of Smyrna Bench. The block gliding may have started simultaneously with the entrenchment of Crab Creek valley by the glacial floods. Subsequent series of floods probably saturated the Ringold Formation and eroded it rapidly from the toe of the bluff along Crab Creek, causing several stages of the block gliding. The stratigraphy of Pleistocene and Holocene sediments overlying the Ringold Formation on Smyrna Bench indicates that the oldest stage of block gliding is late Pleistocene; the main stages that clearly postdate the movement on the Saddle Mountains fault are also late Pleistocene (pre-Pinedale and Pinedale). Carbon-14 dating of material from loess deposits indicates that the youngest block gliding occurred more than 12,000 years ago.

Detailed mapping and trenching on Gable Mountain determined that two thrust faults extend transversely across the anticlinal structure of the Yakima Basalt that forms the mountain. One of the faults is in the central part of the mountain and the other in the western part. Both faults strike generally northeast and dip southeast 17 to 34 degrees. Extensive trenching of the fault in the central part of Gable Mountain disclosed that it has a maximum vertical displacement of about 70 feet. The amount of displacement becomes less to the north, and the fault apparently dies out by passing into numerous small fractures in the sharply folded rocks on the north side of Gable Mountain. The southern limit of the fault was not determined, but its strike changes markedly near and in the sharply folded rocks on the south side of Gable Mountain. These relations indicate that the fault is as old as part of the folding and that both the folding and faulting probably were expressions of the same forces that produced the Gable Mountain anticlinal uplift. The fault is overlain by unfaulted glaciofluvial gravels representing several stages of erosion and deposition by glacial floodwaters. The second oldest of the gravel deposits, exposed in trenches on the south side of Gable Mountain, contains fossil wood fragments that are older than 40,000 years by carbon-14 dating. These deposits do not overlie the fault directly, but lie on older glaciofluvial gravels which, in turn, lie on an erosion surface cut across the folded rocks that are involved in the faulting a few tens of feet away. These relationships indicate that the latest structural movements occurred more than 40,000 years ago. The western fault on Gable Mountain appears to be structurally analogous to the central fault and probably is ancient also. The western fault is not overlain by sediments and has not been dated precisely; however, scouring of the rocks by glacial floodwaters has occurred since the fault was formed. Detailed investigation of Gable Butte determined that a previously mapped fault does not exist, and no evidence of other faults was found.

Reconnaissance investigation of the Rattlesnake Hills-Wallula lineament, and detailed mapping of an area near Wallula Gap have shown that numerous outcrops of breccias occur in linear patterns in this region. Some previous investigators had considered the breccias to be the products of faulting, whereas others had explained them as being the outcrops of stratigraphic units of lava-flow breccia whose linear outcrop bands are a result of exposure by erosion of monoclinal folds. Reconnaissance indicates that the breccias occur in vertical zones that vary in width, locally trend at low angles to the strike of adjacent stratigraphic units, are locally strongly sheared, and have other characteristics which indicate that they are parts of zones of fracturing, shearing, and faulting. The line of anticlines and domes extending southeastward for about 30 miles from the Rattlesnake Hills at Yakima River to Wallula Gap is marked by locally exposed linear outcrops of breccia accompanied at places by offsets of basalt stratigraphic units, indicating the existence and probable continuity of the Rattlesnake-Wallula fault. The Rattlesnake Hills were not examined, but the straight topographic alinement of their northeastern side indicates a probable extension, for about 9 miles northwest of Yakima River, of the structural alinement along which the domes and anticlines lie. The Ringold Formation was not found exposed along the Rattlesnake-Wallula fault with one probable exception at the Finley Quarry southeast of Kennewick. This is the only place found where sediments apparently older than the glacial flooding are preserved. Here, Ringold-like sediments have collected in enlarged fissures that apparently formed after faulting had left a basalt scarp, less than 100 feet away, unsupported. These relations suggest that the fault is of Ringold age. The fault seems to be older than the late Pleistocene glaciofluvial Touchet beds which lie across it at a few places. Although no evidence was found on the fault between Wallula Gap and Yakima River that would indicate displacements occurring since the last glacial flooding, it was not possible to date the last displacements with precision.

Detailed mapping of the Yellepit area near Wallula Gap confirmed the existence of the Wallula Gap fault, which is about 1.5 miles south of and subparallel to the Rattlesnake-Wallula fault. The Wallula Gap fault was traced in reconnaissance southeastward across the Columbia River for about 12 miles. Its trace is marked by bands of locally exposed breccia near the base of the prominent physiographic escarpment on the north flank of the Horse Heaven Hills anticline and south of the Walla Walla River. About 8 miles southeast of the Columbia River the trend of the Wallula Gap fault changes in a manner suggesting that it merges with the Rattlesnake-Wallula fault, whose trace is concealed east of the river. The Wallula Gap fault may extend westward from the river along the base of the Horse Heaven Hills but the lack of outcrops prevented tracing it. The age of the Wallula Gap fault is not known with precision, but the major displacements on it must have occurred at least before the latest glaciofluvial sedimentation, because glaciofluvial gravels lie undisturbed over the fault near Wallula Gap and the Touchet beds lie across it farther east. On the other hand, in the Warm Springs area 6-8 miles east of the Columbia River, a linear surface feature, which may be a fault rupture of the Touchet beds, occurs in general alinement with the Wallula Gap fault zone. Although the nature of the linear feature in the Touchet beds could not be determined definitely by brief field examinations, its topographic situation does not allow readily for its explanation as being the result of either erosion or landsliding, or any other non-tectonic process. The vertical relief of the linear feature is a few inches to several feet and it is subdued because of Holocene loess deposited across it; thus it is not of historic age, although it is less than 12,000 years old. Areas about 15 miles to the southeast, where ground rupturing is reported to have occurred in the 1936 Milton-Freewater earthquake, were not examined.

The structural relations that were observed support an interpretation that the Rattlesnake-Wallula fault and the Wallula Gap fault and other faults along the southeastern segment of the Horse Heaven Hills anticline are parts of a linear, deep-seated, regional structural feature that extends from the eastern part of the Rattlesnake Hills southeastward to at least the Milton-Freewater area in Oregon. The main stage of faulting along this regional structural feature probably occurred during Ringold time, or at least prior to all or most of the glacial flood events. However, the geologically young probable ground rupturing along the Wallula Gap fault east of Vansycle Canyon and the reported ground rupturing during the Milton-Freewater earthquake (1936) suggest that these parts of the regional structural feature may still be tectonically active.

In a preliminary study, a network of U.S. Geological Survey seismograph stations within and around the Hanford Reservation located epicenters of 166 microseismic events from March 23 to December 31, 1969. About one-fourth of these are thought to be explosions that occurred at distances of 80 km to 200 km from the center of the network in the regions west, north, and east of the reservation. Approximately 105 microearthquakes and a few explosions were located within 75 km of the center of the network; all the microearthquakes on or near the Hanford Reservation had Richter magnitudes below 2.0, which is generally below the threshold of (noninstrumental) human perception. Magnitudes were determined for 36 out of more than 230 events that occurred in a small area in the southeastern part of the reservation near the Columbia River.

A few microearthquakes were located in the western part of the reservation. Also, a northwest-trending zone of microearthquakes occurs in the vicinity of the Saddle Mountains north and northeast of the reservation. The results of this period of seismic study indicate that the Hanford Reservation is in a region of microearthquake activity which is moderate by comparison with the microearthquake activity of seismically active regions of California and Nevada where similar monitoring studies have been made. A longer recording period will better define the areas of activity in the Hanford region and the fluctuations of activity with time.

INTRODUCTION

Minor to intermediate earthquakes have affected southeastern Washington in historic time. Differing interpretations of the recency of faulting in the region of the U.S. Atomic Energy Commission's Hanford Reservation have been reported (Jones and Deacon, 1966; Jahns, 1967; R. E. Brown, 1968). At the request of the Division of Reactor Development and Technology (RDT) of the Atomic Energy Commission, a field review of the geology of the region surrounding the Hanford Reservation was held March 25-27, 1968. Among those participating were representatives of the U.S. Geological Survey, Richland Operations Office of AEC, Battelle Pacific Northwest Laboratory, Douglas-United Nuclear Corporation and Atlantic-Richfield Hanford Company. The results of the field review were reported to RDT by H. H. Waldron and M. G. Bonilla (written communication, June, 1968) of the Geological Survey.

On the basis of the field examination, Waldron and Bonilla concluded that there is no evidence of historic (within the last 100 years) faulting at or near the Hanford Reservation. However, they concluded that there is geologically young ground-surface rupturing of undetermined origin on Smyrna Bench north of the Saddle Mountains, a few miles north of the AEC Reservation. They concluded also that the structural details of the Gable Mountain-Gable Butte anticlinal ridge on the reservation, and the Rattlesnake Hills-Wallula Gap structural lineament on and southeast of the reservation had not been established clearly enough to determine the presence or absence of young faulting associated with these structures. Additional geologic investigations were recommended to determine and delineate the faults present in these areas and to determine how recently any such faults may have been active in order to provide background data to aid in the assessment of the potential for future faulting and earthquakes.

In December 1968 the Division of Reactor Development and Technology authorized the Geological Survey to perform the geologic investigations recommended by Waldron and Bonilla, and to install an array of seismographs to record the current seismic activity in the Hanford Reservation and its environs. This report presents the results of the geologic investigations performed from January through September 1969, and the seismologic investigations from March 23 through December 31, 1969.

Previous Investigations

The general geologic environment of the Columbia Plateau in south-central Washington, and in particular of the Pasco Basin, has been described by many authors. The report by Jones and Deacon (1966), reproduces abstracts of many of the pertinent reports. Additional references pertaining to the area can be found in the report by R. E. Brown (1968, p. 51-55) and in the selected references at the end of this report.

Scope of Present Study

Geology

The work for this report consisted of investigations of three principal areas at and near the Hanford Reservation. The investigations included:

1. A study of stratigraphic and structural details at places along the Saddle Mountains fault and Smyrna Bench north of the Hanford Reservation. Detailed geologic mapping, drilling of exploratory test holes, and digging backhoe trenches allowed a determination of the probable minimum age of the main fault and the origin of the ground rupturing associated with the grabenlike features and other lineaments that occur on the bench.
2. A study of the stratigraphy and geologic structure of the Gable Mountain and Gable Butte anticlinal folds on the Hanford Reservation. Determinations were made of the magnitude, extent, and probable age of faulting by detailed mapping and by utilizing bulldozer and backhoe trenches.
3. A reconnaissance study of the Horse Heaven Hills and the Rattlesnake Hills-Wallula lineament south and southeast of the Hanford Reservation. Detailed stratigraphic

and structural studies were made of a selected area near Wallula Gap along the lineament to determine the nature, extent, and probable age of faults observed.

The determination of displacement by faulting requires the identification and mapping of the stratigraphic units on each side of the fault. The identification of the stratigraphic units used in this report is based on reviews of existing literature and on the senior author's previous experience gained in mapping the stratigraphic sequence in the Columbia Basin Irrigation Project area north of the Hanford Reservation.

Seismology

As part of this project the U. S. Geological Survey's National Center for Earthquake Research established a network of seven seismographs in the Hanford area. The network, interpretation of the data, and locations of the epicenters of located seismic events are discussed in a separate section of this report by A. M. Pitt. The epicenters of many of the microearthquakes and other seismic events in the Hanford Reservation and nearby areas are shown in figure 4; all seismic events with located epicenters for the entire region are shown on figure 25.

Acknowledgments

The present work was done as part of a U. S. Geological Survey program of research on geologic, seismologic, and hydrologic factors related to the siting and design of nuclear facilities. The program is sponsored by the U. S. Atomic Energy Commission, Division of Reactor

Development and Technology, under W. G. Belter, Chief of the Environmental and Sanitary Engineering Branch.

The trenching on Gable Mountain was funded partly by the Richland Operations Office of AEC, and partly by the Atlantic-Richfield Hanford Company under informal cooperative arrangements. D. J. Brown of Atlantic-Richfield Hanford Company and R. E. Brown of the Battelle Pacific Northwest Laboratory assisted J. W. Bingham in supervising trenching operations on Gable Mountain.

The chemical and spectrographic analyses of basalt samples were performed in the laboratories of the U. S. Geological Survey at Menlo Park, California. The refractive indexes of basalt were determined by Dr. Bates McKee and Wasant Pongsapich of the Department of Geology at the University of Washington.

The exploratory test drilling on Smyrna Bench was by the rotary method under contract with the R. J. Strasser Drilling Co., Portland, Oreg. The trenches on the Smyrna Bench were dug by a backhoe under contract with Olson Bros. Excavating Co., Warden, Wash.

The aerial photographs of the three areas of primary concern were taken at a scale of 1:6000 under contract with Delano Photographics of the Western Mapping Co., Portland, Oreg.

The writers are indebted to Dr. Roald Fryxell of the Washington State University for his field review of Quaternary deposits on Smyrna Bench.

Field reviews of the three areas and colleague review of the manuscript were by M. G. Bonilla, H. H. Waldron, and Robert Schneider of the U. S. Geological Survey. D. J. Stuart of the Geological Survey's National Center for Earthquake Research also reviewed the manuscript. All contributed considerably to the completeness of this report.

GEOLOGY

History and Stratigraphy[1/]

The major geologic events that influenced the stratigraphy and structural features of the Columbia Plateau were: (1) the extrusion of the basalt of the Columbia River Group in the Miocene and early part of the Pliocene Epochs of the Tertiary Period; (2) the tectonic deformation during the Pliocene and the early part of the Pleistocene Epoch of the Quaternary Period; (3) the lacustrine, fluvial, and eolian deposition during the late Pliocene and early Pleistocene; and (4) the glaciofluvial erosion and deposition during the late Pleistocene.

The basalt of the Columbia River Group is a thick accumulation of flood lavas that were extremely fluid when extruded, allowing them to inundate areas as large as 20,000 square miles in Oregon and Washington. The areal extent of the basalt of the Columbia River Group is shown in figure 1. Within south-central Washington only the upper formation --

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Figure 1 belongs near here.

1/ **This report has not been reviewed for conformance with U. S. Geological Survey editorial style and nomenclature.**

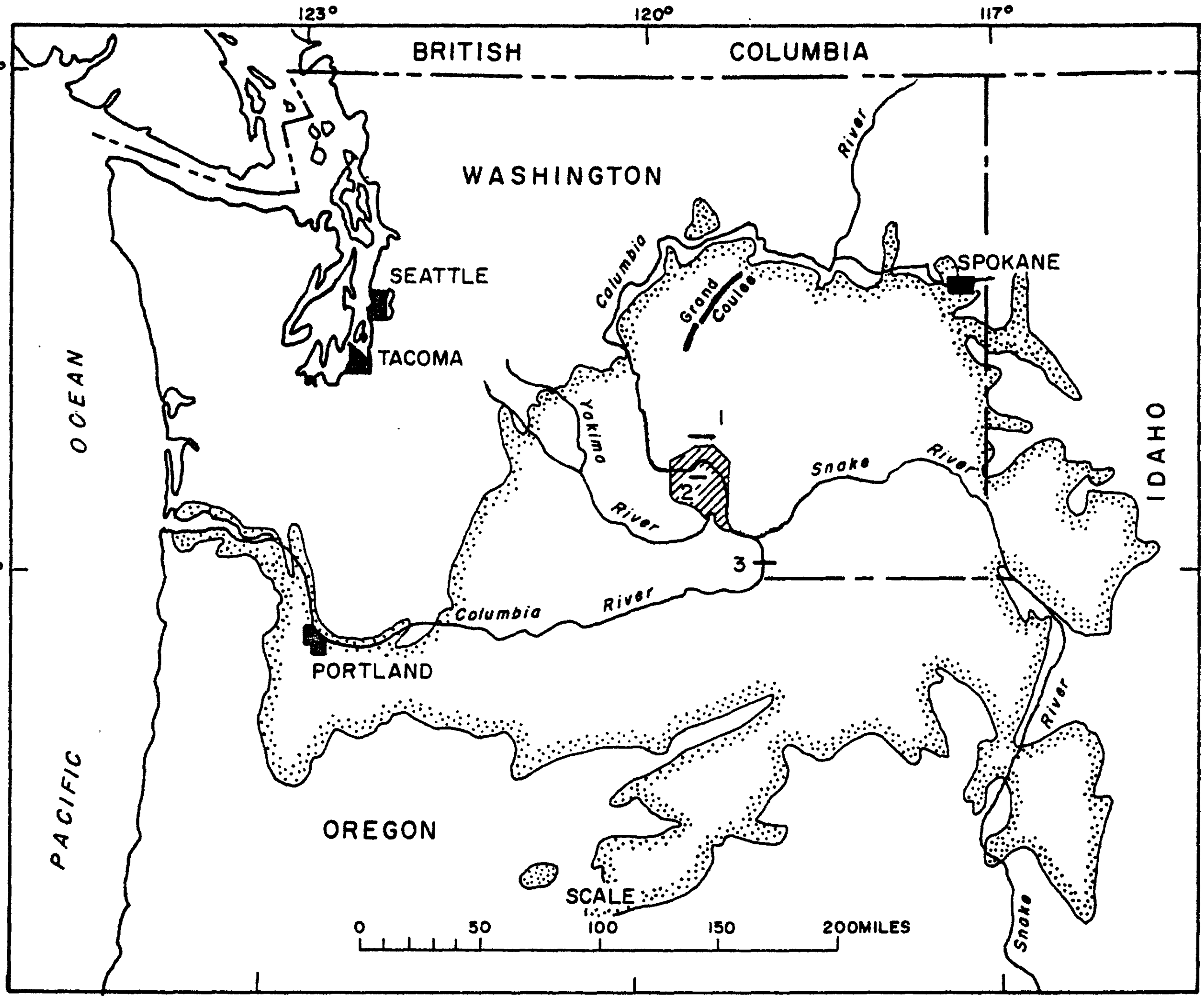

FIGURE 1.--Areal extent of basalt of the Columbia River Group (stippled border; after Waters, 1961) in Oregon, Washington, and Idaho. The AEC Hanford Reservation is crosshatched. Locations of the three areas of detailed mapping are indicated as 1) Smyrna Bench, 2) Gable Mountain and Gable Butte, and 3) Wallula Gap.

the Yakima Basalt -- of the Columbia River Group is exposed. The Yakima is over 2,000 feet thick in the type area along the Yakima River (Diery and McKee, 1969) which is west of the Pasco Basin.

Most of the stratigraphic work on the Columbia Plateau has been concerned with only the uppermost 1,000 feet of the Yakima Basalt -- the flows that lie above the Vantage Sandstone Member of the Yakima. The sequence of stratigraphic units in south-central Washington is shown in figure 2.

Figure 2 belongs near here.

The faulting and folding of the basalt flows and the sedimentary deposits that overlie the basalt are of primary concern in this study. Therefore, the mapping of the detailed stratigraphy was necessary to delineate the structure in the three areas of concern. The major folds, faults, and basins in south-central Washington and the three areas of detailed study described in this report are shown in figure 3.

Figure 3 belongs near here.

Overlying the Yakima Basalt is the Ringold Formation which is composed of material deposited in various continental environments on the basalt surface. Deposition of the Ringold occurred when deformation of the basalt had reached a stage of damming or diverting the traversing rivers. The fluvial, lacustrine, and eolian deposits of the Ringold accumulated in the basins and mixed with the colluvial material eroded from the newly developing anticlinal hills of basalt. During and after

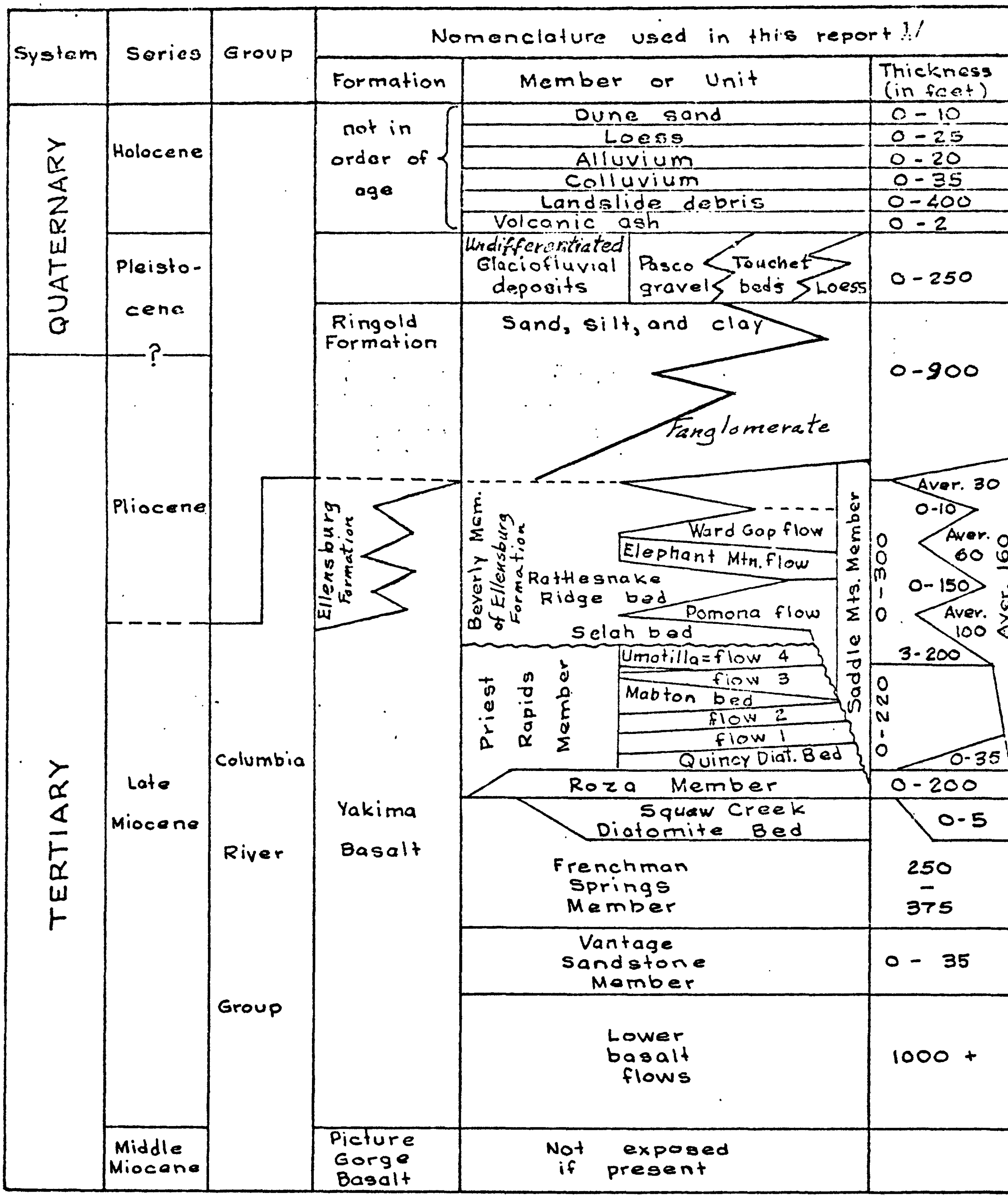

FIGURE 2.--Stratigraphic sequence and relationship of principal rock units described in report.

1/This figure has not been reviewed for conformance with U.S. Geological Survey nomenclature.

