A STUDY OF REPORTED FAULTING
IN THE PASCO BASIN

Randall E. Brown

JANUARY 9, 1968

Water and Land Resources Section
Environmental and Radiological Sciences Department

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INTRODUCTION

Faults are spectacular geologic features, and faulting is a dramatic event in geology, because of their effects upon geologic structures and man-made facilities. Faults, because of offset, pose problems in stratigraphic correlation and structural studies. Fault movement is considered by many authorities to be the major cause of earthquakes, on the other hand faulting sometimes is the result of earthquakes. Numerous faults accordingly suggest that an area has been tectonically (deformationally) unstable, may be a record of the past earthquake history, and may infer an earthquake potential. Fault movement also produces unsound rock susceptible to sliding, hence abundant landslides may suggest fault movement and related earthquakes.

The field study here reported follows the work of Jones and Deacon⁽¹⁾. They recommended that certain key areas identified in photogeologic studies by J. D. Mollard be examined to determine if faults were present, if they were significant in the region's development and if they reflected its seismic history. The study was requested by Douglas-United Nuclear, Inc. and was conducted between October 1966 and June 1967. Isolated field data many times can be interpreted in several ways, however. This study accordingly relates the field data to the total geologic picture of the Pasco Basin. New regional and interrelated concepts were developed as the result of the field work. The new concepts better explain many aspects of the total geological picture and the Basin's development than do previous concepts, based largely on reconnaissance study or detailed study in limited areas only.

Consequently the field work was continued to better verify those concepts. The new concepts also help to answer questions relating to the earthquake potential of the region, hence they and the evidence for them are discussed in some detail.

SUMMARY AND CONCLUSIONS

No evidence was found in available literature or in the field that faults in the Pasco Basin are more than secondary, relatively superficial features of limited extent. That conclusion parallels those of similarly detailed studies elsewhere in the region dating to more than 60 years ago. Preliminary or reconnaissance studies of portions of south-central Washington, even following the early detailed work, commonly suggested major faults. Detailed studies in the same areas repeatedly have emphasized the unimportance and oftentimes the actual absence of such faults.

Offset on faults normally ranges from a few tens of feet to a few hundred feet, the maximum is about 500 feet. In all cases faulting is secondary in importance to folding and developed simultaneously with that slow folding or possibly in the later stages of folding. Fault offset occurred where stresses were not relieved solely by folding. The termination of faults indicates that excessive stresses were local in nature or that they were easier dissipated by processes other than faulting at most places.

Movement well may have been and probably was by slow slippage unaccompanied by earthquakes. No evidence suggests that fault movement occurred abruptly, particularly in Recent time, although uplift and folding appear to be continuing. The faults need not, and probably do not, indicate earthquake activity.

The Olympic-Wallowa lineament does not exist as a through-trending, near-surface structural or tectonic feature in the Wallula Gap to Rattlesnake Hills segment. Deep-seated structures may exist along the so-called lineament but

their nature, orientation, continuity, whether they are in fact related in any way to the so-called lineament, and whether they are of any tectonic significance can yet only be inferred.

Landslides so far studied appear to have formed in two main periods, neither necessarily related to earthquakes nor to faults or fault movement. The older period is believed to be during the repeated flooding of the Pasco Basin by glacial flood and meltwaters from about 20,000 to 10,000 years ago. Scattered, obviously more recent landslides are in some cases clearly attributable to irrigation and in some cases probably to periods of excessive precipitation. Most landslides formed where clay-rich beds are present, commonly where dips are steep. The Altithermal period of higher temperatures and less precipitation than earlier or later, from 8,000 to 4,000 years ago, may prove to be a time of little sliding. Some slide-like areas proved to be merely areas of complex geologic structure. The evidence of what some persons consider earthquake signs accordingly is reduced.

Some of the clastic dikes in the late Pleistocene and early Recent glacio-fluvial deposits (the Touchet beds and associated Pasco gravels) and associated rocks may in part reflect very shallow-seated (near-surface) earthquakes of local origin and extent. Such earthquakes could have occurred because of and during repeated rapid loading and unloading of the Pasco Basin by glacial flood waters.

Geologic evidence, commonly related to earthquakes in other regions, is not equally indicative of earthquakes in the Pasco Basin. Earthquakes of significance may have occurred, but positive evidence for them is sparse or absent.

DISCUSSION

PREVIOUS WORK IN THE REGION

In an early reconnaissance across central Washington, I. C. Russell⁽²⁾ in 1893 described the bold, east-west ridges of the region as fault blocks, analagous to the tilted lava blocks he had earlier seen in southern Oregon and northwestern Nevada. G. O. Smith^(3,4,5) vigorously contested that interpretation and insisted that the ridges were anticlinal and owed nothing of their straightness and abruptness to faulting. Smith's arguments were well documented and the excellent exposures he described make it surprising that a more recent author (Hodge⁽⁶⁾ 1931) returned to the fault-block theory. Other workers, as summarized, unanimously have subscribed to the anticlinal theory. Faults are recognized, particularly where folding is relatively intense, and are generally agreed to be the result of stresses that could not be relieved solely by folding. In all cases, faulting is recognized as subordinate to folding.

Newcomb and Strand⁽⁷⁾ in their work in the Pasco Basin (1953) concluded that:

"the folding or bending of the rocks was by far the dominant type of strain. Shearing and faulting is seen to be confined largely to the steeply dipping parts of the asymmetrical folds. In reality the basalt rock seems to have deformed by bending as far as possible and to have sheared only where further displacement was required by the stresses. The steeply dipping limb of the Rattlesnake Mountain anticline contains shear displacements parallel to the lava flow bedding."

No faults were mapped by them in either the Corral Canyon or Richland quadrangles. Those quadrangles include the northwest-southeast-trending portion of the Rattlesnake Hills, the Benton City to Yakima Horn section of the Yakima River, and the north face of the Horse Heaven Hills for more than half the distance from Benton City to Prosser. Newcomb⁽⁸⁾ in an earlier (1948) unpublished report inferred, however, that faulting was prominent along the

Horse Heaven escarpment south of Kennewick, but cited no evidence for it. In neither case was an adequate stratigraphic sequence of the basalt flows available from which offset could be measured.

Foxworthy⁽⁹⁾, in the Ahtanum Valley southwest of Yakima, concluded in 1962 that most of the deformation resulted from folding, even where tight folding is present as in Union Gap:

"No evidence of major displacement by faulting was found in the area, although some minor displacement, which may have been caused by several small thrust faults, is present."

Waters⁽¹⁰⁾ in 1955 stated that:

"No faults of consequence were noted in the Yakima East quadrangle, though many breaks with 10-20 feet displacement were found."

Of the most prominent fault he encountered he says:

"The steep fault on the north limb of the Selah Butte fold is large enough to show on Plate 1 (note: also shown by Jones and Deacon on their Plate 3) but it is less than 5 miles long, and its maximum dip-slip displacement is probably less than 250 feet."

Mackin⁽¹¹⁾ in 1955 at Priest Rapids identified a thrust fault that he named the Umtanum fault (shown by Jones and Deacon on Plate 3). Mackin believed it was formed where the Umtanum anticline, there displaying locally vertical to overturned basalt flows, was thrust northward. Mackin did not determine the offset along the fault and traced it only for a few miles. Mackin identified another local fault trending northwestward beneath the Priest Rapids Dam and estimated about 30 feet of dip-slip displacement on it. Two other comparable faults were identified beneath the left abutment of the dam. Beneath Wanapum Dam he identified a probable reverse fault with about 100 feet of vertical offset.

Hogenson⁽¹²⁾ in 1964 in the Umatilla Basin recognized that deformation in the Horse Heaven Hills and southward was dominantly, "by folding or warping . . . and associated fracturing and minor faulting." Farther south, in the Blue Mountains, he identified more numerous faults with evidently greater displacement, a conclusion substantiated by Hampton and Brown⁽¹³⁾ in the Upper Grande Ronde River Basin. There they reported major faults on which visible offset ranges up to 3,000 and 4,000 feet, and with abundant faults with visible offset ranging from 100 to 400 or 500 feet.

Newcomb^(14,15) in 1951 mapped a group of faults in the Wallula Gap area and eastward into the Walla Walla Basin. He determined the apparent direction of movement on the faults, but did not determine offset because no stratigraphic section was described there. He also mapped several large and continuous faults east of Walla Walla and traced them for several tens of miles. Those northeast-trending faults are related to the Blue Mountain uplift and may have considerable offset, similar to those noted by Hogenson in the Umatilla Basin region. Actual offset was not determined because of the lack of a described stratigraphic section.

Grolier⁽¹⁶⁾ and Grolier and Bingham⁽¹⁷⁾ in 1965 described the Columbia Basin Irrigation Project in considerable detail and defined the structure and stratigraphy far more completely than ever before. Grolier discussed the Saddle Mountains at length. He pointed out that deformation is greater there than in the Project area farther east where it is quite low in intensity. Still greater uplift and folding occurred west of the Columbia River along the Saddle Mountain axis. Diery⁽¹⁸⁾, however, by reference to a carefully established stratigraphic section found positive evidence of a maximum of only 200 feet of fault offset where Manastash Ridge, the western continuation of the Saddle Mountains, is cut by the Yakima Canyon. No faults were identified by Grolier

and Bingham in the east end of Saddle Mountains. Several faults with significant offset were examined in the central part, and possibly significant faulting occurred at the west end.

Grolier described three faults, in the central part of the Saddle Mountains, that extend westward from the Corfu bench and pass into an overfold.

He says:

"The main fault (the Saddle Mountains fault). . . is south of the Smyrna Bench. The vertical displacement along this fault reaches a maximum of several hundred feet. . ."

He continues:

"On its northern side, the Smyrna Bench also is bounded by a high-angle fault of small displacement (approximately 25 feet)."

At the west end of the Smyrna Bench:

"The overfold has yielded along a thrust zone about 200 feet wide, and the entire section of Yakima Basalt flows that overlie the Vantage sandstone has been thrust northward about 500 feet over the sedimentary rocks of the Ringold Formation, which underlies the Smyrna Bench."

The fault, according to Grolier and Bingham, terminates against a small normal fault at the extreme west end of the bench. Eastward it dies out in less than half a mile. The 500 feet of fault offset evidently is taken up in the sedimentary rocks, including the Ringold Formation, without offset farther east. The fault accordingly is a shallow-seated local feature, as also illustrated by Grolier and Bingham on their Cross Section C-C.

At the west end of the Saddle Mountains data are inexact and the Saddle Mountains' fault, if even existent, is not exposed for more than 11 miles according to Grolier and Bingham. Grolier describes a steep escarpment at the west end of the mountains that truncates the north limb of the eastward-trending syncline that forms the north part of the Saddle Mountains. He states it may be a fault scarp or a sharp flexure. It may represent a northward thrust, or only lateral truncation of an overfold by meltwater streams in late

Pleistocene times. The amount of offset and the full significance of a fault, if even there present, is not determinable.

West of the Columbia River at Sentinel Gap, Laval⁽¹⁹⁾ mapped an east-west-trending thrust fault lying on the north limb of an overturned anticline on the north escarpment of the Saddle Mountains. Presumably the fault is part of the structure that forms the escarpment noted by Grolier, but it was not traced beneath the Columbia River alluvium and bench gravels. Offset is not known. Elsewhere in the region he found suggestive evidence of 100 feet of offset or commonly less on faults. Grolier also identified a thrust fault in the Lind Coulee region where the Roza Member flow was thrust over brown tuffaceous sand of the Ringold Formation. This is the locality illustrated by Jones and Deacon as Plate 16.

Farther east, Waldron^(20,21), Gard⁽²²⁾, and Trimble^(23,24), among others, reported fractures and minor folds trending in northeast, northwest and westerly directions. Tension joints and other minor fractures occur almost everywhere, and small faults and sheared and brecciated zones occur in a few places. Those sheared and brecciated zones range in width from a few inches to 30 feet or more, but rarely do they show measurable vertical displacement. In many sites they bottom at the flow base. Most of those should be classed as joints, perhaps of regional nature. Where they are sufficiently open or where they contain breccia that is easily eroded, they sometimes develop striking lineations followed by stream channels. The Palouse River canyon from Palouse Falls to the Snake River is one such example where abrupt changes in the river's course were controlled by the rectilinear joint system.