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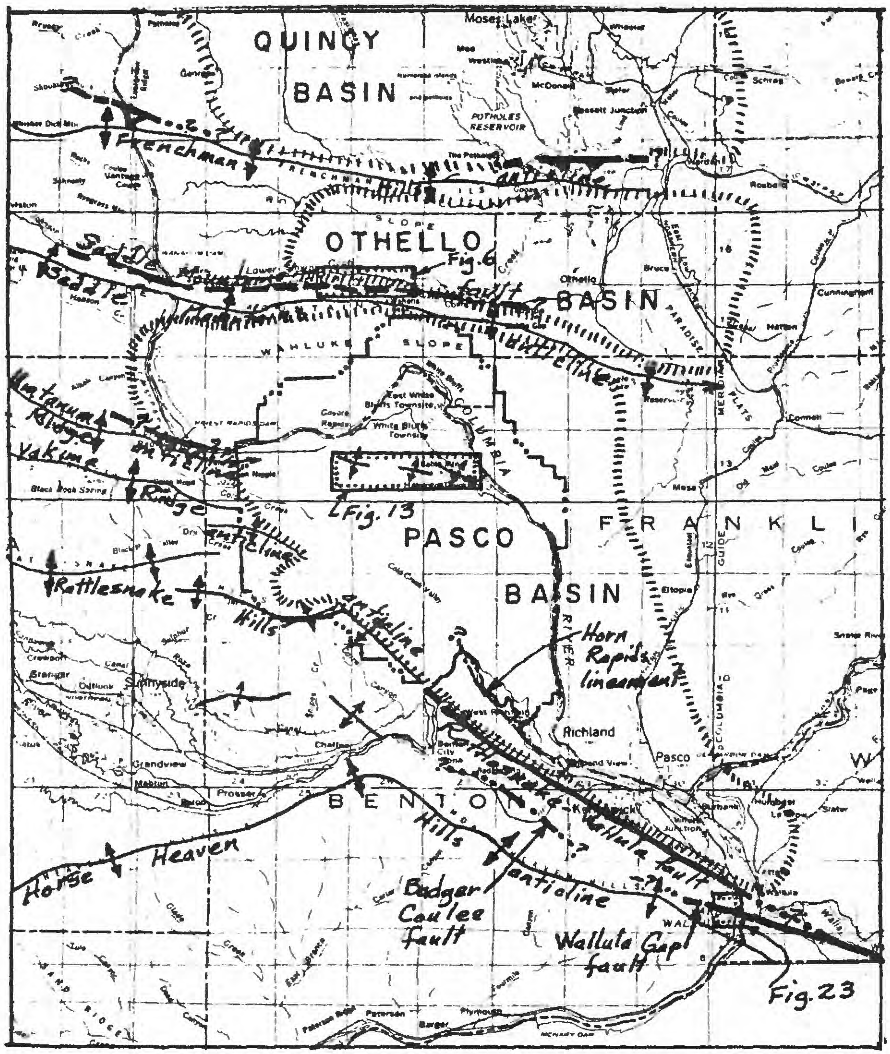

EXPLANATION

Lineament, structure not determined*

Major fault*

Thrust fault

Crest of anticline

Boundary of Hanford AEC Reservation

Arbitrary boundary of structural basin

Area of detailed mapping

*** Dashed where approximately located; dotted where concealed; queried where uncertain**

FIGURE 3.--Major anticlines, faults, and basins in south-central Washington.

this deposition and after the formation of a massive caliche at the top of the Ringold, some folding and faulting continued. Apparently the folding, erosion, and deposition occurred mainly during Pliocene time, with some continued folding and faulting during early Pleistocene time.

During late Pleistocene time, glaciofluvial erosion and deposition in south-central Washington resulted from tremendous volumes of meltwater flowing from the 500-mile long lobate front of Cordilleran continental glaciers to the north of the study area in the northern part of the Columbia River basin. In addition to the large flow of glacial streams, tremendous volumes of water were periodically released from glacier-dammed lakes. This caused water to spill over drainage divides and to create the large, channeled scabland of eastern Washington.

The glaciofluvial deposits on the Columbia Plateau have been studied by Bretz (1919, 1923, 1959, and 1969), and Bretz, Smith, and Neff (1956). In 1965, during the International Congress for Quaternary Research (INQUA), many geologists described in detail the history and geomorphology of the area (Fryxell, 1967; Fryxell and Neff, 1965; Fryxell and others, 1965; and Richmond and others, 1965).

Geologic Problems

Structure

The major geologic structures of the basalts of the Columbia River Group in south-central Washington which have surface expression have been plotted on a 1:500,000-scale map by Newcomb (1970) and are shown in part in figure 3 and figure 4. An explanation of geologic symbols used on the maps and diagrams is shown in figure 5. Where the basalt is concealed

Figure 4 is at the end of the report.
Figure 5 is at the end of the report.

by the Ringold Formation or younger sediments its structure is largely unknown. Within the Hanford Reservation R. E. Brown (in Jones and Deacon, 1966) has inferred the axes of folds from contours on the buried upper surface of the basalt as determined from well logs and geophysical data (R. E. Brown and Raymond, 1964).

The mapping and interpretation of faults in the region investigated for this report are difficult problems because of the scarcity of exposures owing to extensive loess deposits, and because of the weathering and erosion of the generally soft fault breccia or gouge zones. Some workers have inferred that concealed faults exist at places where an apparent change in altitude of the top of gently dipping basalt occurs in short horizontal distances, and others have inferred that concealed faults exist on the limbs of anticlinal or monoclinal folds. At places definite faults have been observed in sharply folded rocks; however, at other places the rocks can be seen to be folded without attendant faulting. Differences in interpretations of some workers have arisen for other reasons, such as difficulties of distinguishing large landslide blocks from fault blocks; distinguishing flow breccias from fault breccias; or misidentifying basalt flows which has led to interpretations of more or less fault displacement than is actually present. The lack of detailed mapping of much of the region has been a handicap.

The problem of distinguishing basalt-flow breccias from fault breccias composed of basalt fragments has led to major differences of interpretation of the geologic structure by various authors at several places. During the field mapping for this report the characteristics listed in Table 1 were useful for differentiating these breccias. The interpretation of outcrops of breccia must be based on several characteristics and upon examination of the total zone in which the breccia occurs; no single characteristic is necessarily diagnostic because, for example, an outcrop might consist of volcanic-flow breccia or volcanic feeder-vent breccia that has been sheared and faulted after it was formed, or the outcrop might consist of fault breccia and volcanic breccia both.

Table 1 belongs near here.

Stratigraphy

The detailed mapping of individual flows of the Yakima Basalt, which is important to determining the geologic structure, had not been done in previous investigations of most of the areas studied for this report. Detailed mapping of the Yakima Basalt in the vicinity of the Hanford Reservation has been limited to the Saddle Mountains (Grolier and Bingham, 1965). Mackin (1955, 1961) and Laval (1957) mapped individual flows, but only in small areas, principally near or along the Columbia River between Priest Rapids Dam and Vantage.

The field identification of the volcanic flows of the Yakima Basalt requires an evaluation of the megascopic characteristics such as: stratigraphic position; thickness; color; number, size, and types of phenocrysts; vesicle size and shape; texture; grain size; jointing habit; and stratigraphic relationship to sedimentary interbeds. The refractive index of glass beads and chemical analyses also are often diagnostic and may help identify certain flows. (The refractive index of a flow is measured on a crushed glass bead made by fusing a crushed sample of the flow in a carbon arc.) The various basalt flows of the

TABLE 1.--Some characteristics of flow breccias and fault breccias in basalts.

Flow breccia (or aa basalt)	Fault breccia
1. Largely vesicular blocks	1. Commonly has nonvesicular blocks
2. Many blocks have welded points of contact and glassy selvages, local baking aureoles may occur anywhere within zone	2. Most blocks have borders of clay gouge with slickensides. Some blocks in clay gouge are rounded and polished by movement
3. Usually not over 30 feet thick in this region	3. Occurs in any width -- over 200 feet wide along some major faults near the Pasco Basin
4. Blocks vary widely in size	4. Blocks are relatively small and tend toward uniform size
5. Stratigraphic unit that parallels basalt-flow contacts and usually is associated with top of flow	5. Usually transverse to flow contacts and truncates flows
6. Indistinct joints	6. Fractures usually closely spaced, subparallel and slickensided
	7. Stratigraphic units are offset on opposite sides of zone
	8. Usually associated with a topographic lineation

Yakima were identified by the characteristics described primarily by Mackin (1961), Grolier (1965), Schmincke (1964, 1967), and Bingham and Grolier (1966).

In the course of this investigation, 10 samples of basalt were taken for chemical analyses (Appendix E). These data were plotted on the variation diagram of Schmincke (1967, fig. 17, p. 1409 and fig. 18, p. 1412) and found to plot within or very near the grouping he depicted for the respective constituent ratios for each flow. Thus, support was given to the field identification of the individual flows where sampled on Gable Mountain and near Yellepit in the Wallula Gap area.

The age of the Ringold Formation is important to dating the faulting in south-central Washington because the Ringold contains sediments which were eroded from the major folded and faulted structures in the basalt of the Columbia River Group, and thus reflects the main stage of deformation of these rocks. The Ringold also was folded and faulted at places during late stages of deformation of the region.

The Ringold Formation has been described in many reports (Merriam and Buwalda, 1917; Strand and Hough, 1952; R. E. Brown and McConiga, 1960; Grolier, 1965; and Grolier and Bingham, 1965) and controversy still exists about its exact age and relationship to the Ellensburg Formation and the upper flows of the Yakima Basalt. In some publications the age of the Ringold has been reported as early to late Pleistocene (Strand and Hough, 1952). However, based on structural and stratigraphic relationships, the lower part of the Ringold may be as old as middle Pliocene, and the upper part no younger than early Pleistocene. Part of the vertebrate fauna found in the Ringold was formerly considered Pleistocene but now is identified as Pliocene (G. Jakeway, Los Angeles County Museum, oral commun., 1970) owing to the presence of the same fauna in the Blanco Formation of Pliocene age in Texas and the Hagerman lake beds (of former usage) which are part of the Idaho Group of Pliocene and Pleistocene age. Most reports referring to the age of the Ringold cite Strand and Hough (1952), who based their opinion of late Pleistocene age largely on the jaw bone and molars of a mastodon. However, W. E. Fry (A.E.C., written commun., 1970) states the mastodon jaw he found in the Ringold suggests a Pliocene age. The age of the Ringold Formation still is controversial and further study is needed to determine its absolute age and its stratigraphic relationships to the Ellensburg Formation and the Yakima Basalt. Charles Repenning (written commun., 1970) considers the Ringold to be of Pliocene and Pleistocene age.

RESULTS OF THE INVESTIGATION

Smyrna Bench

General Features

Smyrna Bench is a north-sloping terracelike feature at the north side of the Saddle Mountains. The Saddle Mountains anticline, the geologic structure which forms the Saddle Mountains, is about 50 miles long and part of it forms the northern boundary of the Pasco Basin and the southern boundary of the Othello Basin (fig. 3).

Smyrna Bench is a sloping area of relatively low topographic relief that is one-half to 1 mile wide and about 8 miles long. The topography of the bench and the central part of the Saddle Mountains is shown in figure 6. The altitude of the bench varies between

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Figure 6 is at the end of the report.

1,050 and 1,450 feet. A steep scarp, about 500 feet high, exists along the north side of the Smyrna Bench; this scarp forms the south side of the valley of Crab Creek which has a floor at an altitude of about 540 feet. The south side of Smyrna Bench is along the steep slopes of the fault-line scarps terminating the ridges which lead to the crest of the Saddle Mountains. The highest point along the crest of the mountains is Wahatis Peak at an altitude of 2,696 feet.

The Saddle Mountains anticline consists of upfolded flows of the Yakima Basalt and sedimentary interbeds of the Ellensburg Formation. In the segment above Smyrna Bench, the anticline is a box fold. The crestal part of the anticline is a gentle arch, and the north and south limbs are steeply dipping monoclines. This segment of the Saddle Mountains has undergone more erosion than the remainder of the mountains. A large part of this erosion occurred in Pliocene time during folding of the anticline, and the coarsegrained, gravelly material eroded from the north side of the mountains was deposited as alluvial fans (fanglomerate) which now comprise most of the Ringold Formation which underlies Smyrna Bench. At the time of this erosion and deposition, Crab Creek was not present in the Othello Basin which was collecting all or most of the debris eroded from the north side of the mountains. Several times a lake was formed in the basin, and fine-grained lacustrine material was deposited. These clay and siltstone beds of the Ringold can now be seen interbedded with the fanglomerate along the north face of the bench -- two test holes also penetrated these lacustrine materials (fig. 6, cross section A-A'). Elsewhere in the Othello Basin the erosional remnants of the Ringold Formation are composed largely of lacustrine material which probably filled the basin until the basin was scoured and deeply eroded by glacial meltwater.

At the end of deposition of the Ringold Formation (probably in early Pleistocene time) the land surface must have sloped gently northward across the area that is now Smyrna Bench. A layer of caliche developed at or a few feet below this surface which is still preserved on the central part of the bench. Canyons and gullies on the Saddle Mountains drained northward onto this surface and the drainage continued northward across the area of the present Smyrna Bench through shallow gullies toward the main drainage of the Othello Basin. During the several episodes of scouring by large floods of glacial meltwater in late Pleistocene time, much of the Ringold Formation was removed from the Othello Basin north of Smyrna Bench, and Crab Creek valley was formed. As a result of these events the lower (northern) courses of the old gullies on Smyrna Bench have now assumed new, very steep gradients near the valley of Crab Creek. (See profile C-C', fig. 6.)

The upper courses of many of the gullies on Smyrna Bench are now interrupted on the southern margin of the bench by an east-west trending series of topographically closed depressions from which there is no external drainage of surface water (geologic map, fig. 6). Deep canyons on the north side of the Saddle Mountains drain into the depressions where alluvial deposits are now accumulating. The upper courses of the gullies on part of Smyrna Bench (some of which appear to be the former lower parts of canyons in the Saddle Mountains) now terminate upstream in windgaps at the north side of the topographic depressions. These relations (profile B-B', fig. 6) indicate that the former northward drainage has been interrupted and some gullies were beheaded relatively recently by subsidence of the south side of the bench.

Topographic features on the Smyrna Bench that were investigated in detail during this study are the alinements of topographically closed basins, the beheaded valleys, the linear swales and small scarps, and the alinements of truncated ridges at the foot of the Saddle Mountains. Most of these features occur in the eastern two thirds of the bench (figs. 6-12).

Problems of Interpretation

The topographic features and some rock outcrops on the Smyrna Bench have been investigated by Jones and Deacon (1966), Jahns (1967), and Grolier (1965). Each arrived at different interpretations regarding the origin of the unusual topographic features and the tectonic history of the area. Jones and Deacon (1966) interpreted the east-west aligned closed basins to lie in a structural graben that is downdropped along the north side of the Saddle Mountains fault. They interpreted the low, south-facing scarps along the north side of the basins as evidence of historic (less than 100 years) movement on this fault. Jahns (1967) interpreted the basins as parts of an erosional valley containing landslide masses and alluvial fans. He said that there are no undrained depressions, no offset streams, no topographic scarps with straight trends, and no linear series of moderate or steep slopes. Grolier (1965, p. 196 and pl. 18, fig. B) and Grolier and Bingham(1965) interpreted the bench to be a graben and horst bounded by faults which were thought to be part of a wide fault zone along the north side of the Saddle Mountains anticline.

Another possible interpretation, which had not been considered previously, is that the topographic features on Smyrna Bench resulted from large-scale landslide or land-creep phenomena related to the glacial-flood events. The possibility of such an explanation is strongly suggested by the large Corfu landslide east of Smyrna Bench. However, the physiography and structural features of the Corfu landslide are considerably different from those of Smyrna Bench.

Saddle Mountains Fault

Exposures with conclusive evidence of a major fault zone along the north side of the Saddle Mountains are very scarce. Despite this, most geologists who have worked in the area have interpreted the geomorphic features as indicating a fault that is downthrown on the north side. The features that indicate a fault are: east-west alinement of high scarps along the north flank of the mountain; and, west of Smyrna Bench, a high erosional scarp with attendant significant stratigraphic offset and little or no apparent folding on the downthrown (northern) side. Estimated stratigraphic displacements range up to 1,800 feet (Grolier, 1965). Laval (1957) investigated the Saddle Mountains fault at Sentinel Gap on the Columbia River and interpreted it as being a thrust fault; however, reconnaissance west of the Columbia River during the work for this report indicates that it is a steeply inclined normal fault. The fault extends at least 3 miles west of the river. East of the river, this fault, or shear zone, probably extends eastward at least to the Corfu landslide, a distance of 25 miles. In the vicinity of Sentinel Gap east of the river, several exposures of broken basalt near the north base of the mountain have parallel, nearly vertical fractures. West of the Columbia, the fanglomerate of the Ringold Formation lies against broken basalt along a nearly vertical contact. This is interpreted to indicate that the Saddle Mountains fault exists in this area and that the major movement on the fault occurred after deposition of some or all of the Ringold fanglomerate, which is the erosional debris from previously uplifted portions of the anticline. Therefore, considerable time appears to have passed between the first uplift of the central segment of the anticline and the major movement on the fault.

In the vicinity of Smyrna Bench, broken and sheared basalt is exposed in two outcrops which are interpreted to be exposures of the Saddle Mountains fault. Both exposures show the basalt along the fault to be broken and sheared along a zone 200 feet wide. One of the exposures is in a deep gully at the west end of the Smyrna Bench (W$\frac{1}{2}$SW$\frac{1}{4}$ sec. 34, T. 16N., R. 25 E.), where the shear zone is nearly vertical and cuts through the Frenchman Springs Member of the Yakima Basalt. In the bottom of the gully, the Frenchman Springs Member has a steep northerly dip, but it becomes overturned higher up on the west side of the gully. The underlying Vantage Sandstone Member, which crops out immediately to the south, does not appear to have been involved in the faulting. It contains imprints of unbroken carbonized leaves alined with the nearly vertical bedding.

The other exposure of the fault is in a deep gully in the E$\frac{1}{2}$SW$\frac{1}{4}$, sec. 1, T. 15 N., R. 26 E. near the east end of the Smyrna Bench. Here it consists of a 200-foot wide zone of sheared basalt that includes both the Roza and Frenchman Springs Members. However, the stratigraphic offset could not be determined because of the steep dips of the flows on both sides of the zone and because of the thick loess cover. Nearby, in a tributary gully, a shear plane occurs between the Roza flow which dips steeply north and the Pomona flow which dips steeply south. No unique solution can be derived from the existing outcrops, but the south-dipping flows of the Pomona must have been lowered more than 500 feet to be in their present position. This structural relief might be due to monoclinal folding, displacement along the Saddle Mountains fault, landsliding, or a combination of all three.

Several probable secondary shear planes also were found in the monoclinal fold along the south side of the Smyrna Bench. One of these occurs in a gully in the NW¼NW¼SW¼ sec. 3, T. 15 N., R. 26 E., where it cuts the Roza Member; however, the offset could not be determined because the fault could not be traced out of the gully. Another fault plane was observed in the east-west segment of a gully in the SW¼SE¼NW¼ sec. 4, T. 15 N., R. 26 E. This plane, which also might be the gliding plane of a large slump block, occurs between Priest Rapids and younger flows at the north that dip 30° N., and other Priest Rapids and older flows at the south that dip 59° N. The only other fault-related features observed were two small outcrops of sheared basalt with slickensides and nearly vertical striations. The outcrops are located high on the west walls of adjacent gullies in the SW¼NE¼NW¼ and near the center of the NW¼NE¼ of sec. 1, T. 15 N., R. 26 E. The outcrops of sheared basalt might be exposures of the main Saddle Mountains fault zone although this was not verified in the nearby backhoe trench. Based on observations in trench 1, the sheared basalt may be due to downslope sliding of a block of rocks containing a segment of the fault zone, or the shearing may have resulted from adjustments within the block while sliding.

Slump Blocks Along Saddle Mountains Fault

The fault-line scarp along the south side of Smyrna Bench is a very conspicuous feature. Along most of its length it is closely associated with the monoclinal north limb of the Saddle Mountains anticline. However, the alinement of the scarp does not follow the strike of the flows in the anticline continuously and the dip of the basalt flows is steeper than the present scarp slopes. Downslope from nearly all the scarps are irregular hills composed of caliche, fanglomerate of the Ringold Formation, Elephant Mountain and (or) Pomona flows, and related sedimentary interbeds. These stratigraphic units do not have strikes and dips consistent with one another nor with the flows in the scarps. These hills appear to be landslide blocks that slid down across the Saddle Mountains fault.

In an effort to obtain an exposure of the main fault zone, Smyrna trench 1 was dug in the SW¼NW¼NE¼ sec. 1, T. 15 N., R. 25 E., near an outcrop of sheared basalt. The trench is about 120 feet long and has a maximum depth of about 12 feet as shown in figure 7 which is a sketch drawing of the west wall of the trench. The

Figure 7 is at the end of the report.

trench did expose considerable broken and sheared basalt that appear to be parts of large blocks slumped from the fault scarp, rather than being part of the main fault itself. Apparently, the main fault zone is largely buried by slump blocks and talus throughout the total length of the Smyrna Bench. As shown in figure 7, the southern half of the trench exposes a caliche-capped block of broken to massive basalt which has dropped below adjacent broken and sheared basalt along an apparent reverse fault. This is shown in detail in the photograph (fig. 8). The flow was not positively

Figure 8 belongs near here.

identified but it appears to be one of the flows of the Priest Rapids Member. The highly broken, sheared, and crushed basalt in the middle part of the trench may be from a single disoriented section of the main fault that is contained in a slump block, or it could represent shear planes of adjustment between separate blocks that slumped at the same time.

Smyrna trench 3 was dug in two segments across the top of a large slump block of basalt in NW¼SE¼NW¼ sec. 4, T. 15 N., R. 26 E. in an attempt to expose the landslide plane between the basalt and the fanglomerate of the Ringold Formation. Sketches of the east wall of these two segments (labeled trench 3S and trench 3N) are shown in figure 9. The basalt exposed in the south end of trench 3S

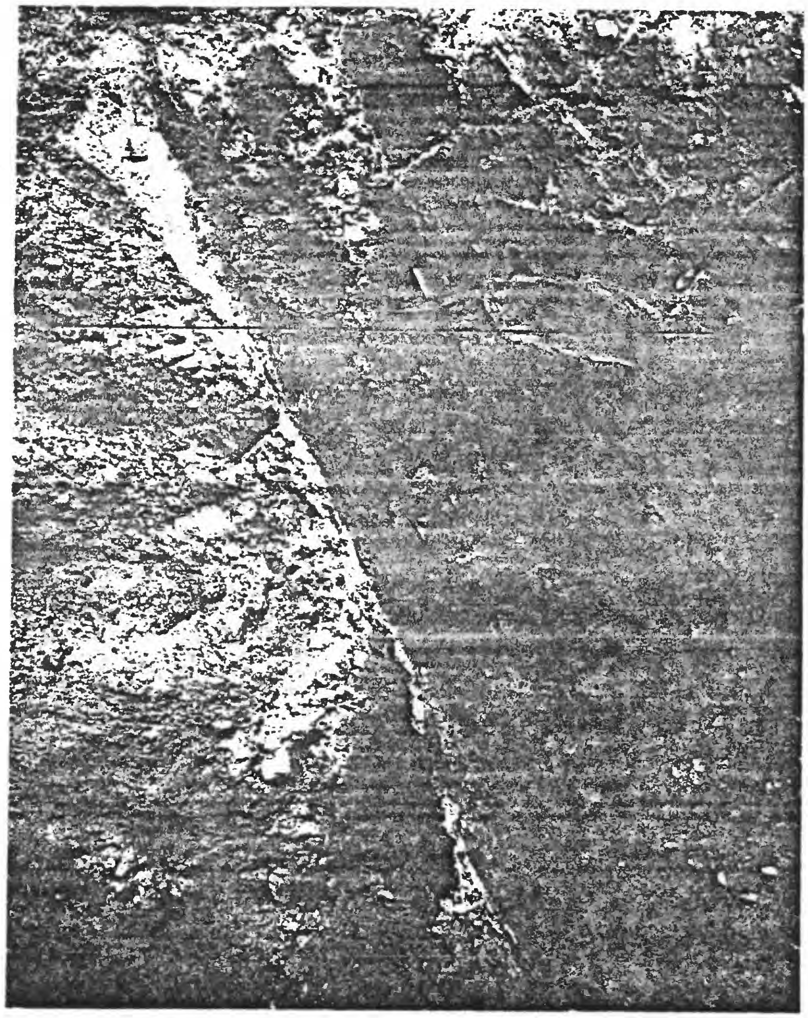

FIGURE 8. -- Closeup view of reverse shear feature in trench 1 on Smyrna Bench.