AREAS STUDIED

Two main areas were identified by Mollard, Jones and Deacon as requiring detailed field study. These were (1) the area on the north side of the Saddle

Mountains adjacent to the Saddle Mountains fault, and (2) the area south of the Hanford Project, extending west-northwest from Wallula Gap for about 50 miles to and beyond the southwest corner of the Hanford Project.

Area 1 is characterized by a fault that Jones and Deacon indicate extends east-west along the north face of the Saddle Mountains from a short distance west of the Columbia River at Beverly to near the eastern end of the Saddle Mountains. Grolier and Bingham, however, are nowhere that certain even of its existence, hence its continuity and importance. Landslides are locally abundant along the steep north face of the mountains between Taunton and Corfu and are thought to be evidence of earthquake activity, perhaps as recent as 1918. Elsewhere along the fault zone Mollard and Jones and Deacon saw what appeared to be recent movement in a graben, and recent stream offset in Crab Creek Valley.

Area 2 lies along a zone that was variously described by Raisz⁽²⁵⁾, Wise⁽²⁶⁾, Watkins⁽²⁷⁾, Cantwell⁽²⁸⁾, and Skehan⁽²⁹⁾ and named the "Olympic-Wallowa Lineament." Skehan interprets the so-called lineament as a major tectonic zone of narrow width that extends for 420 miles from the Wallowa Mountains to the Straits of Juan de Fuca. His identification was based on: (1) the topographic alignment described by Raisz, (2) deep crustal resistivity changes reported by Cantwell in the general region, (3) the occurrence of earthquakes at three sites along that long line, (4) folds and faults mapped by others at intervals along the line and roughly parallel to it, and (5) large amounts of breccia between Wallula Gap and the area southwest of Kennewick. Suggested truncated spurs at Wallula Gap and numerous landslides at various nearby sites suggest recent movement and a possible potential for earthquakes centering there. More recent workers, including McKee⁽³⁰⁾ and Yates⁽³¹⁾, consider that a broad transition zone between different basement rock types fortuitously lies somewhere near Skehan's lineament.

Field work was concentrated between Wallula Gap and the crest of the Rattlesnake Hills near the Rattlesnake No. 1 Well of the Standard Oil Company of California, at the southwest corner of the Hanford Project. Reasons for that concentration were as follows:

1. Past field study of the stratigraphy of the Wallula Gap to Rattlesnake Hills area and the reported fault occurrences there is less detailed than in the Saddle Mountains, where several studies were made and the reports published or made available.
2. The Wallula Gap - Rattlesnake Hills portion of the so-called lineament is critical to connect the northwest-trending structures (faults) in the Wallowa Mountains to similar trending faults and folds in the Cascades. If the zone is structurally unimportant between Wallula Gap and the Rattlesnake No. 1 well, the so-called lineament cannot be considered to exist as a through-trending, near-surface fault zone.
3. The Horse Heaven Hills at Wallula Gap rise to a maximum altitude three miles east of the Gap of 1750 feet (1400 feet above the Walla Walla Valley). Low dips exposed in the Gap clearly indicate that uplift and folding are not sufficient to account for the height of the Hills. Some persons accordingly have inferred that Russell's concept of faulting is there important. They have not obtained the necessary detailed field data to support that concept, however.
4. A fault that roughly parallels the lineament and the face of the Horse Heaven Hills was mapped by Newcomb and appears on the State Geologic Map (1961). It and associated faults to the east are the only significant faults in the entire Pasco Basin shown on that map. The faults as reported presumably cut the basalt flows at a high enough angle to permit determination of offset. Usually faults cut the flows at low angles, especially on the steeply dipping limbs of anticlines, and pass into bedding plane shear zones as indicated by Newcomb and Strand. Determination of offset at those sites is impossible and the importance of those faults cannot be determined. Reported truncated spurs on the mapped fault suggest recent movement.
5. The stratigraphy of the basalt flows in Wallula Gap previously was imperfectly known, consequently the major structures, their significance and relationships to the structures in the Blue Mountains and the Saddle Mountains are but poorly known.

Figure 1

Index Map, Showing Key Localities
And Geologic Features in the Area Studied

6. Recent, very minor earthquakes felt in the region originated only south of Hanford according to the seismograph records of the Blue Mountain Observatory and the Newport, Washington Observatory of the U. S. Coast and Geodetic Survey. Those events suggest a currently tectonically more active area toward the Blue Mountains than along the Saddle Mountains to the north where only one earthquake, at Corfu in 1918, is recorded. That indication is supported by the greater height of the Blue Mountains, a result of uplift, and to the greater offset on faults there.
7. The Rattlesnake No. 1 well of the Standard Oil Company of California lies immediately adjacent to Skehan's lineament, as he recognized. The well was reopened by Battelle-Northwest in June 1967. Interpretation of the in-well logs and tie-in to regional data probably will provide information bearing on the existence and significance, or lack of them, of Skehan's lineament. Some questions that Skehan himself poses hopefully may be answered.

No attempt was made to examine all sites where Mollard, Jones and Deacon suggested possible faults. Instead those sites were studied more intensively where the tectonic activity, indicated by the height and form of the anticlinal ridges, has been greatest and the possibility highest that faults are present.

The Wallula Gap Area

The Horse Heaven Hills at Wallula Gap rise to an altitude of 1750 feet above sea level about three miles east of the Gap (1400 feet above the Walla Walla Valley). Low angle dips in the Gap are insufficient to account for the difference in altitude between the hill crest and the valley, hence some persons feel that faults must be important. Newcomb (1951) mapped faults in the Hills toward Walla Walla but even in 1965 failed to describe the evidence for them. He also did not estimate offset or suggest the importance of faulting relative to folding or to other events in the formation of the Hills.

The first step in studying the area was to identify its stratigraphic units. Work by Grolier and Bingham on the lower Snake River and by Laval and Schmincke^(32,33) in the lower Yakima Valley, at Nine Canyon and The Butte made identification simple and positive. A comparison of nomenclature showing the key marker units is on Figure 2.

<u>Schmincke</u> <u>(Yakima Valley)</u>	<u>This Report</u> <u>(Hanford Region)</u>	<u>(Columbia Basin Irrigation</u> <u>Project)</u>
	Glaciofluvial sediments (Touchet sediments and Pasco gravels)	Glaciofluvial deposits
	Ringold Formation	Ringold Formation
Ward Gap Flow	Undifferentiated younger basalt flows	
Elephant Mountain Basalt Member	Elephant Mountain basalt flow	Saddle Mountains Member (including up to 3 or more basalt flows, not separately identified)
Rattlesnake Ridge Member	Upper part of the Beverly Member	
Pomona Basalt Member	Pomona basalt flow	
Selah Member	Lower part of the Beverly Member	
	← fused tuff →	
Umatilla Basalt Member	Priest Rapids Member (5 flows)	Priest Rapids Member
	Quincy diatomite	Quincy diatomite
	Roza Basalt Member	Roza Basalt Member
	Squaw Creek diatomite	Squaw Creek diatomite
Frenchman Springs Basalt Member	Sentinel Gap flow Sand Hollow flow Ginkgo flow Frenchman Springs Basalt Member	Sentinel Gap flow Sand Hollow flow Ginkgo flow
	Vantage Sandstone Member	Vantage Sandstone Member

Figure 2

Comparison of nomenclature. The fused tuff, identified by Schmincke,
and the Roza Basalt Member flow are key stratigraphic markers.

The Beverly Member pinches out in the Gap. Fused tuff was found on the northwest side of the Gap along the Spokane, Portland and Seattle Railway siding at Yellepit and permitted positive identification of the overlying flow there as Schmincke's Pomona flow. Identically fused tuff also occurs at the base of the Cold Springs quarry near Hat Rock State Park in Oregon. Continuous tracing of the Pomona flow from the quarry northward through the Gap further guaranteed the position in the stratigraphic sequence of the flows on the east side of the Gap. The flows below the fused tuff down to demonstrable Frenchman Springs Basalt Member flows appear to correspond in nature and thickness to the Priest Rapids Member flows. No clear-cut Roza flow was identified. The precise number of Priest Rapids Member flows and exact position of the contact with the Frenchman Springs flows remain to be determined.

The Wallula Fault

The Wallula Fault, according to Skehan, Jones and Deacon, forms a scarp fronting the north face of the Horse Heaven Hills from two miles east of Wallula Junction to one mile west of it where the fault reputedly passes beneath the Columbia River. In that distance, only what are believed to be Priest Rapids Member flows crop out close to the fault as it was mapped. The Pomona and Elephant Mountain flows overlies the Priest Rapids flows a mile and more to the south but are absent from the north face of the Hills here. They are exposed at Ice Harbor dam, at Hover quarry and many other sites to the north and west. They clearly were eroded, following folding and uplift, from the north face of the Hills by glacial floodwaters in late Pleistocene and early Recent times. Unfortunately areas where they presumably were not eroded north of the Hills now are covered by colluvium and glacial

outwash sediments so that neither their current distribution, precise altitude, nor attitude can be determined.

The Frenchman Springs Member flows crop out in Wallula Gap and near the east end of the suggested fault as they rise beneath the Priest Rapids flows, but along the north face of the Hills they generally are covered.

The Priest Rapids Member flow above that exposed in the scarp is exposed from the railroad cut north of Wallula Gap to the mouth of the Walla Walla River. Flow structures in it and northward suggest that it bottoms within a few feet. The similar altitude of the indicated base of that flow and the top of the Frenchman Springs Member flow 350 feet south and behind the suggested fault indicates that stratigraphic displacement is roughly the thickness of the main Priest Rapids Member flow. To the south that flow is 170 feet thick, hence stratigraphic displacement is between 100 and 200 feet as indicated on Figure 3. Total offset can be accounted for by sharp folding without fault offset but some fault offset seems reasonable.

Three miles to the east the suggested fault reportedly terminates in a broad saddle. The saddle lies along the axis of a monoclinal fold where dips steepen from nearly horizontal south of the axis to 30° north just north of the axis. Mapping disclosed that the saddle was eroded along the contact between northward-dipping flows and not along a fault zone.

The monoclinal folds at both ends of the suggested fault thus may be one fold, continuous beneath the colluvium and alluvial-covered slopes fronting the Horse Heaven Hills. The current face of the Horse Heaven Hills thus may have been eroded back from the monoclinal axis by the same floods that eroded the Pomona and Elephant Mountain flows from the mountain front south of the "fault scarp" at the entrance to the Gap.

North

South

Figure 3

Diagrammatic Geologic Cross Section Through the Suggested Wallula Fault,
Showing Stratigraphic Relationships on Both Sides of the Fault,
Monoclinical Folding, and Relationships of Skehan's Breccia Zones
to the Suggested Fault

The breccia that faces the mountain front and purportedly is evidence of tectonic activity shows few characteristics of true fault breccias. Rock fragments commonly are fresh, rather than altered. They appear to be derived solely from the Priest Rapids flows rather than from either the older or younger flows through which the fault, if present, must pass. If offset is more than nominal, fragments from those flows should appear in the breccia. Fragments range down to about one-eighth inch in diameter, reflecting considerable fragmentation, but clay gouge so typical of faults is not present. Interstitial material where present is largely palagonite. Slickensided surfaces, zones of shearing and recognizable fault planes everywhere are absent. Conceivably those features could be absent from a fault in highly jointed basalts. However, a small fault includes all those features five miles to the southwest in a gully bottom in the SE 1/4 NE 1/4 sec. 18, T. 6 N., R. 31 E., at 550 feet altitude. The fault trends N. 40° W. and dips 85° N. It is a reverse fault in which the north side moved upward relative to the south side a vertical distance of only about seven feet as determined from continuous exposures across the fault. The fault zone is six inches to two feet wide and is sharply defined and bordered. It contains little breccia but abundant clay gouge and many slickensided surfaces in spite of small offset. Palagonite and sedimentary interbeds there are absent. The fault resembles in almost no way the hypothesized fault on the northeast side of the Gap.