Figure 9 is at the end of the report.

is unbroken and seems to be dipping about 50°N. Joints in the basalt have been opened slightly and, from the basalt's topographic position, it is believed to be part of a large slump block that originated high on the scarp to the south. Overlying the basalt is a layer, as much as 5 feet thick, of angular basalt cobbles and boulders. This material probably is old talus. This layer, in turn, is overlain by about 18 feet of weathered tuffaceous clay that contains basalt cobbles that decrease in number upward. This clay and the remaining material exposed in trench 3S and throughout the length of trench 3N are all parts of various facies of the Ringold fangomerate, chiefly beds of clay and sand containing varying amounts of pebbles and subrounded to angular boulders of basalt. In both trenches, the fanglomerate is broken by the separation cracks similar to those in trench 2 (fig. 11). Some of these are filled with loess; others contain fragments derived from the walls of the crack. Several of the cracks show some stratigraphic offset, but no gouge zones or slickensides were found.

The fault shown by Grolier (1965, pl. 18B and p. 196) and Grolier and Bingham (1965) to be along the north side of Smyrna Bench is now thought to be another type of block slumping. The basalt flow exposed at the base of the north face is the Elephant Mountain flow and is about 100 feet thick at test hole 4. Underlying this flow is the Rattlesnake Ridge bed, an interbed of sand and clay of unknown thickness. During the glaciofluvial flood erosion of the Crab Creek valley the water must have eroded this interbed and undercut the Elephant Mountain flow. Left without support, thin segments of the flow slumped down, carrying the overlying fanglomerate with it. The present exposures show this vertical slump plane and the top of the basalt to be offset 10 to 25 feet. The bottom of the flow at present is deeply buried by the postflood (Holocene) alluvial fan material. The top of the basalt is 150 to 200 feet above the present bottom of Crab Creek valley so the bottom of the Elephant Mountain flow was exposed to flood erosion; even the bottom of the Pomona flow probably was exposed to erosion downstream from the Smyrna-Royal City highway crossing, although both contacts now are buried by Holocene flood gravels and alluvial fans.

Linear Scarps

Along the middle of the eastern two thirds of the Smyrna Bench, there is a series of low, east-west, subparallel linear scarps (fig. 6). They tend to separate the major linear depression or "graben" on the south from the remainder of the bench. The foreground of the ground-view photograph in figure 10 shows two of the

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Figure 10 belongs near here.

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scarps and the attendant swales extending westward away from the camera viewpoint. Farther to the west, and also to the left of the view, the swales blend into south-facing scarps along the north side of the "graben". A few of the scarps extend to, and probably

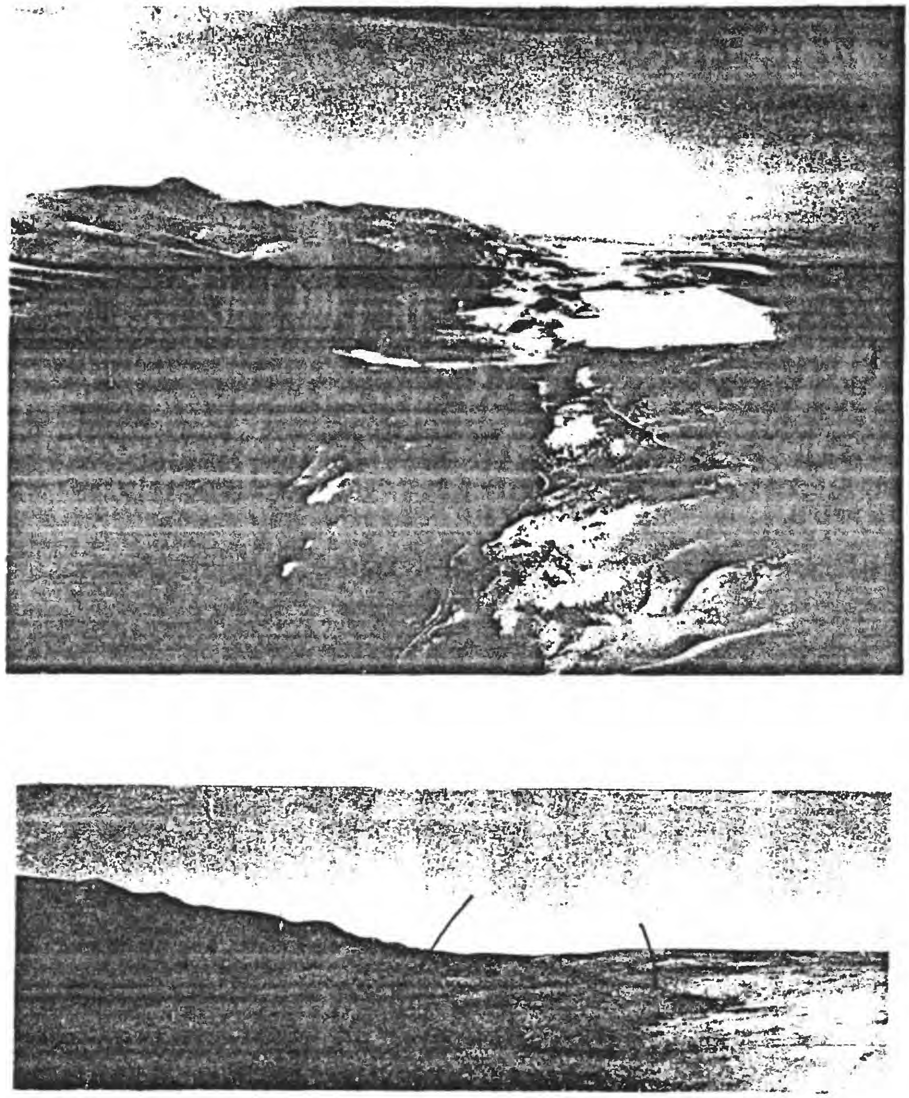

FIGURE 10. -- Aerial and ground views of Smyrna Bench, both looking west. Note irregular linear scarps in the ground view (two dark streaks extending away from camera) caused by large separation cracks in fanglomerate. The ground view was taken from the middle of the near edge of white field on aerial view.

are buried by, the Holocene colluvium and alluvium that partly fills the closed basins. No disturbance or rupturing of this alluvial material was found anywhere on the bench. The "graben" has trapped all the material carried into it by intermittent streams flowing north from the Saddle Mountains.

The linear scarps were thought by Jones and Deacon (1966, p. 4 and photograph 2, pl. 13) to have "confirmed the existence of a Recent fault graben". They also considered two other north-south scarps as evidence of historic fault activity. In this investigation, these north-south scarps were determined to be the sides of an old, broad, beheaded erosional gully, rather than being fault scarps.

Jahns wrote that (1967, p. 6) the entire bench appears to have resulted from erosion controlled in part by the strike of basalt flows and associated sedimentary strata and by differential erosion of the basalt flows and the Ringold Formation. However, in this investigation, no evidence for erosion of a longitudinal (east-west) valley was found. Instead, backhoe trenching has shown that the caliche zone, which caps the northern part of Smyrna Bench, has been ruptured along the scarps and is present beneath the surface in the "graben". This indicates that the former land surface has subsided into the "graben", rather than having been eroded. The topographic closure of the individual basins within the "graben" is mainly the result of segmenting of the depression by the landslide blocks which have slumped northward into the depression from the flanks of the Saddle Mountains. Also, small closed basins occur between some of the subparallel scarps.

Grolier (1965, pl. 18B, p. 194 and p. 196) described and, through diagrams, showed a single fault plane through the middle of the bench. He simplified the linear scarps to represent one fault along the south side of a "horst", which was indicated as bounded by another fault along the north side of Smyrna Bench. The present more detailed investigations indicate that the "horst" is not present on Smyrna Bench, and that the north boundary of the bench is not a fault, but is a slumped block, as previously explained.

During the field investigation for this report, the writers found that the linear scarps and related swales: 1) are subdued by eolian deposition and deflation; 2) have irregular to curvilinear trends; 3) are mostly north of the "graben" area that contains the closed topographic basins; 4) diminish in number and amount of displacement toward the west; and 5) die out completely about 2 miles from the west end of the bench. To aid in determining the origin and age of these scarps, geologic mapping was augmented by test drilling and backhoe trenching. Three backhoe trenches were dug. As previously discussed, trench 1 was near an exposure of sheared and slickensided basalt formerly thought to be part of the Saddle Mountains fault, and trench 3 was across an anomalous ridge within the "graben". Trench 2 was dug perpendicular to a linear scarp.

The Smyrna trench 2, which provided the most critical information, was dug in NE¼SE¼SE¼ sec. 33, T. 16 N., R. 26 E. across one of the linear scarps and swales -- a sketch of the west wall of the trench is shown in figure 11. In this trench four major

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Figure 11 is at the end of the report.

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units of loess and two different layers of caliche overlie the fanglomerate of the Ringold Formation. The trench reveals many well-defined separation cracks that have been filled with the overlying loessal material. The cracks are tension cracks that developed by rupture of the main mass of fanglomerate material of the Ringold Formation. Although some of the cracks show vertical offset, many do not. Most of the cracks vary from 0-1 foot in width and the vertical stratigraphic offset ranges up to about 2 feet, but one of the cracks is about 21 feet wide and has an apparent vertical offset of 6 feet. This large crack underlies a prominent linear scarp and swale that are visible on the ground and on aerial photographs. Although this large crack was the only one exposed by trenching, it is likely that the other linear scarps and swales on the bench are underlain by other similarly large cracks.

The fact that the total amount of horizontal displacement (lengthening) shown in Smyrna trench 2 is much greater than the vertical displacement is strong evidence favoring the hypothesis of large-scale block-glide landsliding on Smyrna Bench. If the main mass of the Ringold Formation moved a short distance northward toward the Crab Creek escarpment as a glide block along a buried gently dipping detachment surface (such as a clay bed) within the formation, or between the Ringold and the underlying Yakima Basalt, the back (southern) side of the mass would be expected to have been pulled apart by north-south tensional forces and to have subsided slightly to form a "graben" as space became available at the back of the glide block. The curvilinear pattern of scarps (fig. 6) in the eastern part of the bench and the presence of large landslide masses to the east also favor this interpretation. As will be discussed later in this report, the age of ground rupturing accords with events of glacial flooding, which also supports an interpretation of landslide-block gliding.

The topographic profile drawn for the geologic cross section A-A' (fig. 6) is along a line connecting the test-hole sites and, not along stream channels. However, a remnant of the caliche-impregnated top of the Ringold Formation that caps the bench between test holes 2 and 4 probably is part of the pre-glaciofluvial, north-sloping, land surface of Smyrna Bench. The depression between test holes 2 and 3 is part of the "graben" which is somewhat shallower in this area than elsewhere.

Subsurface Geology

The test holes were drilled in a north-south line (fig. 6) across the bench where the topography of the "graben" seemed less complex and where the drill rig could be set up near the Saddle Mountains fault zone. Logs of the holes are given in Appendix A.

The holes were expected to penetrate to the top of the Yakima Basalt "bedrock", but holes 2 and 3 were unsuccessful in reaching basalt which appears to be at much greater depth than expected. Test hole 1 was abandoned and redrilled nearby as test hole 2. Three other test holes were placed in a line passing near Smyrna trench 2 between the bluff on the north and the fault-line scarp on the south. The land-surface topography on cross-section A-A' (fig. 6) has been extended to Wahatis Peak and to the north side of Crab Creek valley. At the south side of the valley, the top of the Yakima Basalt (the top of the Elephant Mountain flow) is at an altitude of 725 feet, but at test hole 4 it is at an altitude of 693 feet, indicating a dip of approximately 2 degrees to the south in this locality. By projection under the bench, the top of the basalt was expected in drill holes 2 and 3 between 650 and 750 feet altitude. Test holes 2 and 3 were drilled to altitudes of 408 and 558 feet, respectively, without reaching basalt. This unexpected depth to basalt can be explained several ways, but none of the explanations can be verified with existing data. The top of the basalt below the Ringold Formation could have been displaced by: 1) a sharp, south-facing, monoclinal fold; 2) a vertical fault downthrown on the south side (fig. 6, section A-A'); or 3) a nearly horizontal shear related to block gliding that cut the basalt, leaving a "window" in the Elephant Mountain basalt flow where the test hole was drilled. Figure 6 (section A-A') illustrates the most likely interpretation. If the basalt were continuous at 2°

dip southward between holes 4 and 2, it should have been intercepted at an altitude of about 660 feet in hole 2, but hole 2 was drilled 250 feet below this altitude without intercepting the basalt. However, at an altitude of 580 feet in hole 2, a 6-foot-thick zone of clay with slickensides on most pieces was penetrated within the Ringold Formation. These observations suggest that the basalt surface may be offset by a buried fault between holes 4 and 2, and that the upper part of the mass of the Ringold Formation has slid northward over the lower part along a nearly flat landslide glide plane (fig. 6, section A-A').

On the gamma-radiation logs for holes 2 and 4 (see logs in Appendix B), two distinctive zones occur in the fanglomerate of the Ringold. These zones are interpreted as being two interbeds of lacustrine sand, silt, and clay which interfinger with the fanglomerate. The interbeds correlate very well and have a slight dip northward. In test hole 3, the next hole to the south, these zones are not present. Their absence probably is due to nondeposition of the beds on the upper part of the original slope of the Ringold alluvial fan.

From the foregoing it can be seen that the upper part of the fanglomerate that includes the clay beds has not been faulted between test holes 2 and 4, whereas the basalt surface is displaced more than 250 feet downward below test hole 2. No surface evidence of down-to-the-south faulting or monoclinal folding of this magnitude is visible anywhere in the vicinity of the Smyrna Bench. Regardless of whether the basalt displacement is due to faulting or monoclinal folding, it is likely that the movement took place before or during deposition of the fanglomerate in early Ringold time, and certainly before block gliding occurred.

Summary of Events in Evolution of Smyrna Bench

The evolution of Smyrna Bench and its various physiographic and structural features, is summarized below. The events (A-D) correspond to stages shown diagrammatically on figure 12.

Figure 12 belongs near here.

A. Deposition of the Ringold Formation in structural basins formed on the Yakima Basalt in Pliocene and early Pleistocene time, during the folding and erosion of the Saddle Mountains anticline. Uplift of the Cascade Mountains resulted in aridity and cessation of rapid erosion of the anticline and deposition of the Ringold. The massive caliche at the top of the Ringold in south-central Washington was probably formed as a result.

B. Faulting and continued slight folding resulting in deformation of the Ringold Formation, with basalt faulted against it.

C. Extensive erosion by floods of glacial meltwater several times during last 100,000 years (late

Pleistocene). The erosion of Crab Creek valley left a high bluff (Smyrna Bench) of the Ringold Formation largely saturated and unsupported, so that massive block gliding was initiated and reactivated by several floods. As the block glided, large segments slumped and were detached from its back (south) side, resulting in a linear depression with closed basins between the gliding block of the bench and the Saddle Mountains fault-line scarp. Large landslide blocks of the Ringold and the Yakima Basalt slumped northward off the fault line scarp into the depression and obscured the older Saddle Mountains fault.

D. Post-flood erosion of steep slopes and partial filling of closed basins and Crab Creek valley with colluvial and alluvial deposits.

Age of Faulting

The major stage of movement on the Saddle Mountains fault occurred after deposition of most or all of the Ringold Formation, as shown by exposures along the fault west of the Columbia River. The movement might have occurred before the development of the caliche that caps the Ringold and, thus, before the earliest stages of glacial flooding (about 100,000 years ago). However, no exposures were found with the caliche in place overlying the fault zone to provide definitive evidence of whether or not the

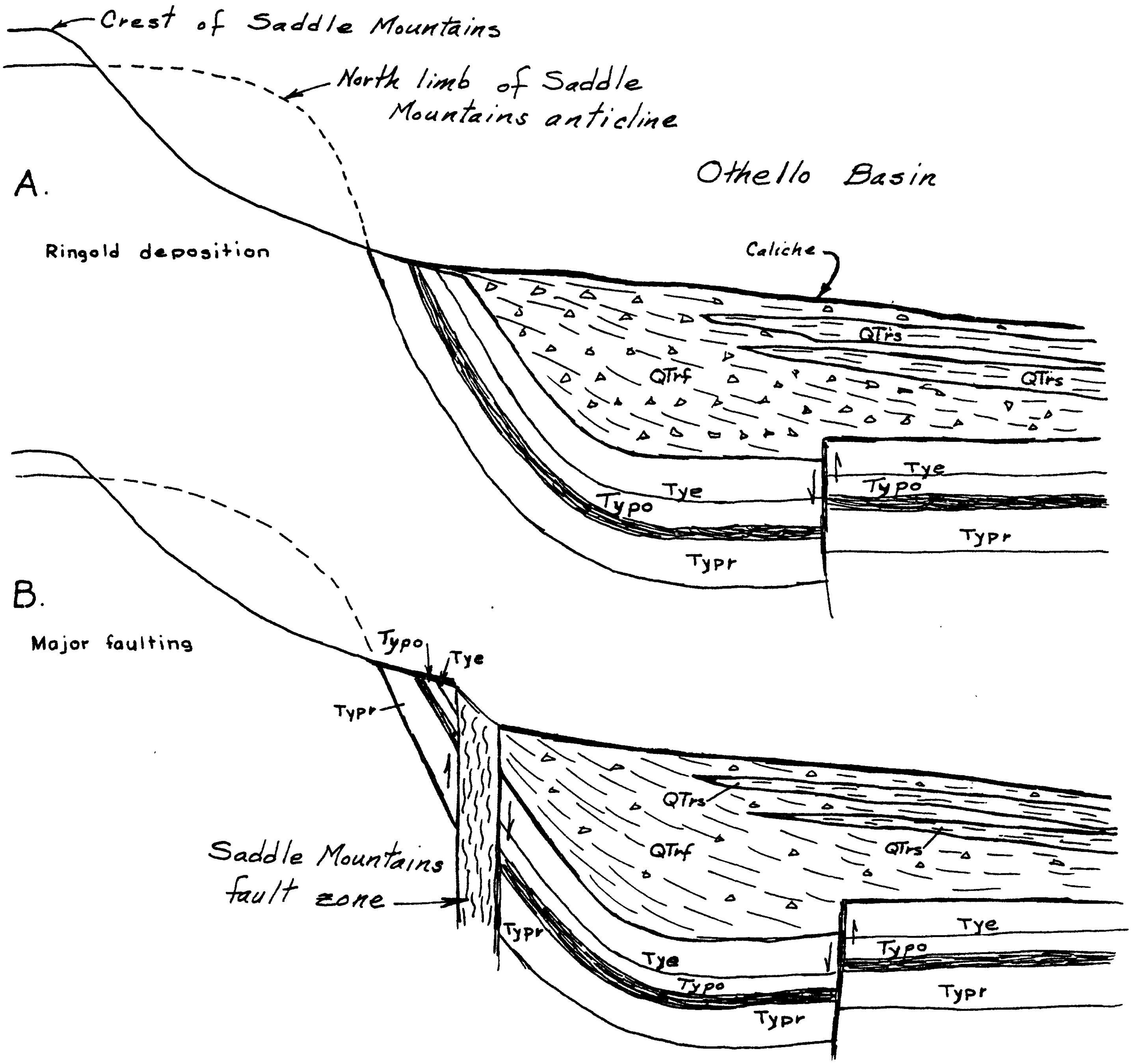

FIGURE 12.--Diagrammatic sketches showing the evolution of Smyrna Bench. See fig. 5 for explanation of symbols.

(To 12 fol.)

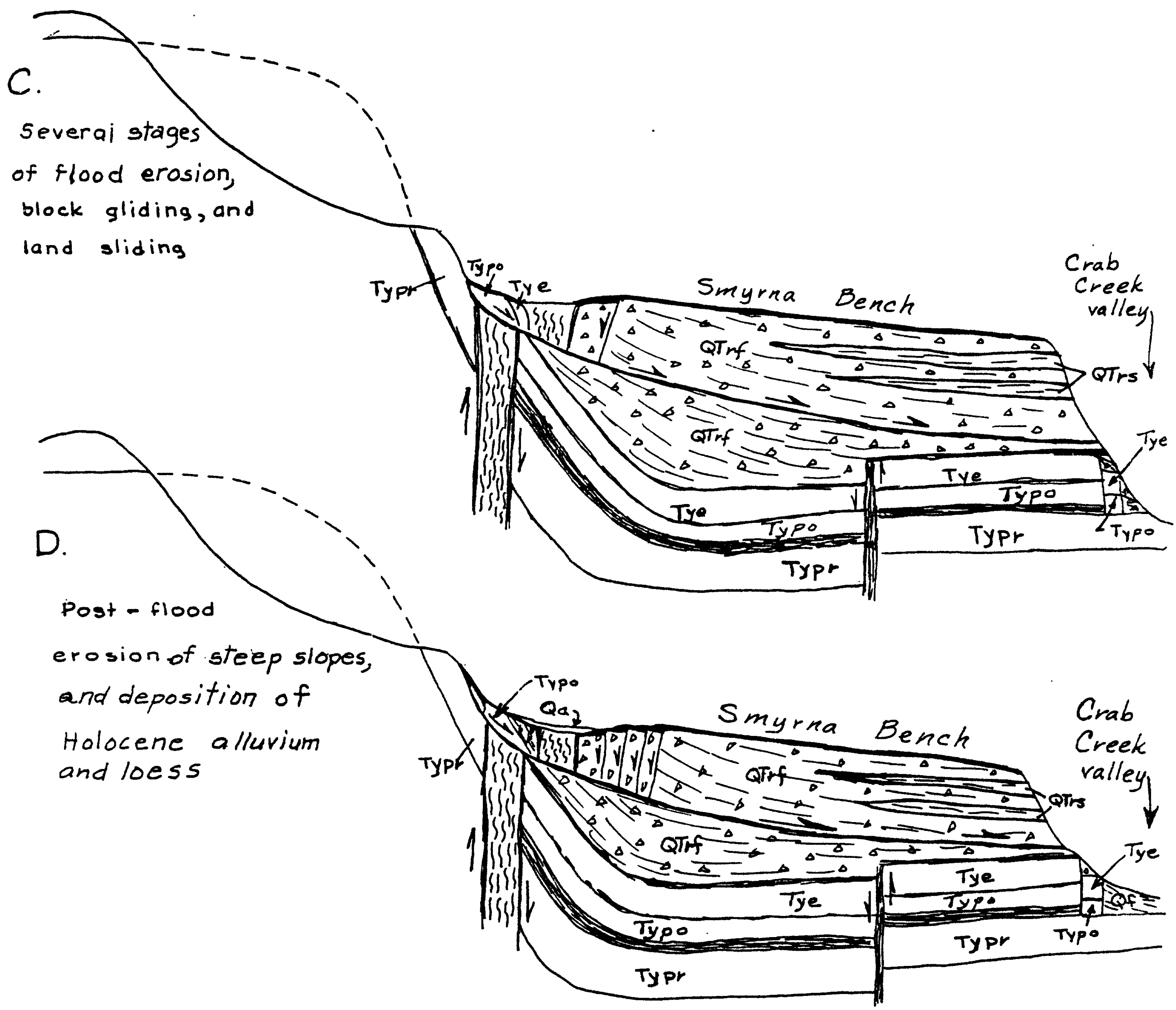

FIGURE 12.--Continued

caliche was involved in the faulting. The landslide blocks on the north side of the Saddle Mountains are younger than the fault and apparently are related to the large-scale block gliding that was caused by glaciofluvial events. As discussed in the next section, evidence from the trenches on Smyrna Bench indicate that much of the block gliding occurred before and during Pinedale time (12,000 to 25,000 years ago in this region). Therefore, the Saddle Mountains fault can be dated only as being older than Pinedale age, although it might be as old as late Pliocene or early Pleistocene.

Age of Block Gliding

The ages of the separation cracks on the Smyrna Bench can be defined within certain limits. They are all definitely younger than the caliche that caps the Ringold Formation. In trench 2, Bull Lake loess fills one crack, but all the other cracks are younger than the Bull Lake loess (Qlbl and Qlbu on fig. 11). Consequently, what appear to be the main episodes of block gliding must have begun after the deposition of the Bull Lake loess sheet (Qlbu); the last movement apparently occurred just prior to 12,000 years ago. This latter date is based on a carbon-14 age determination of 11,950±300 years before present (Dr. Meyer Rubin, U.S. Geological Survey, written commun., 1969, USGS W-2363) obtained from carbonaceous silt (Qlc) found in a lens in the largest separation crack in trench 2, at the base of the late Pinedale and Holocene loess (Ql).