Laval and Schmincke describe breccias in the Pomona flow in the lower Yakima Valley where the relationships clearly indicate flow or cooling breccias up to 60 feet thick at the flow top. Newcomb describes similar materials in unidentified flows in the Walla Walla Basin. The breccias east of Wallula Gap

Figure 4

Wallula Gap from the West Side of the Gap, Showing the Suggested Fault Scarp to the Left of Center, and the Site of Emergence of the So-Called Olympic-Wallowa Lineament

likely are similar in origin, but exposures are complicated by monoclinial folding, palagonite in some sites, locally considerable erosion, and perhaps some faulting. Glacial melt and flood waters, particularly near the Wallula Gap gateway out of the Pasco Basin, extensively eroded the central part of the monoclinial fold and there covered its trace with outwash sediments.

An alternative hypothesis is that some of the breccias may occur in breccia dikes. Reported dikelets of basalt beneath the Walla Walla River railroad bridge and at other sites farther south⁽³⁴⁾, toward the direction from which many of the basalt flows appeared to have come, suggests that possibility. Current evidence favors the cooling or flow breccia concept.

The West Side of Wallula Gap

No significant fault was found west of the Columbia River at Wallula Gap. Laval thought a fault was present but agreed that exposures were unsatisfactory. His work suggested that if a fault were present the south side was downthrown, the opposite of that suggested for the hypothesized fault east of the Gap. Newcomb projected the suggested fault across the river but cited no evidence for its continuation and terminated it within a mile. Skehan carried it less than one-third of a mile west of the river. Jones and Deacon plotted its existence to Nine-Canyon, six miles to the west and Mollard felt, on the basis of topographic expression, that it might continue more than 50 miles to the southwest corner of the Hanford Project.

As noted, fused tuff underlying the Pomona flow was found in a fresh roadcut at Yellepit siding, north of the supposed fault trace. Steep northward dips in the tuff indicate that the Pomona flow can be projected to its nearest exposures in the Gap south of the fault without evidence for or the need of fault offset. Moreover the Pomona and overlying Elephant Mountain

20

Figure 5

The West Side of Wallula Gap from Wallula Junction, Showing the Gully Interpreted as Fault Controlled

The Pomona flow with underlying fused tuff forms the outcrop just above river level on the extreme right of the picture. The flow is traceable to the skyline, to the left then again toward the river where it forms the steep face to the left of center. The gully was eroded along the axis of a monocline plunging toward the Columbia River.

flows can be traced continuously westward for about a mile, then continuously northward across the fault trace without a sign of faulting or offset.

No absolute proof of a significant fault was seen at any locality near the north side of Wallula Gap, and a fault if present must be of small offset and significance. The lack of importance is confirmed by maintenance records of the Union Pacific Railroad⁽³⁵⁾ and the Spokane, Portland and Seattle Railway⁽³⁶⁾, both of which pass through Wallula Gap. Only normal maintenance has been required on both railroads of both the pre-McNary dam and post-McNary dam tracks where the fault and lineament reputedly pass.

The structure at Wallula Gap is a monoclinal fold traceable for six miles and possibly up to 10 miles. It dies out westward south of The Butte. Similar monoclinal folds periodically appear westward, as in the Jump-Off Joe-Zintel Canyon-Johnson Butte area and sites farther west.

West of Wallula Gap many breccia outcrops in part resemble the presumed fault breccia. Skehan records 62 such zones of breccia, gouge and fracturing. He, however, states:

"Preliminary petrographic studies of the breccia do not favor the idea that the breccia is itself of tectonic origin. Field relations and laboratory studies suggest that the fractures in which the breccia is developed and which are oriented more or less consistently relative to the lineament are, however, of tectonic origin."

He does not discuss the origin of the breccia or breccia zones further.

Inspection revealed that some of the breccias contain occasional basalt pillows mixed with breccia, palagonite, volcanic tuff and assorted debris. Some breccias clearly are flow breccias. Some may be peperites, as described by Schmincke, in view of the presence of the Beverly Member in the area. Peperites, like pillow basalts, evidence a wet environment. They form by injection of molten basalt into wet, unconsolidated sediments, whereas

pillow basalt and pillow-palagonites and some flow breccias commonly are believed to form by entry of basalt flows into standing water. Excellent pillow basalts are exposed in railroad cuts along the Yellepit siding. On the east side of the Gap where Skehan also indicated abundant breccia, the Frenchman Springs flows in particular commonly display flow structures such as breccias, pillows, spiracles and palagonite indicating emission into a then wet environment. Similar features occur in the Hover quarry, along the Snake River and the Walla Walla River and suggest that the area at least upstream from Wallula Gap either was repeatedly or long covered by water.

The basalt flow three flows below the Pomona flow was traced northward continuously, high in the cliffs on the west side of Wallula Gap, from a point where it measures 80 feet to its end just south of the presumed fault. Only four or fewer Priest Rapids Member flows are known to the north in the Pasco Basin, but to the south in Wallula Gap five such flows were identified by Laval in Spukshowki Canyon and were encountered in this study on the east side of the Gap. Similarly at least one Frenchman Springs flow was observed to pinch out northward. Those facts, and the absence of Priest Rapids Member flows more than a few miles up the Snake River and beyond Reese on the Walla Walla River suggest that at least some of the flows originated somewhere to the south. Schmincke⁽³²⁾ in the Yakima Valley, found that many of the flows in the upper part of the sequence moved between north and west there. He concluded that they probably originated in northeastern Oregon where huge dike swarms are known and are believed to be the source of at least some of the flows. The Wallula Gap area, because of its position between Schmincke's flow direction determinations and a possible source, and because of the exposure of the stratigraphic section is an important area.

Waters identified two basalt flows in the hills east of the Gap but which were absent west of the Gap. He attributed their absence to erosion by the Columbia River as it shifted down the axis of the Horse Heaven Hills anticline to

the structural low at Wallula Gap. As yet mapping has not progressed far enough east to encounter them, but if they flowed in a northwest direction from Oregon sources as indicated for the earlier flows they well could have encountered already suggested Columbia River floodplains and gentle southward slopes that inhibited their northward spread. If the flows simultaneously were becoming less voluminous near the end of emission as suggested by the decreasing extent from the Roza to Elephant Mountain flows, their termination along the south side of the Pasco Basin reasonably could be expected. Possibly Waters' flows are related to Schmincke's Ward Gap flow farther west.

The anticlinal ridges were rising by Beverly Member time as noted by Mackin⁽³⁷⁾, Grolier and others. The Horse Heaven Hills, however, could not have then existed at the Wallula Gap site, else the Pomona, Elephant Mountain and Waters' two flows would not be present or at least as thick over the anticlinal axis as they now are. More precise dating of the time of uplift awaits identification of Waters' two flows, determination of the extent of the Ward Gap flow, and determination of their relationships to intracanyon flows along the Snake River described by Gard, Waldron, Trimble, and most recently by Clem⁽³⁸⁾.

The Horse Heaven Hills rise to an altitude of 1750 feet about three miles east of the Gap. Low dips exposed in Wallula Gap and Van Sytle Canyon, about one degree, are too low to account for the height of the Hills. The imposing 1400-foot high north face, that together with a breccia-faced scarp suggest 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 monoclinical fold that largely has been eroded by glacial flood waters and buried. The lack of major faults and clear-cut fault breccia also indicates that the so-called Olympic-Wallowa lineament at Wallula Gap does not exist as a shallow-seated fault zone or recognizable structural or tectonic zone.

The Finley Quarry

The Finley quarry lies in the west end of The Butte, a small dome or closed anticline that lies along the projection of the southeast portion of the Rattlesnake Hills. Laval there thought a fault bordered the quarry on the north, with the north side raised. The quarry was cited by Skehan and Jones and Deacon as a site in which some tectonic activity occurred. The quarry is illustrated as Figure 6 by Skehan and Photograph 5 by Jones and Deacon. Numerous zones described as "clay-filled brecciated zones" by Skehan and clastic dikes by Jones and Deacon occur throughout the quarry. Filling material is of basalt from the flows through which the zones pass, and sediments that once overlaid the basalt flows. No fault gouge, slickensided surfaces, positive offset, or other features diagnostic solely of faults were seen.

The basalt flow in the quarry was identified by Schmincke as the Umatilla Member flow (the uppermost Priest Rapids Member flow), above which lies the lower part of the Beverly Member, a trace of fused tuff, and higher on the hill the Pomona and Elephant Mountain flows. All the flows evidently are terminated by the steep north face of The Butte. The uppermost Priest Rapids flow in the quarry, however, is abruptly terminated south of the hill face. A fault may there be present, but no fault was noted to the east on The Butte. Actually a fault, if present, should lie along the north face of The Butte. Moreover only rubble from the higher Pomona basalt flow and colluvium and slopewash debris lie on the north side of the terminated Priest Rapids flow. Determination of offset, if in fact it is a fault, is not possible.

In the canyon immediately west of the quarry the base of the uppermost Priest Rapids flow and the top of the next lower Priest Rapids flow are well exposed for several hundred yards up the canyon without break or offset by any fault. Dips are 7° N., higher than the 2° N. dips encountered farther south. The possible fault bordering the quarry on the north projects across the canyon north of the last

exposure of basalt in the canyon bottom. Road cuts on the west side of the canyon disclose Touchet sediments (fine-grained glaciofluvial outwash) dipping 5° - 7° N., parallel to the underlying basalt. Within the upper part of the water-deposited Touchet beds is a bed of white vitric tuff ("ash") about an inch thick, traceable for several hundred yards down the canyon wall. Nowhere are the ash bed or Touchet beds offset by a fault although small, characteristic clastic dikes cut both. We can conclude that the "tectonic" structures most likely are large joints into which rubble and debris, including slopewash, fell or was washed.

The age of formation and filling of the opened joints appears significant. Probably they developed initially as normal cooling joints, completely traversing the here thin Priest Rapids flow. During folding and uplift they probably opened and initially were filled. Glacial Lake Missoula floodwaters and associated glacial meltwaters inundated the area several times, once to depths 500 feet above the quarry site, and to lower levels at other times. Here, within five miles of Wallula Gap and not protected by hills to the north, the basalt face of the Horse Heaven Hills and The Butte was subjected to repeated strong currents of water draining out of the basin toward Wallula Gap, as indicated by Laval. The hydraulicking action aided perhaps by other mechanisms resulted in movement along the flow contact and resulting block slip. Repeated floods widened the already existing joints and totally removed the blocks formerly lying north of the quarry. Some later and lesser floods deposited the Touchet beds now exposed in roadcuts west of the quarry. Probably the earliest (and greatest?) floods eroded the basalt the most, the subsequent floods may have caused some additional block slip followed by deposition of the Touchet beds in which the ash is incorporated.

Some of the dip of Touchet beds and included ash may be depositional. The high angle of dip, however, compared to the maximum noted in Touchet beds

elsewhere (generally one or two degrees) suggests tilting. The northward dip toward the source of the floodwaters depositing the beds and in the same direction as the underlying basalt also is suggestive. Proximity to Wallula Gap, where anticlinal folding and uplift are quite recent supports the concept. Accordingly, some if not all the dip in the Touchet beds and ash bed may have resulted from uplift and tilting in post-ash bed time, or within the last 10,000 years.

Skehan refers to numerous breccia zones in the Finley quarry, on Nine Canyon Road, in the South Olympia Street quarry near Kennewick and in other sites. As earlier stated, he recognizes that the breccia is not tectonic in origin but feels that the zones filled with the breccia are tectonic in nature.