These loess and caliche layers in Smyrna trench 2 (fig. 11) are correlated with the soil horizons of eastern Washington, as tabulated in INQUA (1965, p. 10-11) and described by Fryxell, Neff, and Trimble (1965, p. 79-81). The loesses correlate in age with the major glaciations and catastrophic flooding of the plateau. The layers present in trench 2 are correlateable with loess deposits of Bull Lake, Pinedale, and Neoglaciation (Holocene) age elsewhere on the Columbia Plateau (Dr. Roald Fryxell, oral comm., 1970). Interpretation from figure 11 indicates that a first episode of block gliding may have occurred before Bull Lake time. Another episode occurred before mid-Pinedale time because a few of the separation cracks are filled with loess of mid-Pinedale age. Thus, the greatest block movement, indicated by the largest cracks, occurred during or before mid-Pinedale time. The small most numerous cracks are filled with late Pinedale and Holocene loess, indicating that block gliding probably reoccurred shortly before 12,000 years ago.

Gable Mountain and Gable Butte

General Features

Gable Mountain and Gable Butte are relatively small anticlinal uplifts that are composed of the Yakima Basalt and are situated near the middle of the Pasco Basin (fig. 3) about midway between the Rattlesnake Hills and the Saddle Mountains and about 20 miles north of Richland. They are almost the only surface expression of the Yakima Basalt within the Pasco Basin. They are surrounded by a glaciofluvial gravel plain (fig. 13) that displays outstanding examples of subfluvial scour and deposition on a tremendous scale.

Figure 13 is at the end of the report.

Material forming the plain was deposited by late Pleistocene glaciofluvial floodwaters (Bretz, 1959, 1969; Bretz and others, 1956; Richmond and others, 1965) which reached a maximum altitude of 1,150 feet in the Pasco Basin. The floodwaters did considerable scouring and eroding of the basalt flows and the Ringold Formation during the multiple events.

Gable Mountain covers about 5½ square miles and reaches an altitude of 1,085 feet at its eastern peak and 1,112 feet at its western peak. The surrounding gravel plain varies in altitude from 420 to 540 feet.

Gable Butte covers an aggregate area of about 1½ square miles of basalt outcrops and reaches an altitude of 760 feet (fig. 13) near the eastern end and 738 feet in the western part. The gravel plain surrounding it varies from 500 to 640 feet in altitude.

The basalt flows exposed on Gable Mountain and Gable Butte are those of the Priest Rapids and Saddle Mountains Members of the Yakima Basalt (fig. 2). In ascending order the flows and intervening interbeds are: two Priest Rapids flows with a thin (±3 ft) intervening interbed of clay; the Selah bed (up to about 10 ft thick); the Pomona flow (about 100 ft thick); the Rattlesnake Ridge interbed (up to 40 ft thick); and the Elephant Mountain flow (60 to 80 ft thick).

Structurally, Gable Mountain and Gable Butte are a series of west-northwest-trending asymmetrical anticlines. Based on R. E. Brown's contours of the top of the basalt in the subsurface of the Hanford area, as shown by Jones and Deacon (1966, pl. 4), the Gable Butte and Gable Mountain anticlines appear to be en echelon structures alined with the anticlinal fold of Umtanum Ridge which is west of Gable Butte (see fig. 4). The contours indicate that the basalt dips northward into the Wahluke syncline from the Gable Butte and Gable Mountain anticlinal structures. The axis (concealed) of the Wahluke syncline (Jones and Deacon, 1966, pl. 4) lies a short distance north of the anticlines; less than a mile north of Gable Butte the top of the basalt is more than 700 feet lower than it is at the northernmost exposures of basalt, and a mile and one-half north of Gable Mountain it is more than 600 feet lower. Cross sections by Jones and Deacon (1966, pl. 5) show that this syncline is filled mostly with Ringold Formation deposits which lie above the basalt and are concealed beneath the surficial glaciofluvial deposits. South of Gable Mountain and Gable Butte the basalt appears to dip gently southward beneath the glaciofluvial deposits (Jones and Deacon, 1966, pl. 4). Further study of the buried flanks of these structures was not within the scope of the present work and probably would require geophysical methods.

Problems of Interpretation

Gable Mountain and Gable Butte were investigated in detail primarily to determine the nature and age of the transverse topographic scarp across the central part of Gable Mountain. Newcomb (1963, written comm.) and Jones and Deacon (1966, pl. 4) have shown it as a fault, but its nature was not entirely clear because the various basalt flows had not been mapped in detail to determine if there are stratigraphic offsets along the scarp.

During this investigation, Gable Mountain and Gable Butte both were mapped in detail, a bulldozer and a backhoe were used to excavate trenches at five places on Gable Mountain and one on Gable Butte, samples for chemical analyses were taken of pertinent outcrops of basalt in the trenches to confirm the geologic mapping interpretation, and many scattered samples of all the basalt flows were taken for determination of refractive indexes.

Gable Mountain

On Gable Mountain the folding has been very complex, resulting in a series of asymmetrical anticlines with sinuous axes, all trending roughly west-northwest (fig. 13). There are two major anticlinal axes, each of which has a smaller anticline branching from its northeast side. The axis of the main anticline of the western half of Gable Mountain is arcuate, plunges east and west, and is strongly asymmetrical, with the south limb having dips up to 62°. The smaller anticline which branches from the northeast side of the western anticline is asymmetrical with the north limb oversteepened. The axis of this branching anticline appears to pass eastward, without plunging, under the transverse fault which divides the mountain topographically and structurally into east and west halves.

The large anticline of the east half of Gable Mountain plunges both west and east, has a gently arcuate west-northwest trend, and is undulating and asymmetrical to the north, with the north limb having considerably steeper dips than the south limb. Toward the east end of this anticline a small, curving anticline, also asymmetrical to the north, branches from its north limb and plunges southeastward.

Detailed Investigation of Faults on Gable Mountain

When the individual basalt flows were mapped, the complex deformation of Gable Mountain became apparent (fig. 13), and the existence of two transverse faults was confirmed. The western fault (fig. 14, NW¼NW¼ sec. 23, T. 13 N., R. 26 E.) was not excavated

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Figure 14 belongs near here.

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because of its relative inaccessibility. The stratigraphic offset across this fault can be seen on the south face of the mountain about 1 mile from the west end. The fault appears to be ~~is~~ an overthrust and its dip is estimated to be about 30° E.; the measured vertical stratigraphic offset is 30 feet for the Pomona flow and probably more for the

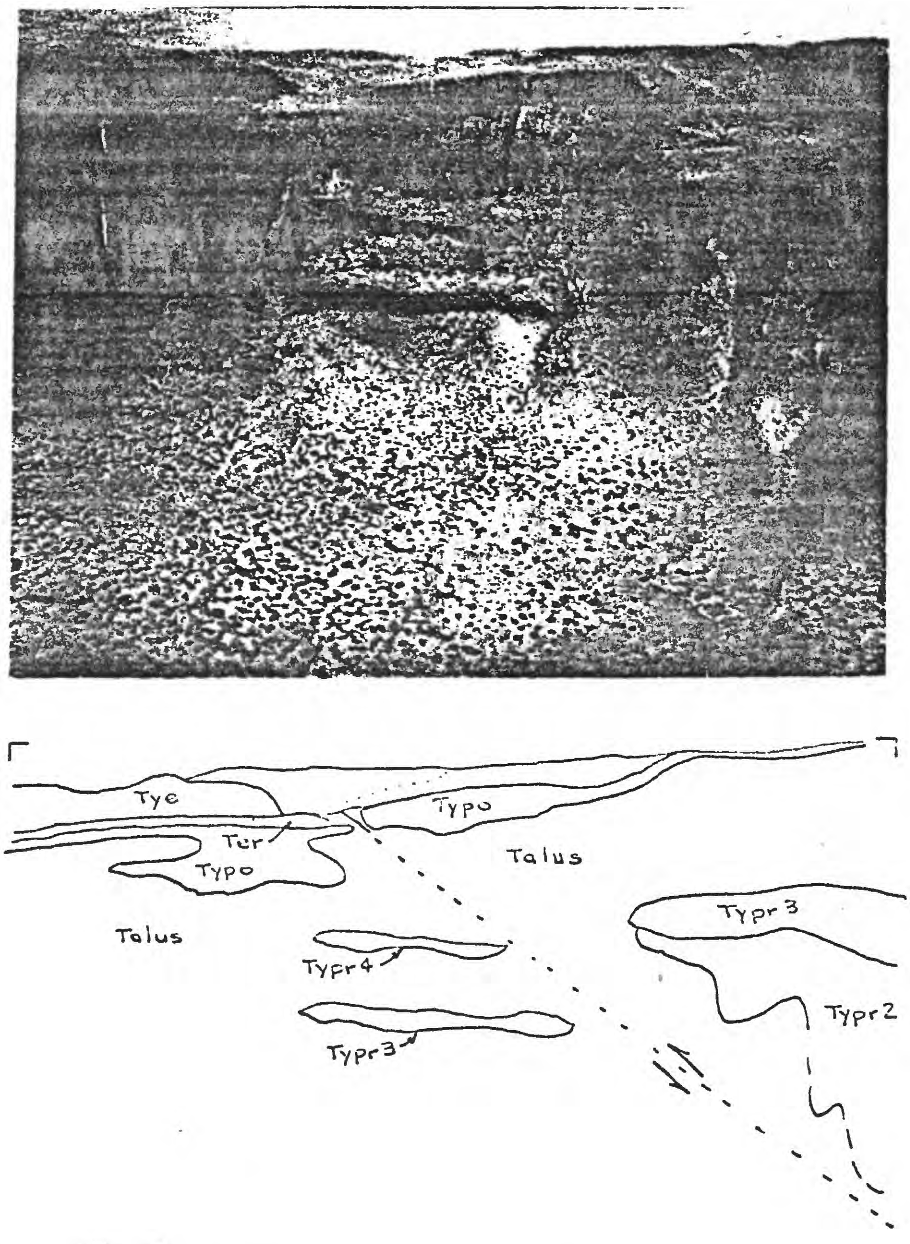

FIGURE 14.--Photograph of western part of Gable Mountain, and sketch showing approximate position of thrust fault. See fig. 5 for explanation of symbols.

Priest Rapids flow. The extension, if any, of the fault north and south of the anticlinal structure is not known because of the thick cover of glaciofluvial gravel.

The other fault on Gable Mountain (fig. 13; sec. 19, T. 13 N., R. 27 E.) is in the central part of the mountain and also is transverse to the anticlinal structure. Erosion along the fault has formed a fault-line scarp as much as 100 feet high across the northern two-thirds of the mountain. Across the southern third of the mountain the scarp is buried by glaciofluvial gravel. Some controversy existed prior to this mapping as to whether the basalt flow at the top of the scarp was the same flow as that in the saddle below the scarp, or whether the flow at the top was stratigraphically higher than the flow below the scarp and had simply been eroded from the saddle by glacial floodwaters. The mapping has shown that they are the same (Elephant Mountain) flow which has been offset along the fault. In addition, trenching, chemical analyses, and refractive index determinations were conducted as a check to the mapping and flow identification. These have all confirmed the presence of the fault as mapped on figure 13.

Bulldozer and backhoe trenches were dug at five sites along the scarp. At three of the five sites (trenches 3, 5, 6, fig. 15) the fault plane was exposed, while at a fourth site (trench 4) the presence of the fault was demonstrated although the fault plane was not exposed because of the depth of gravel. The first two trenches (1 and 2, fig. 15) were dug along the buried part of the scarp but were not

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Figure 15 belongs near here.

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deep enough to reach the bottom of the gravel lying against the scarp face.

The third trench (no. 3 in fig. 15) was the first to expose the fault zone. The east wall of this trench is shown in figure 16. The trench followed the Elephant Mountain flow from the flat area

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Figure 16 belongs near here.

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at the northwest end to the base of the scarp. The trench was then extended into the scarp where it exposed the base of the Elephant Mountain flow, the Rattlesnake Ridge bed, and the fault plane with fault gouge overlying the aa lava of the upper part of the Elephant Mountain flow (fig. 17). The fault plane in this trench strikes

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Figure 17 belongs near here.

N. 88° E. and dips about 30° S. and has an apparent vertical stratigraphic displacement of about 70 feet. The principal shear plane passes through a 3- to 6-inch layer of chocolate-brown clay gouge with slickensides. Underlying the shear plane is a layer of subrounded, shiny, polished, basalt fragments in a clay gouge matrix. This is interpreted to be part of the fault-zone gouge formed by the fracturing and grinding of the underlying materials during movement on the fault. Overlying the shear plane is 6 to 8 feet

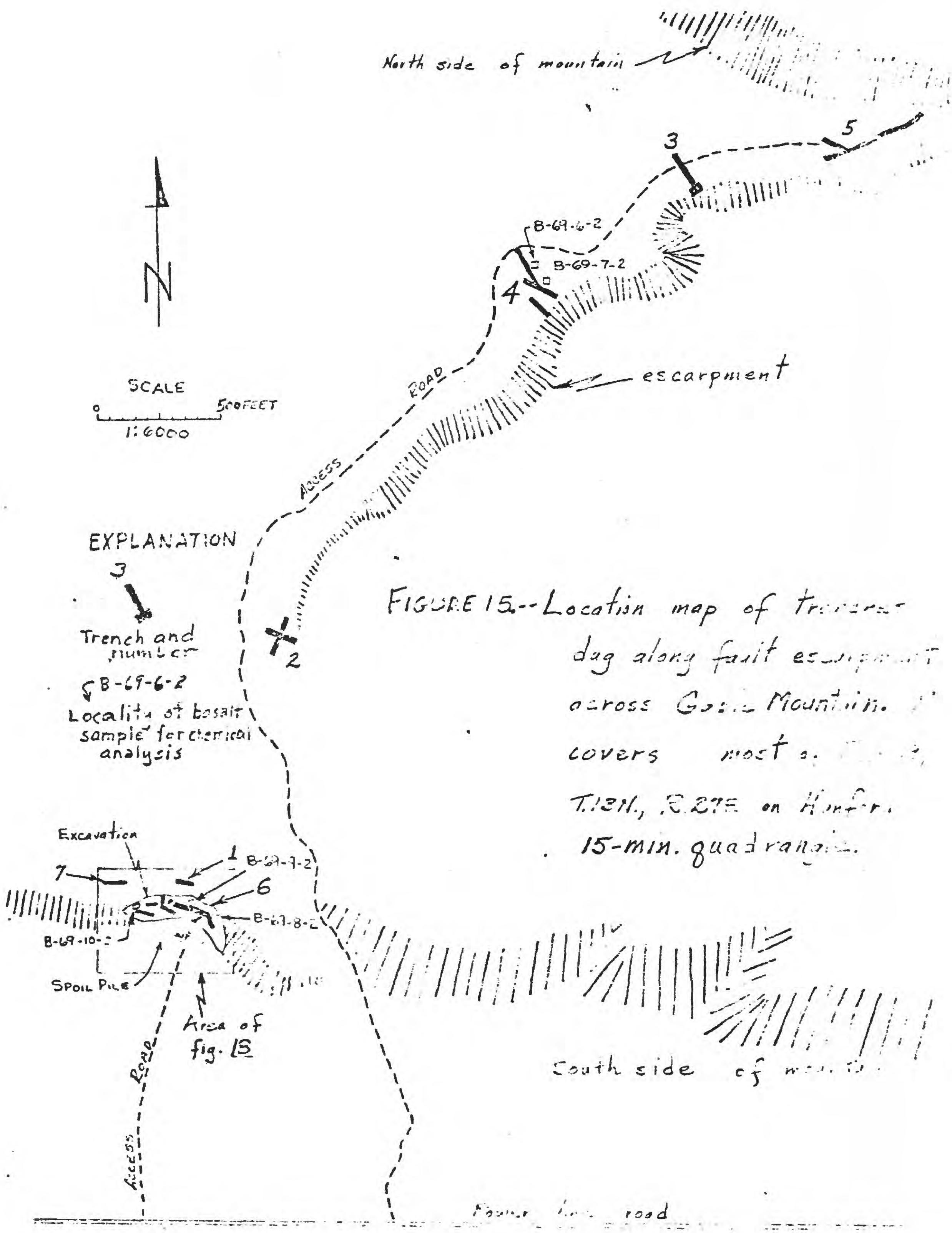

FIGURE 15--Location map of [illegible] dug along fault [illegible] across [illegible] Mountain. [illegible] covers most [illegible], T.13N., R.27E. on [illegible] 15-min. quadrangle.

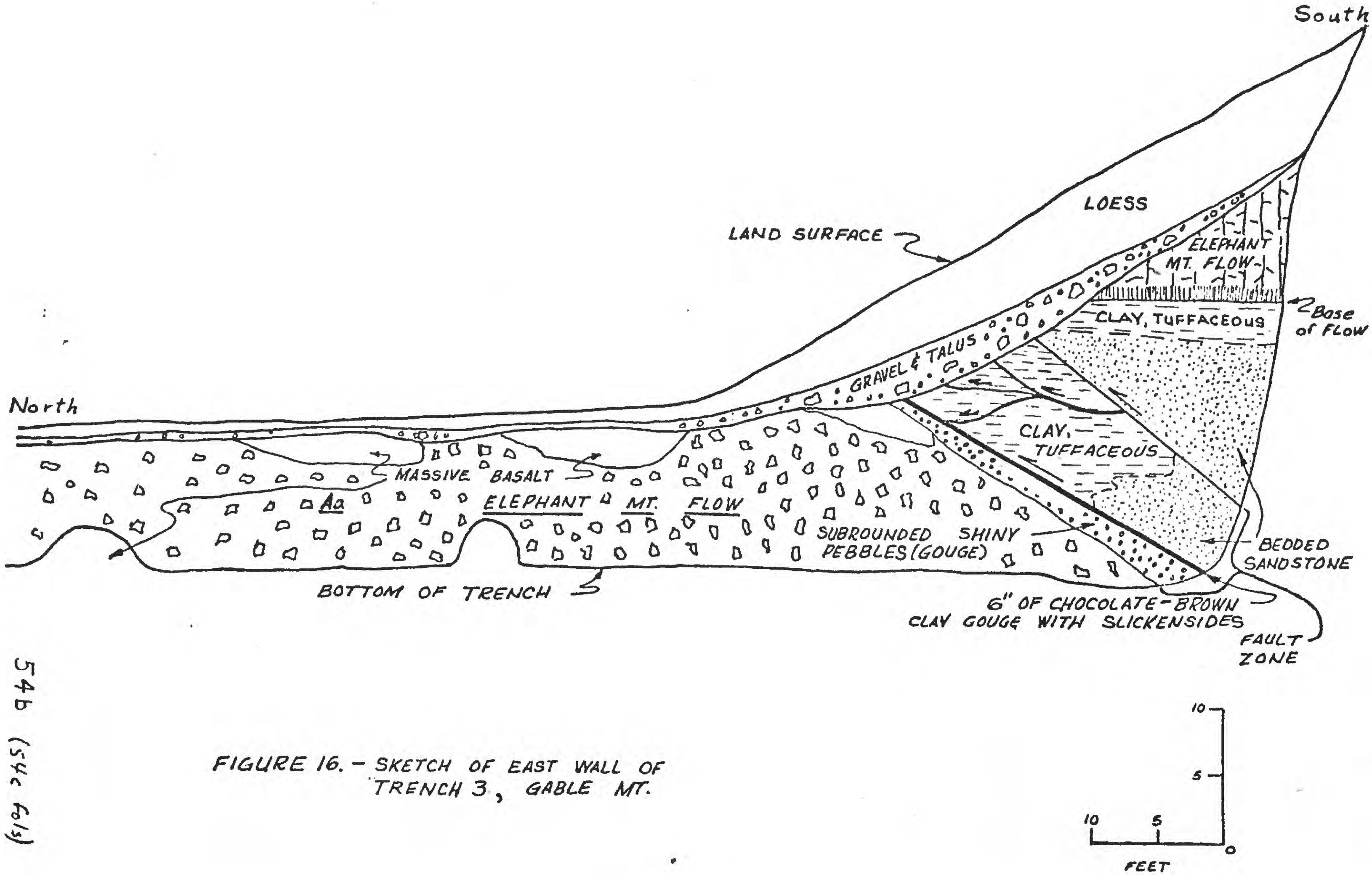

FIGURE 16. - SKETCH OF EAST WALL OF TRENCH 3, GABLE MT.

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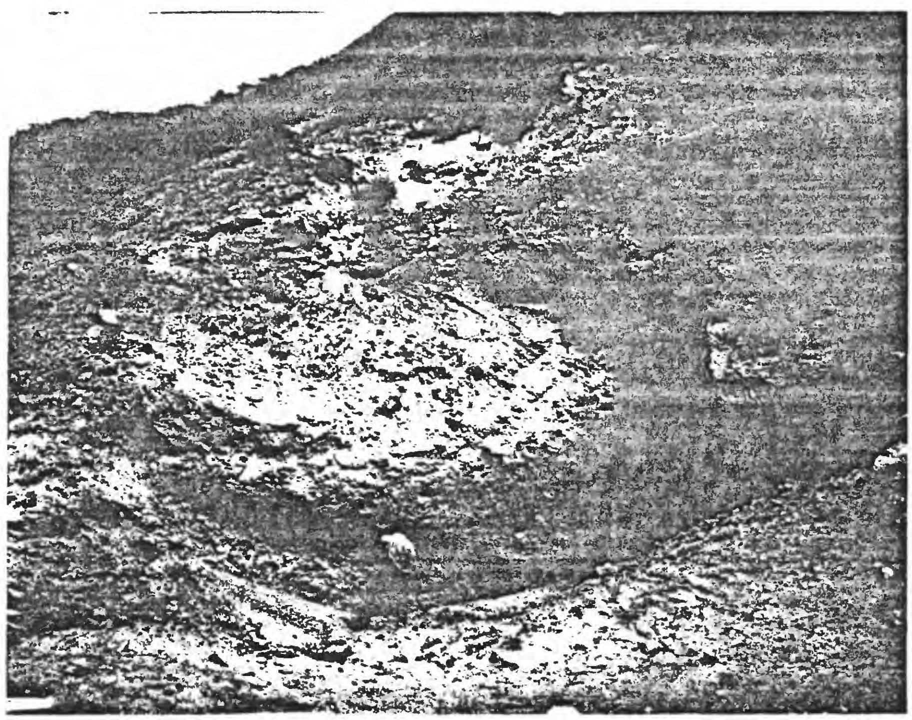

FIGURE 17. -- Exposure of main fault plane at man's head and shoulders in south end of trench 3 on Gable Mountain.

of tuffaceous clay and sandstone of the Rattlesnake Ridge bed which has been cut into multiple segments by minor shear planes. At the top of this fault zone is another nearly planar shear surface which separates the undisturbed Rattlesnake Ridge interbed from the fault zone. The gravel and talus overlying the edge of these shear planes were not disturbed, indicating that the age of faulting is older than at least the last glacial flood scouring at this trench site. The identification of the Elephant Mountain flow above and below the fault zone in this trench is based on its petrology, stratigraphic position, and weathering characteristics. This identification is verified by the refractive indexes of samples 26, 27, and 28 (Appendix C and fig. 13).

Trench 4 (fig. 15) was dug between the basalt scarp and a small outcrop of Elephant Mountain basalt on the flat to the northwest. The Elephant Mountain basalt was exposed for about 50 feet in the north end of the trench before its eroded surface dips below the bottom of the trench (the maximum depth that could be reached by the backhoe). South of the last Elephant Mountain basalt exposure (site of collection of samples for chemical analysis B-69-6-2, Appendix E, and refractive-index 52, Appendix C) in the trench, an interval of about 50 feet of gravel and sand is exposed to a depth of about 35 feet -- the gravel and sand are well bedded and represent several flood episodes. In the south half of the trench the Pomona flow (chemical analysis sample B-69-7-2 and refractive index sample 53) is exposed under 15 to 25 feet of gravel. At the south end of the trench the top of the Pomona is overlain by the tuffaceous clay of the Rattlesnake Ridge bed and the base of the Elephant Mountain flow. Although the fault plane could not be observed, the juxtaposition of Elephant Mountain and Pomona flows at about the same altitudes at opposite ends of the trench confirms the presence of the fault.

In trench 4 several shear planes appear to cut through the Rattlesnake Ridge bed, but the main fault zone is buried under gravel in the deepest part of the trench. The part of the Elephant Mountain basalt exposed in the bottom of the northwestern part of the trench is stratigraphically about 30 feet below the top of the $70^{\pm}$-foot-thick flow. Fifty feet away, horizontally, the upper part of the Pomona basalt is present. The total thickness of the Rattlesnake Ridge bed appears to be 5 to 10 feet in a separate segment of this trench. From these thicknesses, the vertical stratigraphic offset on the fault at trench 4 is about 50 feet. The gravel has not been disturbed in this trench by fault movement. Since the fault plane was not exposed, its strike and dip are not known here.

Trench 5 (fig. 15) is the northernmost trench and shows that the fault apparently ends in the steep north limb of the eastern anticline. The trench starts about 200 yards northeast of trench 3 and continues for about 300 feet northeast to the brink of the mountain escarpment. As the fault zone is followed northeastward, it thins to a 2- to 6-inch-thick shear zone within a rubble and gouge zone less than 1 foot thick. Near the extreme east end of the trench the shear zone becomes indistinct by subdividing and blending into the joints of the basalt flow.

Trench 7 (fig. 15) was dug by bulldozer and did not reach below the erosional surface of the Pomona flow. At this location the basalt was buried under about 5 feet of sandy gravel.

Trench 6 (fig. 15) is the largest of the excavations and provided the most information. The trench started as a bulldozer excavation along the steepest part of the south side of the mountain and ended with a complex of backhoe trenches as shown in figure 18. The fault zone was found in the east end of trench 6a and then followed down dip in trenches 6f and 6g. Figure 18 shows the trace of the fault zone through the excavations

Figure 18 belongs near here.

as well as the geologic units exposed. A sketch of the north wall of trench 6a (fig. 19) shows the fault zone along the top of an

Figure 19 is at the end of the report.

anomalous block of Elephant Mountain basalt (chemical analysis no. B-69-9-2, Appendix E) which has a strike of N. 20° E. and a dip of 32° SE. In contrast, the Pomona flow (chemical analysis no. B-69-10-2), exposed in the west end of the trench and along the scarp to the west, is at the plunging end of the western anticline, with the strike within the trench varying from N. 90° E. to N. 60° E. and the dip varying from 40° to 42° S. Similarly,

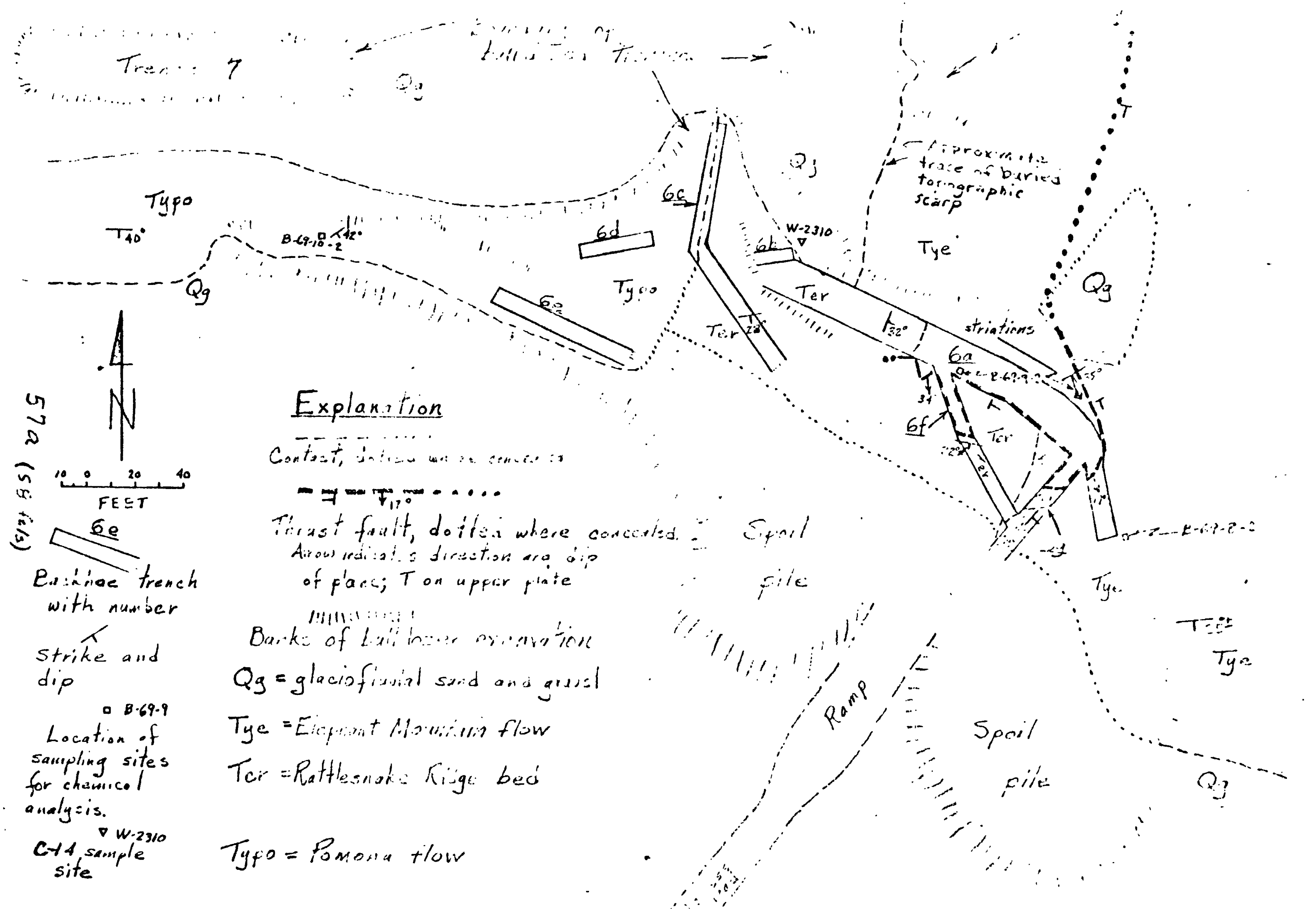

Figure 18.--Location and geologic map of trench 6 on south scarp of Gable Mt., in the SW¼ Sec. 17, T. 13 N., R. 27 E.

the strike of the Elephant Mountain flow (chemical analysis no. B-69-8-2) at the east end of the trench is N. 85° E. and the dip is about 25° S. The contact of the Elephant Mountain flow with the Rattlesnake Ridge bed is exposed in the bottom of trench 6g where the fault can be seen cutting across this contact at a low angle.

The strike of the fault changes direction within the area of trenches 6 a and 6 g as the strike of the stratigraphic units changes, and the strike and dip of the fault are similar to those of the stratigraphic units. The strike changes from N. 60° E. on the north side of trench 6a to N. 85° E. on its south side, near the junction with trench 6f (fig. 17). The fault dips about 35° SE at both sites but flattens to 17° SE at the bottom of the east end of trench 6a. These relations possibly indicate that the fault predates the folding or, more likely, indicate that both the folding and faulting were expressions of the same forces that produced the Gable Mountain uplift.

The fault zone is 1 to 3 feet thick, and consists of rounded shiny basalt pebbles and clay gouge that are cut by a shear zone of chocolate-brown clay gouge. This shear zone varies from 1 to 6 inches in thickness and contains one or more slickensided surfaces with well-developed striations. On the north side of trench 6a, the striations are oriented about 10° to the south of the direction of dip of the shear zone. In trench 6f (fig. 20)

Figure 20 is at the end of the report.

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the fault zone has several shear planes which are within the Rattlesnake Ridge bed.

The buried basalt scarp, which extends from the north into trench 6a, is shown in the west side of the trench (figure 19) where the effects of scouring and deposition by glacial floodwaters are well exposed. As shown in figure 19, there are four units of glaciofluvial sands and gravels which appear to represent four different flood episodes. The second oldest unit contained chips of wood which were dated by the Geological Survey carbon-14 laboratory as older than 40,000 years before the present (Dr. Meyer Rubin, written commun., 1969, sample no. W-2310).

Near the east end of trench 6a is a slumped block of well-sorted and stratified coarse sand (figs. 19 and 21) that has a

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Figure 21 belongs near here.

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dip anomalous to the other glaciofluvial beds. The block lies near the bedrock fault zone, but the disorientation of the block has no determinable relation to the fault. The block has some folded and offset beds near the lower corner and along the west side that appear to have developed at a time when the sediments were still wet or frozen. Probably the slump occurred as glacial floodwater receded or as underlying ice thawed.

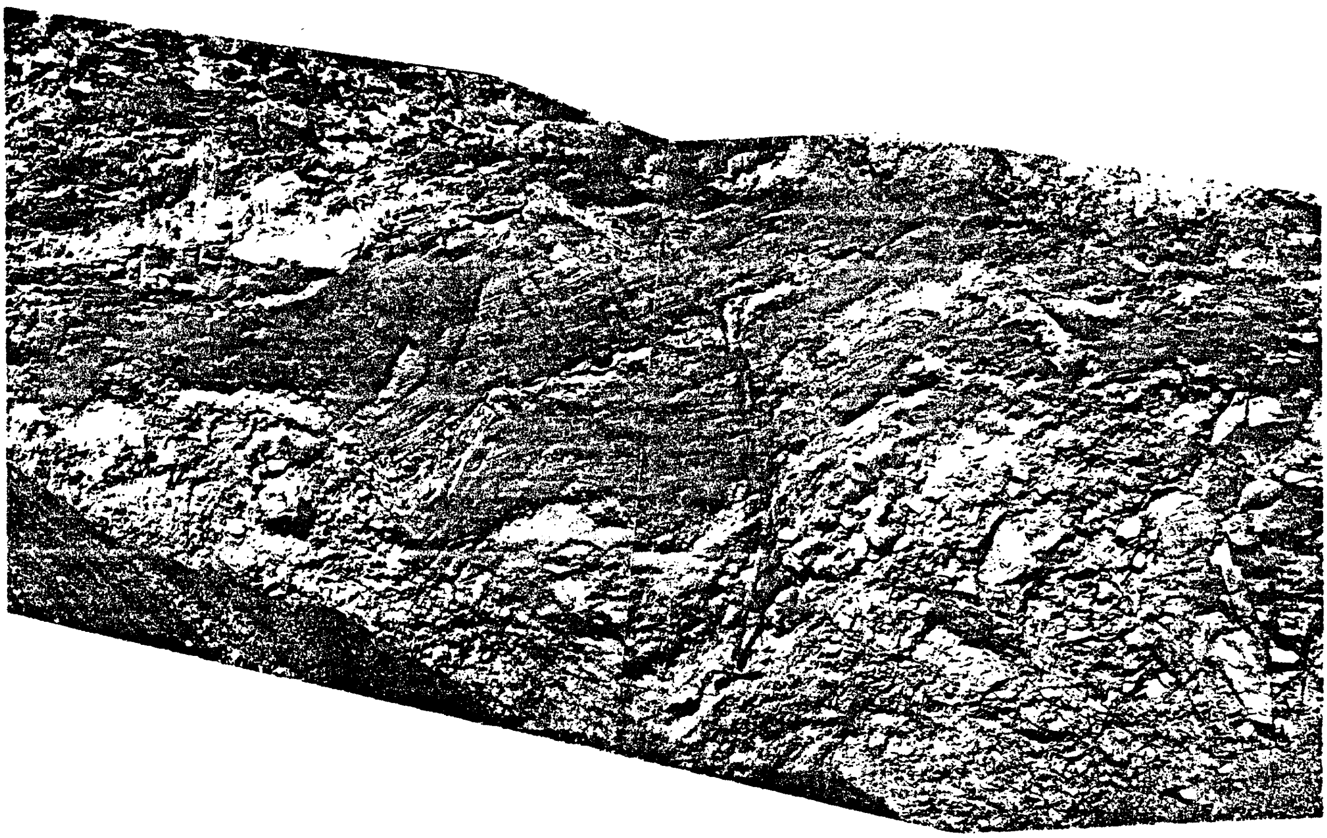

FIGURE 21. -- View of slumped block of stratified sand in trench 6a.

(60 fols)

Age of Faulting

The fault in the central part of Gable Mountain is younger than the Elephant Mountain flow, which is Pliocene in age, but more than 40,000 years old. Only a small patch of the Ringold Formation, which is younger than the basalt, is present on Gable Mountain, and its relationship to the faults is unknown. The fault in the central part of the mountains displaces or terminates the anticlinal axes on the crest of the structure, indicating that the faulting is later than part of the folding. However, the fault dies out on the steeply dipping north limb of the uplift, and bends to conform generally with the strike of the folded basalt flows on the south side of the uplift. These relations, plus the fact that the fault is a relatively low-angle thrust, probably indicate that it was formed at the same time as part of the folding. By analogy with other anticlinal folds in the region the Gable Mountain-Gable Butte anticlines are thought to have been formed at the time the Ringold Formation was being deposited. Thus, the faulting on Gable Mountain probably is Pliocene to early Pleistocene age, and at least older than the glacial-flood events which began more than 100,000 years ago (INQUA, 1965, p. 10-11; and Bretz, 1969, p. 520). The glaciofluvial deposits that overlie the fault are not disturbed in any of the trenches. Several stages of glaciofluvial erosion and deposition are recorded by these gravels, but their maximum age is not known with certainty. The second oldest beds of sand and gravel in trench 6a contain the fossil wood fragments that are older than 40,000 years by carbon-14 dating. This sand and gravel lies on a still older glaciofluvial gravel which lies on the erosional surface scoured by glacial flooding across the fault and the folded basalt flows and interbeds. Therefore, there appears to be no evidence of fault movement within at least the last 40,000 years. The western fault on Gable Mountain seems to be structurally analogous to the fault in the central part of the mountain, and probably had about the same history. The rocks on either side of the western fault have been scoured by glacial floodwater since the fault was formed, but there are no glaciofluvial sediments deposited across it.

Gable Butte

Gable Butte is about 2 miles west of Gable Mountain and is situated on a series of structurally low, breached anticlines. These anticlines were breached by the plucking and scouring action of the glacial floodwaters as they passed over the area. The west-northwest trending anticlinal axes are undulating and sinuous. In the central part of The Butte (fig. 13) is a shallow syncline which is transverse to the other axis of the uplift. Cross-section C-C' (fig. 13) shows the structure to be much simpler than on Gable Mountain. The stratigraphic units present on Gable Butte consist essentially of the same ones as on Gable Mountain -- the Elephant Mountain, Pomona, and upper Priest Rapids flows. The interbeds are not exposed because of the gravel and talus cover.

A fault shown near the west end of Gable Butte in the SE¼NE¼ sec. 14, T. 13 N., R. 25 E. by Jones and Deacon (1966, pl. 4) was investigated by both stratigraphic mapping and bulldozer trenching. The mapping indicated no stratigraphic offset and the bulldozer trench showed the basalt to be continuous and unbroken across the saddle where the fault had been previously mapped. No other evidence of faulting was found in the Gable Butte area.

Horse Heaven Hills and Rattlesnake Hills-Wallula Lineament

General Features

The Horse Heaven Hills and the Rattlesnake Hills-Wallula lineament are topographic features that trend southeast from near Benton City (on the Yakima River) to the west end of the Walla Walla valley (see fig. 4). The structure of this part of the Horse Heaven Hills is a broad, slightly asymmetrical anticline which crosses the Columbia River at Wallula Gap and continues southeastward to blend into the Blue Mountains. The anticline has a sinuous and undulating axis which extends about 30 miles west-northwest from Wallula Gap before turning to a west-southwest direction south of Benton City, and continuing southwestward as a more complicated anticline for about another 45 miles. The Horse Heaven Hills constitute a major drainage divide across southern Washington that is breached only by the Columbia River at Wallula Gap (photograph in fig. 22). Wallula Gap serves as a control for all the ground water moving out of central Washington and for all

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Figure 22 belongs near here.

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the surface-water drainage from the entire upper Columbia River basin -- which includes most of eastern Washington, nearly all of Idaho, all of Montana west of the continental divide, part of southeastern Oregon, and part of Canada. During late Pleistocene glaciations this also was the case, and meltwater from approximately 500 miles of glacier fronts near the Canadian border combined to pass through Wallula Gap. In addition to the flow of this meltwater, the glacially dammed Lake Missoula released tremendous volumes of water eight times (Bretz, 1969, table 2). The water flooded across eastern Washington, creating the channeled scablands and many other associated spectacular fluvial features. The volume was so great that Wallula Gap acted as a constriction to the flow and hydraulically dammed the water in the Pasco Basin up to an elevation of 1,100 to 1,200 feet (Bretz, 1969, p. 518-520) for short durations even though the Gap is about 1 mile wide and 850 feet deep (between present water level and the highest scabland channel).

The Rattlesnake Hills-Wallula lineament, which lies 2 to 8 miles north of the Horse Heaven Hills between Wallula Gap and Benton City, is an alinement of topographic hills that diverges slightly from the trend of the Horse Heaven Hills. The hills along the lineament are folded structural domes of basalt or the faulted and eroded

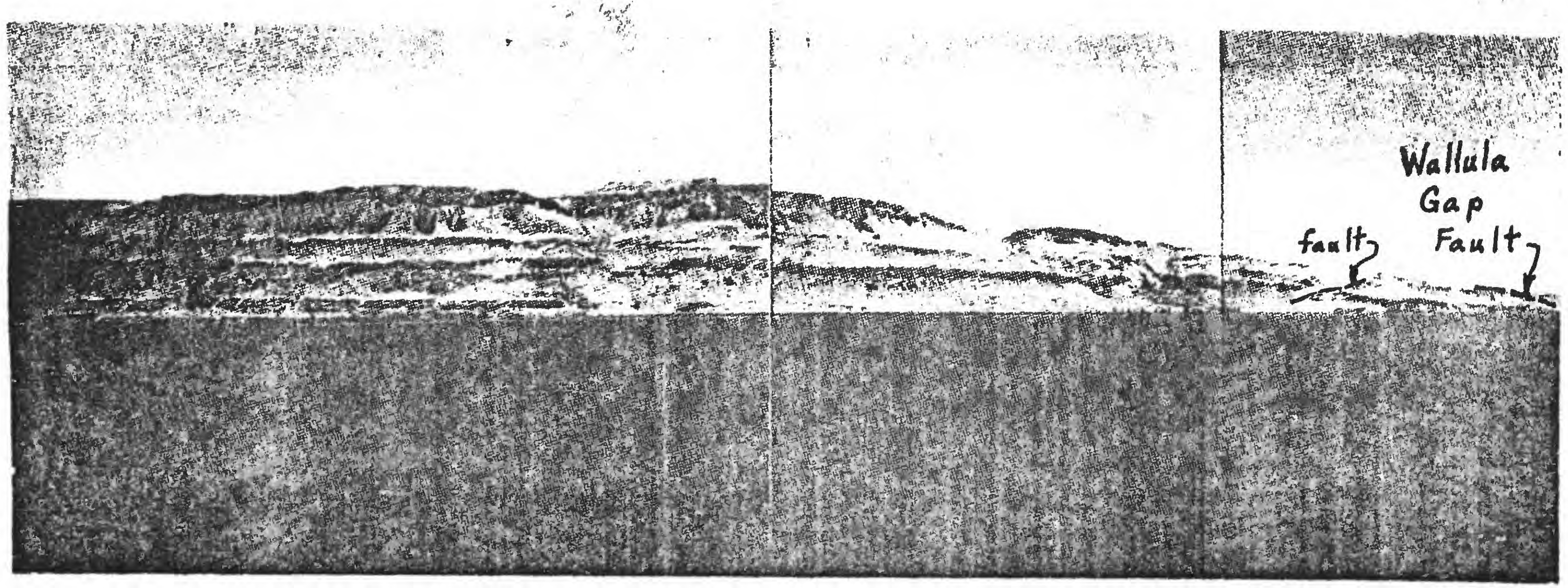

FIGURE 22. -- View of west side of Wallula Gap showing broad Horse Heaven Hills anticline. Highest elevation in center of view is about 750 feet above river level. Yellepit siding is at extreme right. The Pomona flow is along the skyline for most of the distance and a prominent Frenchman Springs flow can be followed across the middle of the bluff to where it dips below river level at Yellepit.

remnants of domes. On the basis of a photogeologic study, J. D. Mollard (in Jones and Deacon, 1966, pls. 2, 3, 11) had inferred that a fault or fault zone extends along the topographic lineament from Wallula Gap to the eastern part of the Rattlesnake Hills. During the present investigation, reconnaissance between Wallula Gap and the Yakima River determined that linear outcrops of basalt breccia occur on or alongside all the domes. The outcrops are interrupted by loess on the domes and by recent alluvial deposits between the domes; however, the alinement of the breccia outcrops is a slightly curved, northwest-oriented trace that is nearly congruent with the alinement of domes. As explained later, this alinement of breccia outcrops is interpreted by the writers as indicating a zone of shearing and faulting, the Rattlesnake-Wallula fault.

Two smaller alinements of hills occur in the Richland-Benton City area. One alinement of six basalt hills, here called the Horn Rapids lineament, diverges at its north end from the Rattlesnake Hills-Wallula lineament by curving from a northwesterly to a north-northwesterly direction. The Horn Rapids lineament, which corresponds partly to a feature shown as an anticline by Jones and Deacon (1966, pl. 3), extends from a basalt hill, nearly buried by gravel, about 2 miles north of Horn Rapids on the Yakima River to a hill directly south of Richland. Except for the northernmost hill, all are along the south side of the Yakima River. Poor exposures and lack of time precluded the determination of the structure of these hills during this investigation.

The other small alinement occurs between the north scarp of the Horse Heaven Hills and the Rattlesnake Hills-Wallula lineament. This consists of Goose Hill, 2 miles southeast of Benton City, and an unnamed hill 6 miles farther southeast, at the inside of the bend in Badger Coulee (fig. 3). From reconnaissance examination, Goose Hill appears to be an anticline with an east-west axis and a faceted end facing southwest. The unnamed hill apparently is a mesa of flat-bedded basalt flows with a faulted northeast side -- the flows here appear to have been offset downward about 300 feet on the north side. This probable fault, not previously described, is called the Badger Coulee fault. It seems to be a wide, sheared zone and probably is the same as the one exposed on the opposite side of Badger Coulee, at the outside of the large bend. At this site (fig. 3 and 4) in NW¼SW¼ sec. 23, T. 8 N., R. 28 E., the stratigraphic offset is at least 200 feet and a poorly exposed breccia zone is over 200 feet wide. The fault cuts vertically across the Pomona and Elephant Mountain flows exposed to the north. No other exposures of breccia were found during the brief reconnaissance along this alinement.

Problems of Interpretation

In the vicinity of Wallula Gap and along the Rattlesnake Hills-Wallula lineament, the interpretation of the geologic structure is more difficult than elsewhere because the key stratigraphic marker, the Roza Member of the Yakima Basalt, is not present and because there is a porphyritic flow, above the Elephant Mountain flow, that was not encountered in the other two areas of detailed mapping (fig. 6 and 13). It is possibly the Ward Gap (?) flow of Schmincke (1964, 1967) or an unnamed flow not previously recognized. In this investigation, chemical analyses (Appendix E) and refractive index determinations (Appendix C and D) were used along with the usual field-identification methods to identify the flows. The Pomona flow, Elephant Mountain flow, and the Priest Rapids Member have distinctive physical and chemical characteristics which lend themselves well to these methods of identification.

The breccias along the Rattlesnake-Wallula lineament have been interpreted variously, by previous investigators, as fault breccias or flow breccias. The characteristics listed in table 1 were useful for distinguishing the different kinds of breccias during this investigation. However, as with stratigraphic determinations of flows, the decisions as to whether any isolated outcrop of breccia represents a fault breccia or a flow breccia (or combinations of volcanic-tectonic breccias) must depend on several criteria, rather than one.