The lack of slickensided surfaces or offset across the breccia zones agrees with Skehan's conclusion that the breccia is not of tectonic (fault) origin. The zones in which the breccia occurs are filled with materials from the basalt flow traversed and from the basalt flows overlying one in which the zones occur, the Ringold Formation and the glaciofluvial (Touchet) sediments. That indicates that the zones at one time were open, similar to the clastic dikes in the Touchet beds. Clastic dikes also are known in the Ringold Formation, in the Pasco gravels of the glaciofluvial deposits, in the Ellensburg Formation, and in some basalt flows. The possibility thus exists that the breccia zones are generally merely clastic dikes filled by materials that were locally available.

The origin of clastic dikes is controversial. Recent hypotheses by Brown and Brown⁽³⁹⁾ suggest that some formed when the Pasco Basin was being subjected to rapid loading and unloading of the earth's crust resulting from glacial Lake Missoula floods. Stresses that accumulated during folding and uplift of the ridges may have been accentuated by deep flooding of the basin to 1200 feet above sea level and subsequent rapid drainage. Very shallow

seated (near-surface) local earthquakes could have occurred, triggering compaction and consolidation of the supersaturated Touchet sediments and causing fissures in them and in the older rocks into which material from higher levels fell or was washed. That hypothesis better explains clastic dikes in the Ringold and Ellensburg Formations and in basalt flows than other theories such as giant mud cracks or simple dewatering by lateral or upward injection of contained waters. The great variety and wide area in which dikes occur suggest that several or even many mechanisms may have helped create them.

Most clastic dikes and breccia zones in the basalt evidently occur in the Pomona flow. The seeming concentration may be because (1) the flow is exposed throughout the Pasco Basin in contrast to older flows, (2) the flow characteristically has closely spaced columns oftentimes grading into brickbat structure that easily separates unlike more massive basalt, (3) the flow commonly is underlain by a clay-rich interbed that may readily permit local lateral sliding sufficient to open the zones. That the concentration is related to the jointing and is not just apparent is suggested by the brickbat structure and the breccia zones in the Priest Rapids Member flow in the Finley quarry.

No studies of the clastic dikes and breccia zones have as yet included data on their distribution with respect to upfolded area, rock types involved, or their orientations with respect to tectonic areas (anticlinal folds). Conceivably such studies may disclose meaningful relationships.

The Butte To Rattlesnake Hills Section

The southeast-trending portion of the Rattlesnake Hills and its continuation through Red Mountain, Badger Mountain, The Butte and unnamed smaller hills was studied. Identification of flows and mapping of the structures readily

disclosed that each hill is an elongate dome, or doubly terminated or closed anticline, as indicated by Laval, with basalt flows and interbeds dipping radially outward from the crest. Erosion was minimal in their formation and gaps such as the Yakima water gap south of Horn Rapids are structural lows. At all sites between domes the basalt flows and interbeds are essentially flat-lying without offset by faults. Although Laval found some breccias that he interpreted as fault breccias they were not traceable for more than 100 feet and in fact trend northeast-southwest.

The Yakima River Water Gap

The Yakima River water gap is one of the best exposed sections across the axis of the Rattlesnake Hills anticline. It lies between the Rattlesnake Hills and Red Mountain where the relief along the structural axis is up to 1400 feet in 1.5 miles. Thus the stratigraphic section was stressed parallel to the Rattlesnake Mountain-Red Mountain axis and normal to it. Conceivably faults, if significantly involved in the formation of the Rattlesnake Hills and the domes toward Wallula Gap, should occur there. The Priest Rapids to Elephant Mountain stratigraphic sequence (Figure 2) was traced continuously through the gap without sign of offset or even of a recognizable fault. Examination of the U. S. Geological Survey maps, made in 1953, showed identical conclusions differing only in stratigraphic nomenclature and local detail. We can conclude that the faults suggested by Mollard are not present.

The site is interesting owing to the presence of a landslide on the Rattlesnake Hills side of the gap extending from the Yakima River to an altitude of about 1,000 feet. The Yakima River at the gap flows northwesterly for one-half mile parallel to and along the projected axis of the hills, as if fault controlled, before resuming its more northerly course.

Figure 6

View Southeastward Along the Axis of the Rattlesnake Hills Anticline Southeast

The Yakima River water gap crosses the axis of the anticline in the picture center. The asymmetry of the anticline is shown, together with a landslide on the steep left slope in the near distance. The isolated hills in the distant center of the picture are elongate domes or doubly terminated anticlines along the projection of the Rattlesnake Hills Anticline Southeast.

Study showed no evidence for a fault controlling either the river course or causing the slide. Probably the river followed a northwest-trending joint in the there massive Elephant Mountain flow, such as was noted in regional systems to the east and northeast by Waldron, Gard, Trimble and Newcomb. Once the Elephant Mountain flow was breached, the soft interbed beneath it and the still lower highly jointed Pomona flow were eroded, resulting in entrenchment of the river in the northwest-trending segment of the channel.

The landslide occurred along the upper and lower parts of the Beverly Member which are separated by the Pomona flow; they dip 10° - 15° SE. toward the Yakima River. Most movement occurred on the lower bed which, according to mapping and the logs of the Weaver and AEC wells (10/26-25HI and 10/26-30N1 respectively), lies at or near river bed level. Sliding may have resulted from oversteepening of the slope when the Yakima River undercut the toe of the slope. The age of the slide could not be determined, but no historic movement is recorded or evident.

The Age of Folding and Consequent Faulting

The repeated association of faults, albeit minor, with zones of folding emphasizes the point made by earlier workers in the region that faults developed where folding was relatively intense and where stresses could not be relieved solely by that folding. Consequently the faults should be somewhat younger than the beginning of the related folding and uplift.

The Beginning of Folding

Anticlinal folding and uplift of the Saddle Mountains began in Beverly (early Pliocene) time according to Mackin. This was about 10,000,000 years ago. Grolier suggests an earlier rise for a nearby ridge because basalt fanglomerate overlies and underlies the thick pumicite bed in the Beverly

Member on the Saddle Mountains. He does not identify the ridge. Rock fragments in the fanglomerate are dominantly Priest Rapids and Roza basalt. Umtanum Ridge is the highest and nearest ridge covered by those flows. Pinchout of the Priest Rapids No. 4 flow, the Pomona flow, and both parts of the Beverly Member along the nose of the plunging anticline on the east end of the ridge near Vernita indicates that the ridge to the west was rising earlier or faster than Mackin indicated for the Saddle Mountains, and well could have been the source of the fanglomerate.