Horse Heaven Hills

Faulting associated with the Horse Heaven Hills has previously been reported at Wallula Gap (Laval, 1957; Jones and Deacon, 1966; Newcomb, 1965) and along the south side of the Walla Walla Basin (Newcomb, 1965). During the present investigation a fault (referred to as the Wallula Gap fault in this report) was mapped along the north flank of the hills near Yellepit, where the stratigraphic units are exposed on both sides of the fault. Elsewhere west of Yellepit, along the north side of the Horse Heaven Hills, the fault zone and the downthrown block on the north side both are buried, and direct evidence of stratigraphic offset is generally lacking. On the basis of a photogeologic study, J. D. Mollard (in Jones and Deacon, 1966, pls. 2, 3) inferred a possible fault, along the base of the Horse Heaven Hills, extending from Wallula Gap northwestward past Benton City on the Yakima River and across the Rattlesnake Hills into Dry Creek Valley. The possible existence of this inferred fault between Wallula Gap and Benton City is suggested by the following reconnaissance observations:

(1) alinements of topographic scarps, (2) the apparent truncation of basalt flows where several transverse valleys cross the trend such as in Zintel Canyon, (3) narrow breccia zones along State Highway 12 in sec. 4, T. 7 N., R. 29 E., and (4) the presence of springs or shallow ground water in valleys crossing this trend, such as in Nine Canyon, Coyote Canyon, and Amon Canyon.

The Wallula Gap fault, shown by Jones and Deacon (1966, pl. 13, photographs 6 and 4), was found to exist in the gully that extends about 1 mile west of the Columbia River at Yellepit. East of the river, the fault zone was traced southeastward in reconnaissance for about 12 miles along the fault-line scarps and sporadic outcrops of fault breccia between Wallula Junction and the foothills southwest of Touchet. East of the river, evidence interpreted to indicate displacement along the Wallula Gap fault can be seen in several of the deeply incised canyons descending from the crest of the Horse Heaven Hills. Along the walls of these canyons the basalt flows on the upthrown (south) side of outcrops of breccia (shown on fig. 4) can be seen to have a gentle north dip adjacent to the fault-line scarp without evidence of sharp monoclinal folding. These flows are low in the stratigraphic section, and the stratigraphically high (Pomona and Elephant Mountain) flows are high above in the upland to the south. On the other hand, immediately north of the scarp and the breccia outcrops, as in ~~the~~ sec. 29 and 30 of T. 7 N., R. 32 E. the stratigraphically high basalt flows (Elephant Mountain and others) are near or not far above the level of the Walla Walla River, apparently indicating hundreds of feet of vertical displacement along the Wallula Gap fault in this area.

Detailed stratigraphic mapping west of the river in the Yellepit area (fig. 23) disclosed that vertical stratigraphic offset of more

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Figure 23 belongs near here

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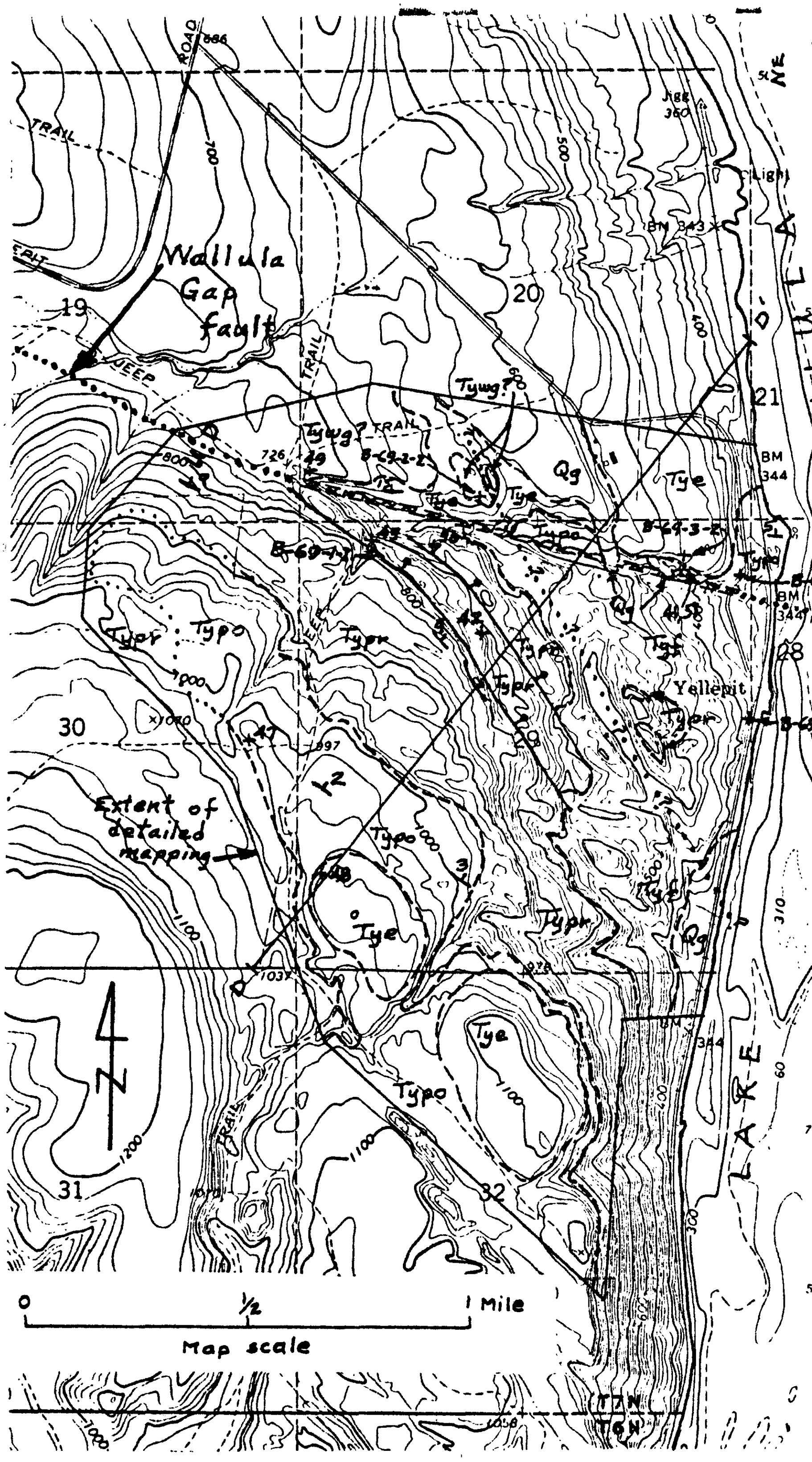
than 200 feet occurs along the Wallula Gap in this area. R. E. Brown (1968, p. 19 and 21) interpreted the structure in the Yellepit area as being part of a monocline because he felt that monoclinal dips could be projected across the fault zone without need for stratigraphic offset (faulting) and because he felt that some basalt flows could be traced continuously westward from the Columbia River for about a mile, then continuously northward across the fault trace that had been shown by previous investigators. However, the data newly obtained during the detailed geologic mapping of this area for this report (fig. 23) support an interpretation of faulting. The Pomona and Elephant Mountain flows crop out along the railroad tracks north of the fault and can be followed only about half a mile westward up the gully. There they are overlain by a basalt flow (possibly the Ward Gap (?) flow of Schmincke 1964, 1967, or a previously unrecognized or undescribed flow) that is younger than the Elephant Mountain, and also are overlain by glaciofluvial gravel bars containing unusually large boulders. At the head of this short, 1-mile gully the previously undescribed youngest basalt is covered by loess, so the continuous outcrops from south to north sides of the gully do not exist.



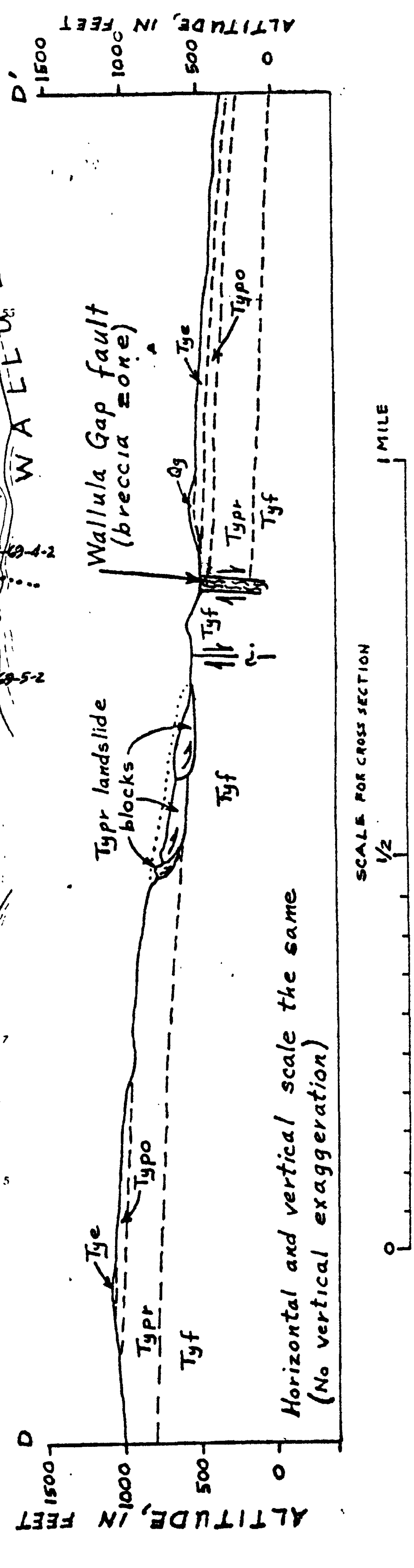


FIGURE 23.--Geologic map and cross section of Yellepit area at Wallula Gap. See figure 5 for explanation of geologic symbols.

South of the fault (which is marked by local outcrops of strongly sheared basalt breccia), the Priest Rapids basalt (Schmincke's Umatilla flow) is exposed in a scarp and can be traced toward the east in several landslide-slump blocks. The Pomona flow is higher up the slope to the south and has been eroded back from the fault zone in this area probably by the glaciofluvial floodwaters. The Pomona and Elephant Mountain flows form subdued "mesas" farther up the slope. Below the Priest Rapids flows, south of the fault, are two of the underlying Frenchman Springs flows which are exposed to river level.

At the railroad siding of Yellepit, just south of the fault, there are several narrow zones of brecciated basalt in the Frenchman Springs Member that trend at an angle of about 15° to the Wallula Gap fault. (There are many more exposed in the first quarter mile south of the fault than farther south, and none north of the fault in the Pomona flow outcrop.) These breccia zones are minor shear zones secondary to the east-west-trending Wallula Gap fault.

About a quarter mile west of Yellepit another minor fault probably secondary to the Wallula Gap fault occurs in a straight valley that trends southeasterly toward the river (fig. 22), although no outcrops of breccia are exposed. Across this valley the top of a prominent Frenchman Springs flow is offset about 50 feet.

The Wallula Gap fault, along the north side of the Horse Heaven Hills east of the Columbia River, seems to be joined by a concealed eastern extension of the Rattlesnake-Wallula fault (described in the next section of this report) just east of Vansycle Canyon. The combined faults then appear to continue southeastward along the south side of the Walla Walla Basin and the north side of the Horse Heaven Hills anticline. Some faults have been mapped by Newcomb (1965, pl. 1) on a projected extension of this fault zone east of Warm Springs Canyon along the south edge of the Walla Walla Basin, but they were not investigated during the course of this study. Newcomb mapped a series of southeasterly trending en echelon faults from Vansycle Canyon to near Milton-Freewater, Oregon. The projected extension of the Wallula Gap fault (of this report) would lie along the north margin of the Horse Heaven Hills anticline and be buried by the Touchet beds. The en echelon structures may be a separate set of faults or they might be faults secondary to the Wallula Gap fault zone.

While following the projection of the Wallula Gap fault zone southeastward in reconnaissance from Vansycle Canyon, a geologically youthful, curved, linear feature that seems to be a ground-surface rupture was observed and briefly investigated in the field (fig. 24).

Figure 24 belongs near here.

Here, the bedrock and the fault zone are mainly concealed by glaciofluvial deposits of the late Pleistocene Touchet beds and by Holocene loess. The linear feature appears to slightly displace the Touchet beds but to be topographically subdued because of slight erosion and subsequent deposition of Holocene loess. Although the nature and origin of the linear feature could not be determined definitely by the brief field examination, its topographic situation does not allow readily for its explanation as being a result of erosion or landsliding, or any other non-tectonic process. The trace of the feature crosses most of the drainage gullies and shallow valleys nearly at right

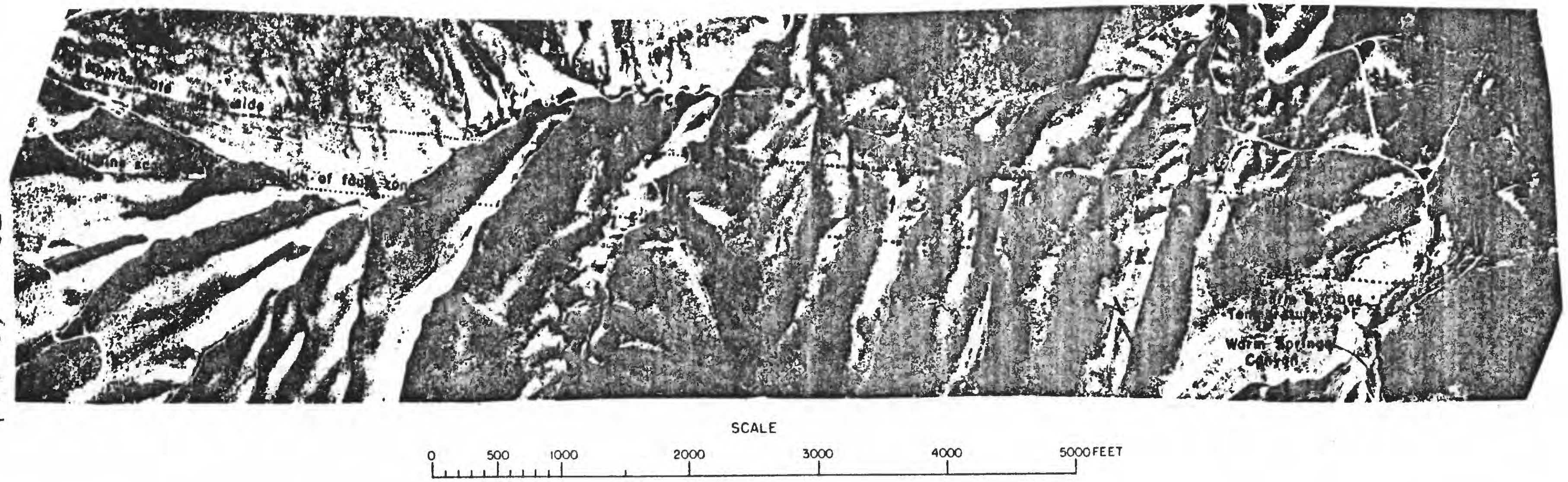


FIGURE 24.--Vertical aerial photograph showing probable Holocene ground-surface rupture near Warm Springs Canyon. The arrows point to the probable rupture which trends along the combined Wallula Gap fault and the Rattlesnake-Wallula fault along the south side of the Walla Walla Basin. The approximate margins of the fault zone are shown by the dotted lines. At most places the fault zone is concealed by the Touchet beds and by loess.

angle and does not have an apparent relation to the pattern of stream channels. The area is one of low topographic relief and low stream gradients, so that rupturing associated with landsliding is not a likely cause. The present subdued vertical relief of the linear feature is a few inches to several feet, with the north side being generally lower than the south. Toward the southeast end of the linear feature (see fig. 24) cattle have used it as a natural trail except where it passes under a fence and the cattle trail swings away to a nearby gate. The feature extends about 1½ miles west-northwest of Warm Springs along a projected segment of the Wallula Gap fault in an area where the bedrock is mainly concealed by the glaciofluvial Touchet beds.

For all these reasons the linear feature appears to be ground-surface rupturing due to relatively recent tectonic fault movement along the Wallula Gap fault. This probable fault movement occurred after the deposition of the Touchet beds, and thus less than 12,000 years ago; however, the movement was not historic (the last 100 years) because Holocene loess lies across the fault.

Rattlesnake Hills-Wallula Lineament

Extending about 35 miles southeastward in a slightly curved line from the northeast end of the Rattlesnake Hills near the SE¼ of T. 11 N., R. 25 E. to near the Wallula Gap on the Columbia River is a line of rounded domical hills, each of which is an upfolded dome of Yakima Basalt.

Much has been written about this Rattlesnake Hills-Wallula topographic lineament, but to date there is no widespread agreement as to the origin of the lineament or the breccias associated with it. On the basis of a study of aerial photographs, Jones and Deacon (1966, pl. 3) inferred the existence of a fault along the lineament and referred to it as part of a "Rattlesnake Mountain-Wallula-Milton-Freewater fault system".

Raisz (1945) indicated that the alinement of hills in the Rattlesnake Hills-Wallula Gap region is a segment of a major lineament that extends a distance of about 400 miles from the Wallowa Mountains in northeastern Oregon to the northwestern corner of the Olympic Mountains in western Washington. Raisz called the major lineament, in its entirety, the Olympic-Wallowa Lineament but was undecided whether it was caused by a deep-seated structure or a fortuitous alinement of topographic features. Jones and Deacon (1966) concluded that the Olympic-Wallowa Lineament is principally an expression of tectonic features on the Columbia Plateau and decided that neither geologic nor seismic evidence supports its extension outside the plateau.

Brown (1968, p. 23) believes there is a lack of evidence to indicate the existence of the Olympic-Wallowa Lineament as a major shallow-seated fault zone at the Wallula Gap. He said (p. 23) "The imposing 1,400-foot high north face, that together with a breccia faced scarp suggests an impressive amount of fault movement, owes at most only a token amount of its height to faulting, and most of its height to a monoclinal fold that largely has been eroded by glacial flood waters and buried". However, during the present investigation, no indication was found of a monocline nor of significant erosion by glacial floodwaters, except for some scouring within one-half mile of Wallula Gap. The structure with dipping beds just west of the mouth of Vansycle Canyon, which appears to be a hogback from a distance (and thus might suggest a monocline), is actually the north half of a faulted dome that probably is related to the line of domes in the Rattlesnake Hills-Wallula lineament. The strikes and dips of the basalt flows on this half dome are, respectively: N. 10° E. and 30°N. at the west end; S. 80° E. and 35° N. at the highest point; and S. 75° E. and 55° N. at the east end. A broad band of breccia on the south side of this half dome is part of the Wallula Gap fault zone.

Laval (1957, p. 138-139) reported that breccia outcrops along the line of domes between the Rattlesnake Hills and Wallula Gap were not traceable for more than 100 feet and trend northeasterly (p. 136). However, he also stated that the fault breccia at the west end of Red Mountain probably continues to the Rattlesnake Hills (northwest across the Yakima River water gap) and appears to extend southeastward along the alinement of domes (p. 137 and 139). He also reported a fault zone 500 feet wide on the west end of the dome east of The Butte, which is along this alinement. The Elephant Mountain flow appears to be stratigraphically offset along the north slope of

Rattlesnake Hills near the center of sec. 24, T. 10 N., R. 26 E., although the brief reconnaissance made by the writers in this area of poor exposures did not disclose outcrops of breccia.

During this investigation, 15 outcrops of breccia were found along the Rattlesnake Hills-Wallula lineament west of the Columbia River. The breccias in these outcrops have many or all of the characteristics of fault breccia as listed in table 1 and are considered as being within a persistent zone of faulting and shearing -- the Rattlesnake-Wallula fault (fig. 4). Most of the fracturing within the breccias has a predominantly northwesterly orientation. The outcrops usually are less than 200 feet in length and are widely spaced along the lineament because of extensive cover by loess in many places. Commonly, the fault breccias do not crop out because the shattered rock has been weathered and eroded more deeply than the adjacent firm basalt. In the study area most of the exposures of fault breccia found are isolated masses that have been locally cemented and made resistant to erosion since they were formed; the cemented parts apparently form only a small part of the entire zone. The continuity of the fault-breccia zone between outcrops can usually be inferred by the presence of subdued topographic features, such as straight scarps, saddles, and gully alinements, along which the breccia is usually concealed by loess deposits between outcrops of firm basalt.

By plotting the axes of the domes and a line connecting the breccia outcrops on a map (fig. 4), it can be seen that the breccia outcrops lie on a slightly curved line, and that the axes of the domes are not all parallel to the alinement of the breccia. For example, the breccia outcrops on Badger Mountain and its satellite domes to the east and west are all principally north of the axes of the domes; the hills in sec. 8, T. 8 N., R. 29 E. (south of Vista Siding) and in sec. 30, T. 8 N., R. 30 E. have their anticlinal axes north of the outcrops of breccia. The hill mainly in sec. 18, T. 7 N., R. 31 E., has an anticlinal axis that lies mainly south of the breccia outcrops and trends about 25° from the direction of alinement of the breccia outcrops. Exposures on this hill provide a good example of the breccia cutting across several different basalt flows with horizontal angular discordance and attendant vertical stratigraphic displacement. This provides evidence that the breccia is not a stratigraphic unit of flow breccia.

At the west end of The Butte, in Finley Quarry, a Frenchman Springs basalt flow is vertically truncated by the fault zone; only a few feet of the fault gouge and breccia are exposed at the north end of the quarry. No basalt is exposed on the north side of the breccia where it is faulted down. However, about half a mile east, at the top of the hill, the stratigraphically much higher, Pomona and Elephant Mountain flows on the part of the dome north of the fault are dipping north about 30° and immediately south of the fault, in juxtaposition, the Priest Rapids flows are flat lying. The large "clastic dikes" in the Finley Quarry reported by Jones and Deacon

(1966, plate 13, photograph 5), Jahns (1967, fig. 11), and R. E. Brown (1968, p. 26) are not Touchet-age clastic dikes, but instead are older sedimentary fillings of joints and fissures that opened up as the blocks tipped slightly northward, probably toward an unsupported fault scarp. The sediments that have filled them appear to be well weathered and stained and cemented with caliche, suggesting that the material is part of the Ringold Formation, and that the fault movement began in Ringold time or earlier.

The eastward extent of the Rattlesnake-Wallula fault is not known with certainty, because it is concealed by recent sediments from the Columbia River southeastward. However, as previously discussed, a southeastward projection of the fault intersects the Wallula Gap fault east of the river just east of Vansycle Canyon several miles east of Wallula Gap.

To summarize the evidence available from the present reconnaissance investigation, the domal uplifts along the Rattlesnake Hills-Wallula lineament are parts of a southeast-trending regional structural alinement that connects the eastern part of the Rattlesnake Hills anticline with the faulted north flank of the southeast-trending part of the Horse Heaven Hills anticline east of the Columbia River. The Rattlesnake-Wallula fault is a zone of shearing with attendant vertical stratigraphic offsets, which is younger than the folded domes, but which is parallel to and almost congruent with the overall Rattlesnake Hills-Wallula lineament of domes. All these features support an interpretation that the Rattlesnake Hills-Wallula lineament and the

Wallula Gap fault and other southeast-trending fault zones along the north flank of the southeastern segment of the Horse Heaven Hills anticline are parts of a linear, deep-seated, regional structural feature that extends from the eastern part of the Rattlesnake Hills southeastward to at least the Milton-Freewater area in Oregon. The major stage of faulting and shearing that produced the basalt fault breccias along this regional structural feature probably occurred during the deposition of the Ringold Formation as shown by the occurrence of probable Ringold sediments in fissures at Finley Quarry. This stage of faulting is much older than the late Pleistocene glacial-flood events as shown by the fact that at places, such as east of Red Mountain and at the mouth of Badger Coulee, the Touchet beds lie across the Rattlesnake-Wallula fault. Near Yellepit, glaciofluvial gravels lie undisturbed across the Wallula Gap fault.

However, east of Vansycle Canyon the Touchet beds lying across the Wallula Gap fault appear to have been ruptured possibly by relatively recent (but prehistoric) minor fault movement. At most other places the exposures are not adequate to determine definitely whether or not there have been minor episodes of faulting during or since the last episodes of glacial-flood deposition. The reported ground rupturing during the Milton-Freewater earthquake (1936), and the geologically young, probable rupturing along the Wallula Gap fault east of Vansycle Canyon suggest that these parts of the linear regional structural feature may still be tectonically active.

OCCURRENCE OF MICROEARTHQUAKES

by

A. M. Pitt

The U.S. Geological Survey has operated a network of short-period seismograph stations within and around the Hanford Reservation of the Atomic Energy Commission since March 23, 1969. The data from 7 vertical seismometers (6 before August 9, 1969) are telemetered to Menlo Park, California, where they are recorded on film. Earthquake epicenters are determined by computer.

The network was established to determine the level of microearthquake activity in the vicinity of the Hanford Reservation. Within the network, microearthquakes with magnitudes as low as 0 can be located when the background noise level is low. At 200 km, the practical limit at which epicenters can be determined by the network, microearthquakes of magnitude 2 or greater can usually be located. The accuracy of epicenter determination is greatest for microearthquakes occurring within the network and decreases rapidly as the distance of the microearthquake from the network increases.

Epicenters for 166 seismic events were located for the period from March 23 to December 31, 1969 (figure 25 and table 2). Approximately

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Figure 25 is at the end of the report.

one-fourth of these are thought to be explosions rather than microearthquakes. Most of the explosions occurred 80 km west, 200 km north, and between 80 and 150 km east of the center of the network. Approximately 105 microearthquakes were located within 75 km of the center of the network, as were some explosions (table 2 and fig. 4).

Table 2 belongs near here.

Most of the microearthquakes in the immediate vicinity of the Hanford Reservation occurred in two separate zones. One very restricted zone, near the center of the triangle formed by stations B, E, and G, produced over 230 detectable events, 36 of which have been located. These microearthquakes generally have the most precisely determined epicenters of any in the region because of the advantageous distribution of stations. Activity in this zone began in May, increased to a peak in August, and continued at a reduced level until the end of 1969. The second active zone near the Hanford Reservation extends from a point between stations O and E in a northwest direction to the vicinity of station S. Approximately 500 detectable microearthquakes occurred in this area with most of them concentrated at the two ends of the zone. Seismic activity fluctuated along this zone, reaching peaks at the east end in April and November, the west end in May, and the center in October. A small amount of additional seismic activity on the Hanford Reservation occurred along a north-trending zone between stations M and G. All of the microearthquakes detected on or near the Hanford Reservation had Richter magnitudes below 2.0, which is generally below the threshold of (noninstrumental) human perception.

(794 fols)

TABLE 2. -- Located microearthquakes and other seismic events in south-central Washington, March 23-December 31, 1969.

Note: The numbers in this table are reproduced from the computer output where values for origin time, latitude, longitude, and magnitude are computed to two decimal places. These values have no meaning beyond one decimal place. Relative evaluation is based upon the quality of P and S arrivals, the distribution of stations, the number of stations available, and the P-arrival time residuals at the stations used to determine the epicenter. The letters indicate the following maximum probable epicentral errors: A-1 km, B-3 km, C-5 km, D-10 km, E-15 km, F-25 km. *Origin time is given in Greenwich Mean Time (GMT).*

-	Date	Origin Time(GMT) hr min	sec	Latitude ° '	Longitude ° '	Richter Magnitude	Relative Evaluation	Remarks
1	0324	2232	19.54	46.34.82	118.55.43	-0.01	D	explosion
2	25	1911	52.75	47.41.64	120.19.18	1.29	F	
3	26	2232	7.29	47. 7.78	118.58.52	1.45	E	
4	27	4 3	1.71	48.16.81	119.16.21	1.98	F	
5	27	2240	47.42	46.36.10	119.10.08	-0.14	D	explosion?
6	31	1715	18.90	46.39.19	119. 6.29	0.89	C	
7	0401	311	17.15	47.59.51	118.50.49	1.96	F	
8	01	419	54.75	46.39.27	119. 6.64	0.83	D	
9	01	20 3	49.38	46.33.38	118.52.63	0.20	E	[illegible]
10	05	15 5	50.79	47.10.42	119.43.39	1.30	F	
11	06	1515	57.94	46.59.42	119.11.41	0.75	F	
12	08	226	4.28	47. 2.85	119. 3.54	0.96	F	
13	08	649	17.29	47.10.44	119.59.07	1.15	F	
14	08	1115	54.38	47. 1.52	119.34.88	1.01	E	
15	10	112	11.87	46.42.40	117.46.80	1.83	E	[illegible]
16	11	035	28.98	46.59.08	119. 1.87	0.99	E	
17	12	321	45.04	47. 8.10	119. 2.78	1.10	E	
18	12	1110	29.27	46.59.12	120.27.37	1.39	C	
19	19	546	2.18	45.47.35	119.41.54	2.10	E	
20	20	219	14.13	48.17.50	118.53.59	2.56	F	
21	21	1416	34.34	47.11.94	119.43.23	1.85	E	
22	22	2059	50.60	46.36.06	119. 8.84	1.16	D	
23	24	143	0.91	46.43.67	117.41.96	2.05	E	[illegible]
24	24	12 3	56.67	47. 9.51	119.41.35	1.29	E	
25	24	12 9	34.78	47.10.92	119.41.83	1.28	E	
26	29	15 8	0.77	46.36.13	119. 9.45	0.09	D	
27	30	2033	1.71	47. 9.90	119.36.81	1.21	F	
28	30	2143	58.23	46.39.80	119. 6.16	0.57	D	
29	0501	052	36.39	48. 7.84	118.44.84	2.06	F	[illegible]
30	01	1652	3.15	46.59.10	119.49.20	1.29	E	
31	02	1836	59.79	46.35.93	119. 9.75	0.01	D	
32	04	925	3.82	47. 9.80	119.41.23	1.35	E	
33	05	1835	4.60	46.36.14	119.10.01	0.05	D	
34	05	1926	25.34	48.11.13	118.49.79	1.94	F	explosion
35	06	034	0.83	46.38.44	117.43.94	1.83	F	explosion

TABLE 2. -- continued

	Date	Origin Time (GMT) hr min	sec	Latitude	Longitude	Richter Magnitude	Relative Evaluation	Remarks
36	07	548	37.29	46.49.53	119.20.79	0.52	E	
37	07	2036	20.22	46.25.66	119.37.51	0.21	E	
38	08	1556	21.31	46.36.23	119. 9.65	0.23	D	
39	09	19 6	8.24	47.41.00	119.47.64	2.34	E	
40	10	1441	12.55	46.41.54	117.26.11	2.00	F	explosion
41	10	1937	21.61	46.49.83	119.35.46	1.75	C	
42	10	1955	34.92	46.49.55	119.36.83	-0.08	D	
43	11	350	11.13	48.11.04	118.58.70	2.23	F	explosion?
44	14	2321	47.53	47. 1.73	119.34.41	1.05	E	
45	0517	0 1	28.53	46.39.13	119. 7.77	0.16	D	
46	18	145	41.60	46.49.33	119.38.81	-0.10	D	
47	18	3 0	32.66	46.51.15	119.45.09	-0.14	D	
48	19	1859	24.52	47.49.60	118. 3.40	2.77	E	
49	22	148	1.94	46.44.74	117.33.67	2.09	F	explosion
50	22	933	22.64	46.44.34	119.20.94	0.22	D	
51	23	945	42.31	46.51.57	119.46.22	0.09	D	
52	0601	1216	44.96	46.25.30	119.16.74	0.15	B	
53	03	413	3.06	46.42.79	119.35.47	-0.07	C	
54	06	926	43.24	47. 7.61	119. 5.15	1.06	E	
55	08	9 3	58.91	46.49.22	119.23.62	0.57	D	
56	08	1236	12.26	46.25.24	119.16.17	0.84	B	
57	10	1450	27.30	46.25.37	119.16.42	1.37	B	
58	15	453	36.40	46.25.28	119.16.13	0.27	B	
59	23	5 7	45.03	46.56.55	119.42.25	1.01	D	
60	27	241	20.33	46.25.49	119.16.27	0.72	B	
61	0701	622	38.18	46.25.57	119.16.75	0.54	B	
62	02	2333	21.39	46.35.95	117.55.09	1.73	F	explosion
63	11	2340	45.09	46.35.39	117.58.54	1.76	F	explosion
64	15	430	1.00	46.25.15	119.15.50	1.25	B	
65	15	2354	10.52	46.25.37	119.16.28	1.05	B	
66	18	431	39.68	46.47.45	120.24.95	1.86	D	
67	23	255	14.57	47. 3.01	119.14.62	1.24	E	
68	23	257	38.46	47. 2.68	119.14.71	1.16	E	
69	24	7 8	10.68	47.41.77	120.22.23	1.83	F	
70	24	1013	36.35	46.25.25	119.16.27	0.92	B	
71	28	1555	1.23	47. 3.76	119.12.91	1.23	E	
72	29	1429	24.01	46.19.28	119.32.43	0.12	E	
73	31	614	22.14	46.25.43	119.17.01	1.79	B	
74	31	21 9	45.65	46.25.46	119.16.46	1.25	B	
75	0801	1036	52.83	46.25.33	119.16.29	0.77	B	
76	01	1248	20.17	46.25.58	119.16.25	1.25	B	
77	01	1558	23.83	47.47.17	119.35.68	2.51	F	
78	02	3 4	14.71	47.11.92	117.22.54	2.80	E	
79	02	2141	39.13	46.25.38	119.16.62	1.02	B	
80	04	1531	8.44	47.47.44	119.56.95	2.60	F	
81	05	2339	24.85	46.35.55	118. 3.72	1.88	E	explosion
82	07	1918	27.65	47. 0.65	119.22.54	0.85	E	
83	08	7 5	48.07	47.36.19	119. 8.90	2.03	F	
84	08	17 4	50.62	47.46.41	119.33.96	2.45	F	
85	08	2240	16.99	46.15.06	118. 0.57	1.62	F	
86	11	550	15.64	46.25.49	119.15.73	0.96	B	
87	11	1336	34.92	46.42.32	119.55.46	1.46	D	
88	12	1418	3.09	46.25.47	119.16.06	0.63	B	
89	14	1631	45.27	47.41.26	119.33.90	2.69	E	
90	15	1141	53.75	46.25.47	119.16.31	0.50	B	

TABLE 2. -- continued

	Date	Origin Time (GMT) hr min	sec	Latitude	Longitude	Richter Magnitude	Relative Evaluation	Remarks
91	15	1623	4.07	46.25.17	119.16.73	1.51	B	
92	18	1439	18.64	46.48.92	119.28.97	0.33	C	
93	18	1850	57.30	46.25.32	119.16.12	0.53	B	
94	21	148	30.04	46.25.70	119.16.95	0.56	B	
95	22	844	1.46	46.25.37	119.14.91	1.09	B	
96	31	252	28.09	46.25.58	119.16.75	0.22	B	
97	31	1118	7.74	46.25.74	119.16.87	1.59	B	
98	31	1119	31.32	46.25.44	119.17.24	1.48	B	
99	31	1627	32.91	46.16.83	120.53.29	2.14	F	
100	0901	035	47.99	46.25.41	119.16.85	0.47	B	
101	01	2027	43.19	46.25.41	119.16.85	0.20	B	
102	02	0034	10.30	46.25.19	119.16.15	1.07	B	
103	02	1241	52.47	46.25.92	119.16.81	1.21	B	
104	02	2150	30.71	46.41.42	119.35.73	1.61	A	21km deep
105	04	1817	11.31	46.25.53	119.15.53	1.09	B	
106	0906	2228	34.86	46.25.55	119.15.55	1.15	B	
107	10	1214	58.18	46.57.65	119.37.10	1.64	D	
108	12	021	52.36	46.35.40	118.22.84	1.77	E	explosion
109	13	830	46.00	47.47.89	119.23.57	2.37	E	
110	21	1021	21.06	46.25.92	119.16.78	0.47	B	
111	26	1436	6.26	46.42.65	119.34.28	0.04	C	
112	27	1 2	45.42	46.38.30	118. 1.53	2.12	E	explosion
113	1002	059	1.63	46.58.69	118.18.12	1.88	F	
114	02	214	27.50	46.26.01	119.16.35	0.99	B	
115	02	3 0	47.75	46.42.31	119.21.44	0.35	C	
116	02	637	45.20	46.25.87	119.16.35	0.22	B	
117	03	156	50.98	46.41.18	119.14.45	0.61	C	
118	06	1158	5.96	46.25.82	119.17.69	0.62	B	
119	06	12 4	1.30	46.25.59	119.17.55	0.61	B	
120	06	2230	18.09	46.52.55	120.34.59	1.87	E	explosion
121	14	724	57.71	46.40.97	119.15.94	0.79	B	
122	15	834	58.31	47.19.12	122. 5.86	3.12	F	
123	15	1952	58.35	46.49.70	119. 2.90	0.76	D	
124	15	2046	6.80	46.40.79	117.41.67	1.58	F	explosion
125	16	1530	45.90	46.48.91	120.29.83	1.62	E	explosion
126	16	1913	43.33	46.41.47	119.14.52	1.17	B	
127	17	1810	36.40	46.48.78	120.28.62	1.68	E	explosion
128	17	20 8	0.13	46.42.45	117.50.74	1.51	F	explosion
129	19	730	22.37	46.15.55	118.17.27	1.91	D	
130	20	2329	3.17	46.41.84	117.48.46	1.28	E	explosion
131	21	2048	16.11	47.38.51	118.14.14	1.99	F	
132	21	2235	38.72	46.31.56	118. 6.26	1.42	E	explosion
133	23	1741	10.14	46.52.52	120.32.14	1.82	E	explosion
134	23	2348	43.49	46.49.37	120.29.70	1.72	D	explosion
135	24	447	5.24	46.41.12	119.14.01	0.25	C	
136	28	039	46.44	46.50.25	120.30.00	1.90	E	explosion
137	28	416	57.28	46.44.12	119.19.33	0.21	D	
138	28	513	3.17	46.44.32	119.19.86	0.86	C	
139	29	034	36.37	46.50.06	120.31.43	2.04	E	explosion
140	30	1616	35.83	46.48.74	120.31.75	1.89	E	explosion
141	1101	0 0	23.50	46.51.13	120.29.14	1.91	D	explosion
142	01	112	46.82	46.51.89	120.30.62	2.23	E	explosion
143	03	2246	23.52	46.43.54	119.15.68	0.40	D	
144	05	041	27.22	47. 5.92	118. 3.37	2.51	F	
145	05	1940	44.77	46.50.18	120.29.82	1.84	D	explosion

TABLE 2. -- continued

	Date	Origin Time (GMT) hr min	sec	Latitude	Longitude	Richter Magnitude	Relative Evaluation	Remarks
146	06	021	30.04	46.48.60	120.29.86	1.81	D	explosion
147	08	1140	20.70	46.43.23	119. 6.28	1.22	C	
148	08	12 2	0.60	46.43.50	119. 6.82	0.53	C	
149	10	056	15.41	46.33.22	119.39.00	0.94	C	
150	10	814	16.49	46.46.20	119. 3.91	0.84	D	
151	10	852	18.52	46.43.48	119. 6.85	0.73	C	
152	10	1859	8.10	46.43.59	119. 7.08	1.34	C	
153	10	19 3	27.03	46.43.87	119. 7.02	0.93	C	
154	18	1817	38.04	46.36.70	119.38.21	0.31	D	
155	21	423	57.88	46.30.42	119.37.36	0.07	D	
156	21	1631	56.04	46.37.29	118.53.06		D	
157	23	5 8	31.68	46.42.44	119.22.40	1.18	C	
158	26	1216	25.96	46.32.30	119.38.69	-0.03	D	
159	26	2231	8.73	46.25.60	119.15.65	0.55	B	
160	30	240	41.85	46.38.03	118.43.18	1.22	D	
161	1201	23 1	44.75	46. 8.95	118.35.26	1.41	E	
162	03	2018	48.69	46.46.42	119.45.66	1.49	D	
163	13	1755	57.02	46.40.62	119.13.29	0.58	D	
164	18	2137	59.96	46.41.02	119.13.77	0.35	D	
165	18	2257	39.70	46.41.08	119.13.17	0.93	B	
166	30	141	57.00	46.40.58	119.12.85	0.50	C	

Most of the microearthquakes near the Hanford Reservation appear to be less than 10 km deep although it has generally not been possible to accurately determine their depths. Accurate determination of the depth of focus of an earthquake requires a distribution of stations around the epicenter with at least one station having an epicentral distance less than the depth of focus of the earthquake. These criteria generally are not met for the Hanford events. A few of the better recorded microearthquakes in the main zones of activity appear to have occurred at depths of 5 km or less. Significantly deeper events were microearthquake number 104 with a well determined depth of 21 km and microearthquake number 149 with a depth of around 11 km, both of which occurred along the north-trending zone of minor activity between stations M and G. Other microearthquakes located along this zone were too poorly recorded to make accurate depth determination possible.

A few of the seismic events on or near the Hanford Reservation are explosions rather than microearthquakes, but the great majority within or close to the network have dilatational first motion at one or more stations which precludes their being explosions. Landslides would probably not be mistaken for earthquakes because landslides have a distinctive signal on a seismogram. There is no apparent association between irrigation activity and the seismic activity of the region, and there are microearthquakes occurring on the Hanford Reservation where no irrigation takes place.

The results of the U.S. Geological Survey seismic study indicate that the Hanford Reservation is in a region of microearthquake activity which is moderate by comparison with the microearthquake activity of seismically active regions of California and Nevada where similar monitoring studies have been made. The loci of activity have fluctuated between several zones during the recording period. A longer recording period will better define the areas of microearthquake activity in the Hanford region and the fluctuations of activity with time.

RECOMMENDATIONS

An improved understanding of the geologic and seismologic characteristics of the Hanford Reservation could be obtained by additional interrelated investigations on the reservation and in adjacent areas. These investigations are summarized as follows:

1. Monitoring of microearthquakes with an augmented network of seismographs. An additional seven seismographs, positioned on the basis of data gained from the existing network, would allow more precise determination of epicenters and their relations to geologic structures, and would provide a means for better definitions of areas and depths of activity and better assessments of fluctuations of activity with time. One of the seismographs should be portable for movement to areas of continuing microearthquake activity, such as along the Columbia River north of Richland, to determine precisely the focal depths of the microearthquakes.
2. Geophysical profiling of the subsurface geologic structure in the Hanford Reservation. Profiling of selected areas by seismic-reflection methods may allow a better definition of the bedrock geologic structure concealed beneath the recent dune sand and glaciofluvial deposits of the Pasco Basin,

and would provide a more definitive basis for analyzing the significance of areas of continuing microearthquake activity on and adjacent to the Hanford Reservation. The interpretation of the geophysical investigations would benefit by test drilling and coring at selected localities along lines of seismic profiling to calibrate the geophysical data and to provide definitive bases for correlation of various stratigraphic units to interpret their structures.

3. Detailed geologic mapping, trenching, and stratigraphic study of selected areas. Additional detailed geologic investigations along the Wallula Gap fault in the vicinity of Warm Springs east of the Columbia River are recommended to confirm the nature of the geologically young probable fault rupture. Further investigation of the geologic structure of the vicinity of Milton-Freewater, where ground rupturing occurred in 1936, also would be desirable to determine the relationship of the rupturing to the regional lineament that apparently extends from this region to the Rattlesnake Hills, and to provide a better basis for assessing its current tectonic state.

4. Detailed, systematic, geologic mapping of the Hanford Reservation and its environs on topographic base maps, with emphasis on engineering geology and geologic structure. Such mapping would provide a considerably improved understanding of the basic geologic framework of the area and would provide areawide integrated data that are desirable for engineering judgments concerned with the evaluation and operation of existing facilities and the construction of new facilities.

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APPENDIX A

Driller's Logs of test holes drilled on Smyrna Bench

Material	Thickness (feet)	Depth (feet)
16/26-33R1.[1] USGS test hole 1. Altitude about 1,250 ft. Drilled by R. J. Strasser Co., 1969.		
Loess --	14½	14½
Caliche --------------------------------------	6½	21
Fanglomerate ---------------------------------	11	32
Sand ---	3	35
Fanglomerate with caliche cement ------------	4	39
Fanglomerate without caliche (some caving) hard and soft streaks --------------------	144	183
Hole abandoned - fanglomerate erodes easily causing enlarged hole and poor or no return of cuttings.		
16/26-33R2. USGS test hole 2. Altitude about 1,240 ft. Drilled by R. J. Strasser Co., 1969.		
Loess soil ---------------------------------	14	14
Caliche ------------------------------------	9	23
Fanglomerate -------------------------------	85	108
Fanglomerate (slower drilling) -------------	24	132
Fanglomerate, red sand ---------------------	9	141
Fanglomerate, no sand ----------------------	8	149
Fanglomerate, sand -------------------------	13	162
Fanglomerate, little sand ------------------	38	200
Fanglomerate, sand -------------------------	72	272
Fanglomerate, clay with small amount of sand	110	382
Fanglomerate, mostly sand, very small amount of gravel --------------------------------	8	390
Fanglomerate, slight increase in gravel ----	88	478
Fanglomerate, sandy brown clay -------------	6	484
Fanglomerate, fine gravel with hard brown sand -----------------------------------	61	545

(continued)

1/Locations of the test holes are shown on fig. 6.

Driller's logs--continued

Material	Thickness (feet)	Depth (feet)
16/26-33R2--Continued		
Fanglomerate, blue-gray clay, with sand and gravel, some caliche	19	564
Fanglomerate, large boulder, dark gray to black	9	573
Open space	1½	574½
Fanglomerate, basalt pebbles with green poorly formed opal and harder white opal	5½	580
Fanglomerate, rounded basalt pebbles	60	640
Fanglomerate, coarse gravel with caliche pebbles and assorted basalt, cemented with hard chocolate brown silty sand and layers of gray clay and buff clay	12	652
Fanglomerate, coarse basaltic gravel, with pebbles or layers of dark brown and green opal, brown sand, clay, and caliche	6	658
Fanglomerate, coarse basaltic gravel with pieces of dark brown clay that has slickensides on most pieces	6	664
Fanglomerate, caliche layers, with dark brown silty sand, gray clay, and some basalt pebbles	24	686
Fanglomerate, dark brown silty sand with large basalt pebbles	17	703
Fanglomerate, dark brown silty sand with fine gravel	68	771
Fanglomerate, caliche, opal, and basalt pebbles, little sand and clay nodules	50	821
Fanglomerate, basaltic gravel with clay matrix	11	832

Drilling stopped because of water in the hole washing and caving the sand and gravel, thus creating a hole-diameter enlargement which stopped adequate circulation.

Driller's logs--Continued

Material	Thickness (feet)	Depth (feet)
15/26-3D1. USGS test hole 3. Altitude 1,200 ft. Drilled by R. J. Strasser Co., 1969.		
Loess --	10	10
Fanglomerate and caliche ------------------	53	63
Fanglomerate ------------------------------	160	223
Fanglomerate, boulders and gray clay -------	35	258
Basalt, weathered and clay -----------------	24	282
Basalt(?), broken, vesicular, with gray opal ------------------------------------	24	306
Fanglomerate, with some brown sand ---------	49	355
Fanglomerate, with brown and gray clay, caliche ---------------------------------	76	431
Fanglomerate, dense, brown sandy clay ------	72	503
Fanglomerate, with hard clay ---------------	43	546
Fanglomerate, with soft clay ---------------	9	555
Fanglomerate, dense ------------------------	17	572
Fanglomerate, with soft clay ---------------	14	586
Fanglomerate, brown sand and clay ----------	19	605
Clay, light tan, hard clay and fine gravel - (water-bearing at 638 ft., static level 546 ft.)	37	642
Stopped drilling because of caving and hole enlargement above bit.		
16/26-33J1. USGS test hole 4. Altitude about 1,200 ft. Drilled by R. J. Strasser Co., 1969.		
Pebbles, brown, with caliche ---------------	10	10
Pebbles, brown, with basalt chips ----------	10	20
Basalt, chips with pebbles, harder ---------	6	26
Clay, brown with basalt pebbles ------------	23	49
Basalt gravels with caliche ----------------	28	77
Basalt chips, large and brown clay ---------	32	109
Clay, brown, soft --------------------------	29	138
Clay, chocolate brown with pebbles ---------	44	182
Clay, tan with cemented gravels ------------	55	237
Basalt, pebbles, tan, clay -----------------	38	275
Basalt pebbles, cemented fine brown sand ---	26	301

(continued)

Driller's logs--Continued

Material	Thickness (feet)	Depth (feet)
16/26-33J1--Continued		
Gravel, fine, cemented, with tan clay	24	325
Gravel, fine, cemented	8	333
Gravel, fine, cemented, chocolate brown	12	345
Gravel, fine, cemented, with brown clay	14	359
Clay, soft brown	3	362
Gravel, cemented with chocolate brown clay	39	401
Sand, coarse, with mica	4	405
Sand, coarse, fine gravel, with mica	60	465
Gravel, fine, with soapstone and mica	35	500
Gravel, white, coarse sand, gray clay, and soapstone	7	507
Basalt, broken with pebble gravel	5	514
Basalt, chips, with white gravels, brown clay	5	519
Basalt, chips, with white gravel	45	564
Basalt, with white, gray and brown gravels	7	571
Basalt, large chips, with gravel and clay balls	5	576
Basalt, with white gravels	14	590
Basalt, with fine gravels and clay balls	12	602
Basalt, with white gravels and clay balls	8	610
Basalt, with white gravels	8	618
Sand, coarse, with mica, fine gravels, and conglomerate	2	620

Stopped drilling because water in interbed (618-620 ft) washed sand and gravel into hole, diluting drilling foam.

15/26-3E1. USGS test hole 5. Altitude about 1,220 ft. Drilled by R. J. Strasser Co., 1969.

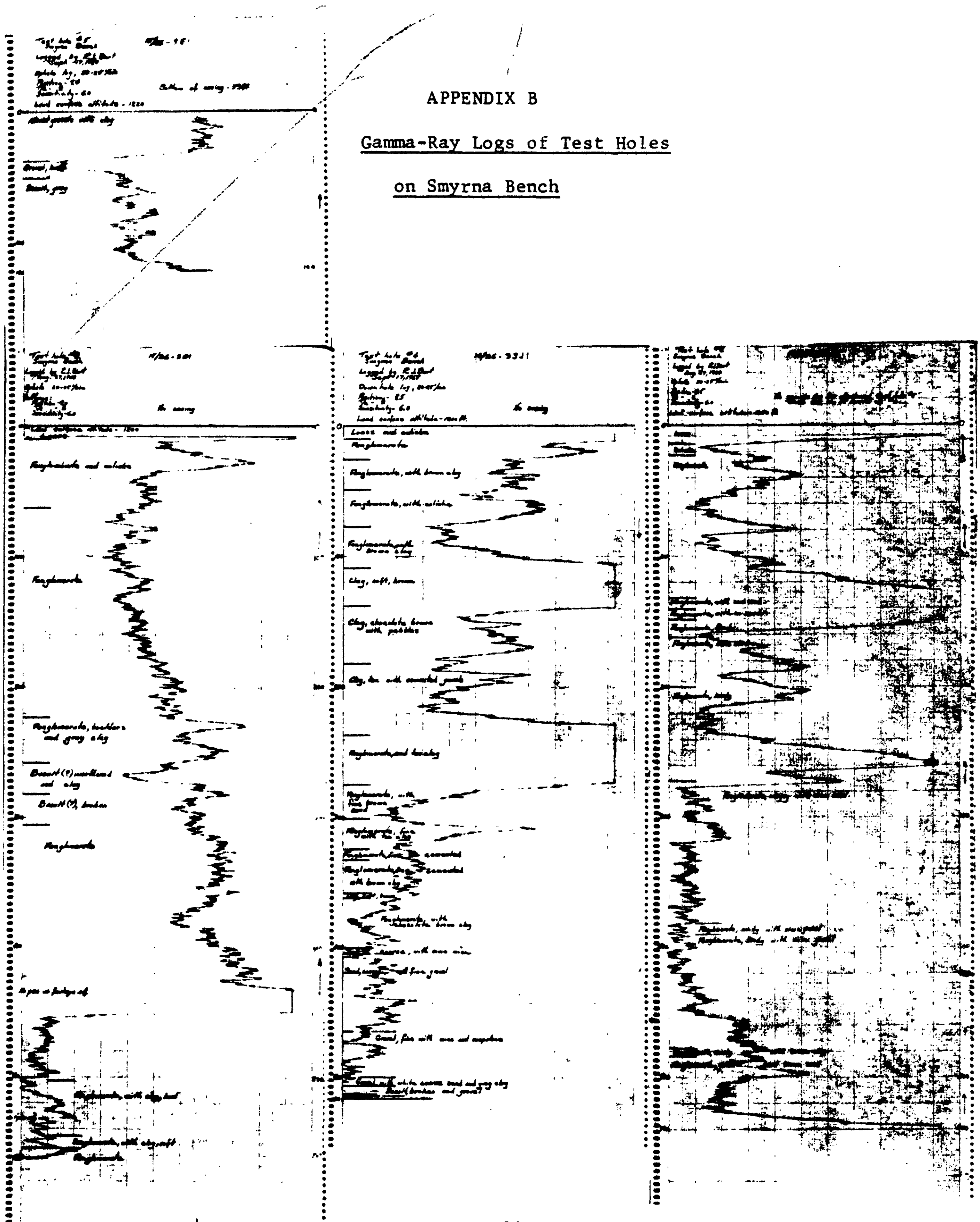
Material	Thickness (feet)	Depth (feet)
Gravel, alluvial, with clay	38	38
Gravel, loose	13	51
Basalt, gray	73	124

Stopped drilling because of broken air hammer.

APPENDIX B

<u>Gamma-Ray Logs of Test Holes</u>

<u>on Smyrna Bench</u>



APPENDIX C

Refractive Indexes of Basalt Samples[1/]

Obtained by measuring indexes of three glass beads made by fusing crushed basalt

Sample no.	Flow and/or location	Refractive index Bead no. 1	2	3	Average
1	Roza basalt, type area	1.6040	1.6035	1.6010	1.6028
2	Pomona basalt (Holmgren), type section (S Selah Butte)	1.595	--	1.599	--
3	Pomona basalt-Gable Mountain quarry	1.591	1.592	1.592	1.592
4	Elephant Mountain-Gable Mountain quarry	--	--	--	--
5	Priest Rapids basalt (Umatilla flow)-Gable Mountain quarry	1.597	1.598	1.598	1.598
6	Priest Rapids basalt, flow #3-Gable Mountain quarry	1.592	1.592	1.595	1.593
7	Priest Rapids basalt, 2 mi SW of Sulphur Lake	1.6130	1.6150	1.6140	1.6140
8	Roza basalt, 1 mi S of Connell	1.599	1.599	1.600	1.599
9	Valley-fill basalt, Devils Canyon	1.6115	1.6070	1.6055	1.6080
10	Frenchman Springs basalt-Devils Canyon	1.594	1.595	1.598	1.596
11	Roza basalt, Devils Canyon	1.6030	1.6040	1.6030	1.6033
12	Valley-fill basalt, 6 mi NE of Hooper	1.5990	1.6020	1.6010	1.6007
13	Roza basalt, 2 mi E of Benge	1.6120	1.6050	1.6070	1.6080
14	Priest Rapids(?) basalt, 3 mi S of Keystone	1.6130	1.6130	1.6150	1.6137
15	Roza basalt spatter, U. S. 10, W of Ritzville	1.6125	1.6170	1.6130	1.6142
16	Roza vesicular basalt with cinders, 11 mi W of Ritzville	1.6090	1.6030	1.6110	1.6077
17	Roza basalt cinder, 11 mi W of Ritzville	1.6205	1.6185	1.6190	1.6193

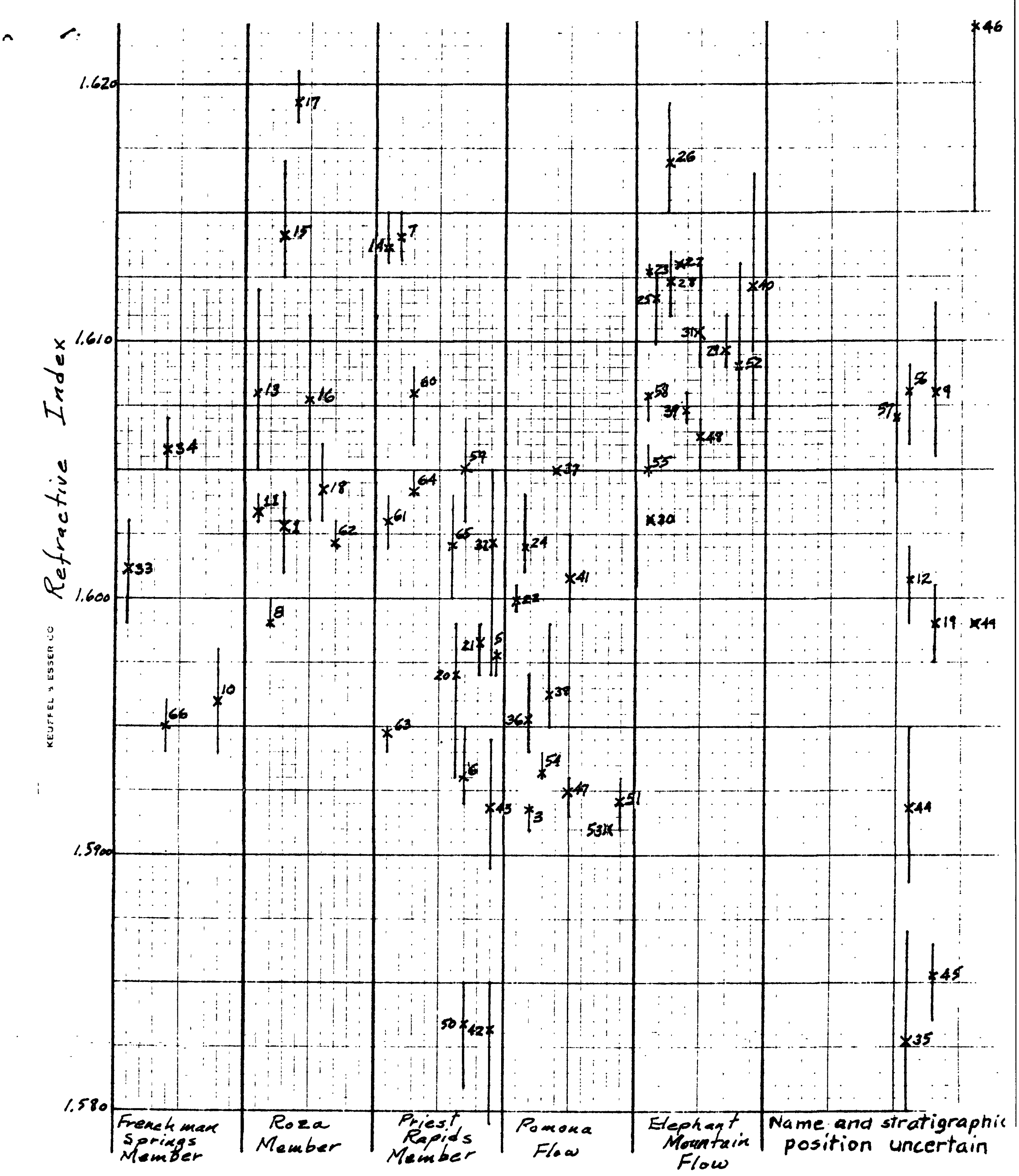
[1/] Analyses by Dr. Bates McKee and Wasant Pongsapich, University of Washington.

Refractive Indexes of Basalt Samples -- Continued

Sample no.	Flow and/or location	Refractive index: Bead no. 1	2	3	Average
18	Roza basalt, massive over cinder rubble	1.6035	1.6030	1.6060	1.6042
19	Othello-Warden valley-fill basalt, at county line	1.5990	1.5975	1.6005	1.5990
20	Priest Rapids (flow #3) basalt, 13/26-23 NE	1.5930	1.5990	1.5990	1.5970
21	Priest Rapids (flow #4) basalt, 13/26-23 NE	1.5990	1.5970	1.5990	1.5983
22	Pomona basalt, 13/26-23 NE	1.5995	1.6005	1.5995	1.5998
23	Elephant Mountain basalt, 13/26-23 NE	1.6125	1.6130	1.6125	1.6127
24	Pomona basalt (above scarp) 13/27-19 NE	1.6010	1.6010	1.6040	1.6020
25	Elephant Mountain basalt (above scarp), 13/27-19 NE	1.6120	1.6100	1.6130	1.6117
26	Elephant Mountain basalt (above scarp), 13/27-19 NE	1.6185	1.6150	1.6170	1.6168
27	Elephant Mountain basalt (below scarp, trench 3) 13/27-19 NW	1.6130	1.6130	1.6130	1.6130
28	Elephant Mountain basalt (W end, trench 3), 13/27-19 NW	1.6110	1.6135	1.6125	1.6127
29	Elephant Mountain basalt(?), lg. col. Gable Mountain, 13/27-19 NW	1.6110	1.6090	1.6090	1.6097
30	Elephant Mountain flow, entabl., 13/27-19 NWNW	1.6030	1.6030	1.6030	1.6030
31	Elephant Mountain flow, upper entab., 13/26-23 NE	1.6090	1.6090	1.6130	1.6103
32	Priest Rapids basalt, Wallula Jct., 7/31-27 SE NE NW	1.6045	1.6050	1.5970	1.6022
33	Roza(?) or Frenchman(?) Springs basalt, Wallula Jct., 7/31-27 SE NE NW	1.5990	1.6015	1.6030	1.6012
34	Frenchman Springs basalt, Wallula Jct. 7/31-27 SE NE NW	1.6050	1.6070	1.6050	1.6057

Sample no.	Flow and/or location	Refractive index			
		Bead no.			Average
		1	2	3	
35	Elephant Mountain(?) basalt, Nine Canyon, 7/30-9 SESW	1.5870	1.5800	1.5810	1.5827
36	Pomona aa, basalt with xenolith(?), Eltopia	1.5940	1.5950	1.5970	1.5953
37	Pomona flow entab., Eltopia	1.6050	1.6050	1.6050	1.6050
38	Pomona flow unit, column, Eltopia	1.5950	1.5990	1.5950	1.5963
39	Elephant Mountain basalt, Corfu	1.6070	1.6080	1.6070	1.6073
40	Ward Gap(?) basalt, Corfu	1.6130	1.6070	1.6165	1.6122
41	Pomona basalt, Yellepit	1.5995	1.6025	1.6000	1.6007
42	Priest Rapids basalt, Yellepit 7/31-29 SW NE NW	1.5795	1.5850	1.5850	1.5832
43	Priest Rapids basalt, Yellepit 7/31-29 NW NW NW	1.5945	1.5915	1.5895	1.5918
44	Top porphyritic flow, Zanger Jct. 7/32-32 SE SW NW	1.5890	1.5910	1.5950	1.5917
45	Pomona(?) basalt, Zanger Jct. 7/32-32 SE SW NW	1.5835	1.5865	1.5860	1.5853
46	Top porphyritic flow, Zanger Jct. 7/32-31 SE SW NE	1.6150	1.6230	1.6285	1.6222
47	Pomona basalt, Wallula Quad. 7/31-30 SE SE NE	1.5930	1.5930	1.5915	1.5925
48	Elephant Mountain basalt, Wallula Quad. 7/31-29 NW SW SW	1.6070	1.6070	1.6050	1.6063
49	Top. porphyritic flow, Wallula Quad. 7/31-20 SW SW SW	1.5990	1.5990	1.5990	1.5990
50	Priest Rapids basalt(?), Wallula Quad 7/31-29 NW NE NW	1.5810	1.5845	1.5850	1.5835

Sample no.	Flow and/or location	Refractive index			
		Bead no.			Average
		1	2	3	
51	Pomona basalt, Wallula Quad. 7/31-29 NW NE NE	1.5930	1.5910	1.5930	1.5923
52	Elephant Mountain basalt, Gable Mountain trench 4 (N end)	1.6050	1.6130	1.6090	1.6090
53	Pomona basalt, Gable Mountain trench 4 (S end)	1.5910	1.5910	1.5910	1.5910
54	Pomona basalt, Gable Butte	1.593	1.593	1.594	1.593
55	Elephant Mountain basalt Gable Butte	1.604	1.605	1.606	1.605
56	Ward Gap(?) basalt Gable Mountain	1.606	1.608	1.609	1.608
57	Ward Gap(?) basalt Sentinel Gap Quarry	1.605	1.607	1.608	1.607
58	Elephant Mountain basalt Gable Butte	1.607	1.608	1.608	1.608
59	Priest Rapids basalt, flow #3, Sentinel Gap	1.603	1.606	1.607	1.605
60	Priest Rapids basalt, flow #2, Sentinel Gap	1.606	1.608	1.609	1.608
61	Priest Rapids basalt, flow #1, Sentinel Gap	1.602	1.603	1.604	1.603
62	Roza basalt, Sentinel Gap	1.602	1.602	1.603	1.602
63	Priest Rapids basalt, flow #1,Vernita	1.594	1.595	1.595	1.595
64	Priest Rapids basalt, flow #2, Vernita	1.604	1.604	1.605	1.604
65	Priest Rapids basalt, flow #3, Vernita	1.600	1.601	1.604	1.602



APPENDIX D

Plot of refractive indexes of basalt, by stratigraphic units

APPENDIX E

Chemical and spectrographic analyses of samples from the Yakima Basalt, Benton County, Washington

Sample locations

Lab. No.	Field No.	Sample name and description	Location
M108789W	B-69-1-2	Basalt - Priest Rapids (Umatilla) flow	NW¼NW¼ sec. 29, T. 7 N., R. 31 E.
M108790W	B-69-2-2	do. Ward Gap(?) flow	SE¼SW¼ sec. 20, T. 7 N., R. 31 E.
M103791W	B-69-3-2	do. Elephant Mt. flow	NE¼NE¼ sec. 29, T. 7 N., R. 31 E.
M108792W	B-69-4-2	do. Pomona flow	Do.
M108793W	B-69-5-2	do. ✓Frenchman Springs Member	SW¼NE¼ sec. 29, T. 7 N., R. 31 E.
M108794W	B-69-6-2	do. Elephant Mt. flow	SE¼NW¼ sec. 19, T. 13 N., R. 27 E.
M108795W	B-69-7-2	do. Pomona flow	Do.
M108796W	B-69-8-2	do. Elephant Mt. flow	SW¼SW¼ sec. 19, T. 13 N., R. 27 E.
M108797W	B-69-9-2	do. do.	Do.
M108798W	B-69-10-2	do. Pomona flow	Do.

Chemical and spectrographic analyses -- Continued

Chemical analyses, oxides of principal constituents, in weight percent[1/]

Lab. No.	M108 789W	M108 790W	M108 791W	M108 792W	M108 793W	M108 794W	M108 795W	M108 796W	M108 797W	M108 798W
Field No.	B-69-1-2	B-69-2-2	B-69-3-2	B-69-4-2	B-69-5-2	B-69-6-2	B-69-7-2	B-69-8-2	B-69-9-2	B-69-10-2
SiO_2	53.8	48.5	51.2	51.7	50.7	50.9	51.2	50.4	50.4	50.5
Al_2O_3	14.5	13.4	13.6	15.0	13.5	13.6	14.9	13.2	13.3	14.8
Fe_2O_3	2.3	6.7	3.0	2.7	2.8	5.6	3.4	2.8	2.7	3.1
FeO	9.7	7.4	10.0	6.9	10.5	7.3	6.5	11.5	11.4	6.7
MgO	2.9	4.5	4.0	5.6	4.2	4.0	5.9	4.1	3.9	6.0
CaO	6.2	9.2	8.6	10.5	8.1	8.3	10.7	8.0	8.1	11.2
Na_2O	3.1	2.3	2.3	2.3	2.6	2.3	2.3	2.6	2.6	2.3
K_2O	2.5	.93	1.2	.62	1.3	1.2	.62	1.3	1.2	.55
H_2O-	.47	1.4	1.1	2.1	.96	1.4	1.6	1.1	1.1	1.5
H_2O+	.38	.60	.50	.50	.74	.60	.70	.20	.90	1.0
TiO_2	2.5	3.5	2.9	1.6	3.0	3.6	1.6	3.6	3.6	1.6

1/ Chemical analyses by P. L. Elmore, J. Glenn, J. Kelsey, L. Artis, and H. Smith, U. S. Geological Survey. Methods used were those described in USGS Bull. 1144-A (supplemented by atomic absorption techniques) and USGS Bull. 1084-G.

Chemical and spectrographic analyses -- Continued

Chemical analyses, oxides of principal constituents, in weight percent -- Continued

Lab. No.	M108 789W	M108 790W	M108 791W	M108 792W	M108 793W	M108 794W	M108 795W	M108 796W	M108 797W	M108 798W
Field No.	B-69-1-2	B-69-2-2	B-69-3-2	B-69-4-2	B-69-5-2	B-69-6-2	B-69-7-2	B-69-8-2	B-69-9-2	B-69-10-2
P_2O_5	.88	.91	.60	.26	.62	.62	.27	.60	.61	.27
MnO	.20	.21	.18	.15	.21	.19	.15	.17	.18	.16
CO_2	.06	.10	$<.05$	$<.05$	$<.05$	$<.05$	.05	$<.05$	.05	.30
Sum	99	100	99	100	99	100	100	100	100	100
Total Fe as FeO	11.8	13.5	12.7	9.3	13.1	12.3	9.6	14.1	13.8	9.5

Chemical and spectrographic analyses -- Continued

Chemical analyses, oxides recalculated to 100 percent, water free basis (both H_2O- and H_2O+ removed)

Lab. No.	M108 789W	M108 790W	M108 791W	M108 792W	M108 793W	M108 794W	M108 795W	M108 796W	M108 797W	M108 798W
Field No.	B-69-1-2	B-69-2-2	B-69-3-2	B-69-4-2	B-69-5-2	B-69-6-2	B-69-7-2	B-69-8-2	B-69-9-2	B-69-10-2
SiO_2	54.9	49.5	52.7	53.2	52.2	51.2	52.2	50.9	51.4	51.5
Al_2O_3	14.8	13.7	14.0	15.4	13.9	13.9	13.2	13.3	13.6	15.1
Fe_2O_3	2.4	6.8	3.1	2.8	2.9	5.7	3.5	2.8	2.7	3.2
FeO	9.9	7.5	10.3	7.1	10.8	7.4	6.6	11.6	11.6	6.8
MgO	2.9	4.6	4.1	5.8	4.3	4.1	6.0	4.1	4.0	6.1
CaO	6.3	9.4	8.8	10.8	8.3	8.5	10.9	8.1	8.3	11.4
Na_2O	3.2	2.3	2.4	2.4	2.7	2.3	2.3	2.6	2.6	2.3
K_2O	2.5	.95	1.2	.64	1.3	1.2	.63	1.3	1.2	.56
TiO_2	2.5	3.6	3.0	1.6	3.1	3.7	1.6	3.6	3.7	1.6
P_2O_5	.90	.93	.62	.27	.64	.63	.28	.61	.62	.28
MnO	.20	.21	.18	.15	.22	.19	.15	.17	.18	.16
CO_2	.06	.10	$<$.05	$<$.05	$<$.05	$<$.05	$<$.05	$<$.05	.05	.31

Spectrographic analysis for minor elements, in parts per million. [1]

Field No.	B-69-1-2	B-69-2-2	B-69-3-2	B-69-4-2	B-69-5-2	B-69-6-2	B-69-7-2	B-69-8-2	B-69-9-2	B-69-10-2
Lab. No.	M108 789W	M108 790W	M108 791W	M108 792W	M108 793W	M108 794W	M108 795W	M108 796W	M108 797W	M108 798W
Mn	1,300	1,500	1,500	1,100	1,500	1,300	1,200	1,400	1,500	1,100
Ba	1,500	900	650	280	650	900	360	550	550	400
Co	28	38	42	40	38	43	40	40	42	42
Cr	N2	170	28	170	50	34	170	32	32	170
Cu	18	44	32	55	42	34	50	32	34	60
Ga	20	22	26	16	22	26	20	20	26	22
Ni	N2	30	20	60	20	20	46	18	20	50
Sc	40	45	40	45	45	45	60	50	45	60
Sr	300	300	300	280	500	380	270	270	300	360
V	210	400	440	400	550	600	380	500	480	400
Y	70	80	70	40	50	80	40	50	80	40
Yb	5	7	5	3	5	6	3	5	6	4
Zr	450	320	280	160	200	280	150	260	280	170

The above results have an overall accuracy of ±15 percent except that they are less accurate near the limits of detection. N = not detected, at limit of detection, or at value shown.

1/ Spectrographic analyses by R. E. Mays, U.S. Geological Survey