Southward the anticlinal ridges generally are covered progressively with younger basalt flows. The Rattlesnake Hills are extensively covered by the Pomona basalt, by thin but identifiable sediments of the Beverly Member, and by patches of the Elephant Mountain flow. Uplift was later or slower than that of the Saddle Mountains, and appreciably later than that of Umtanum Ridge. The main mass of the Horse Heaven Hills from Kiona west is extensively covered by the above flows and interbeds and locally by the Ward Gap flow, according to Schmincke. They accordingly rose last. Anticlinal uplift evidently began toward the north and progressed southward. If anticlinal uplift lasted a comparable and finite period of time in each ridge, the Horse Heaven Hills are more likely to be tectonically active today than are more northerly ridges. On the other hand, all could be equally active or inactive. Recently detected earthquakes in the region have occurred solely to the south, in the Horse Heaven Hills or Blue Mountains, and not to the north. This suggests that at least some parts of the Horse Heaven Hills are tectonically more active than other ridges.

Uplift also was variable from place to place on any one anticline. Thus, the youngest flows of all constitute the crest of the Horse Heaven Hills

Figure 7

Geologic Cross Section Through the Horse Heaven Hills from Ice Harbor Dam To Cold Springs Quarry and Showing Lack of Fault Offset at the West End of the Wallula Monocline

anticline at Wallula Gap, but pinch out westward. Other anticlinal ridges also show greater height to the west and more intense folding there. The Horse Heaven Hills probably did not begin to rise until post-Elephant Mountain flow time and then initially in the west. Uplift at Wallula Gap probably began much later when the entire basalt sequence, including those flows now 1,100 feet above sea level at the Gap, was laid down. Uplift, which formed the anticline, raised the Elephant Mountain flow and Pomona flow roughly 500 feet above their altitudes just north of Wallula Gap. This is over a distance of about 4 miles at an average dip of 1.5° , comparable to measured dips today.

End of Basalt Emission and Deposition of the Ringold Formation

The highest flows in Wallula Gap, at an altitude of 1,100 feet, initially must have been laid down at an altitude of about 600 feet in order to have been raised the 500 feet indicated. In the Pasco Basin center only the Ringold Formation sediments existed at a then 600-foot altitude just before deposition of the glaciofluvial sediments. Probably because of basin sagging, beds deposited at that altitude then are somewhat lower today. That the most recent basalt flows pinch out northward suggests that an extensive floodplain helped to terminate the flows north of the Horse Heaven Hills; probably this was the Ringold floodplain. If the Beverly Member is lowermost Pliocene in age, then the latest of the basalt flows may be middle Pliocene in age depending on the rate of emission of the post-Beverly Member flows.

The Ringold Formation traditionally is believed to be Pleistocene in age or less than about 1×10^6 years old. The latest work by the U. S. Geological Survey⁽⁴⁰⁾ suggests a middle to possibly late Pleistocene age. Newcomb and Strand recognized deformation of the lowermost or "blue clays" part of the Formation, but claim that deformation ceased prior to deposition

of the higher beds. Conceivably that deformation then ceased a hundred thousand or more years ago by their accounts. On the other hand, they assert a youthfulness of deformation and consequent earthquake potential hardly in keeping with cessation of deformation that long ago.

Brown and McConiga⁽⁴¹⁾ showed a progressive decrease of dip upward to the top of the formation in the type section in the White Bluffs. It reflects essentially continuous deformation throughout deposition of the formation. Supporting the concept that tectonic activity continued through Ringold Formation deposition is the overthrust of basalts over Ringold Formation sediments in Lind Coulee and at the west end of the Smyrna Bench.

Jakway⁽⁴²⁾ in 1966 and 1967, as a result of studies of extensive collections of Ringold Formation Fossils and his own extensive excavation and fossil collection in the White Bluffs, concluded that the Ringold Formation was fully Pliocene in age. The uppermost basalts appear to be equivalent to some part of the Ringold Formation. Overthrust of basalt over Ringold Formation sediments then could have begun up to several million years ago rather than within the last several hundred thousand years. Recurrent movement or a continuation of very slow thrusting could, of course, be continuing today.

The Rate of Deformation

Comparison of the suggested rate of deformation in the Pasco Basin to other, more earthquake-prone areas, is enlightening.

If uplift began roughly 10,000,000 years ago in the Rattlesnake Hills, the stratigraphic displacement provides a means of estimating the average rate. Thus the Elephant Mountain and Pomona flows lie a few hundred feet below sea level beneath part of the Hanford Project. They lie between 3000 and 3500 feet above sea level on the crest of the Rattlesnake Hills. The average rate of uplift (or combined uplift and basin sagging) is about 1 foot/3,000 years.

Evernden⁽⁴³⁾ determined the age of the Ginkgo flow as 13.4×10^6 years by K-Ar age dating, and the Ellensburg Formation near Selah (about equivalent to the Pomona flow) as 10^7 years old. Eight basalt flows occur in the stratigraphic section between those two flows in the general area. An average rate emplacement there is one flow per 400,000 years. Probably three flows lie above the Pomona flow in Wallula Gap. If the emplacement rate continued, the latest flow in Wallula Gap may be roughly 8.8×10^6 years old. However, a greater number of flows may have been emitted in the 3.4×10^6 years than determined from the section near Priest Rapids. For instance, five Priest Rapids flows occur in Wallula Gap. Consequently the emission may have been at a greater rate than evidenced farther north. On the other hand, the extent of flows apparently decreases from the Roza flow to the latest flow in Wallula Gap, suggesting an exhaustion of the magma chamber supplying the lavas. Conceivably flow emission also was at less frequent intervals, offsetting the above suggested greater rate.

If we accept the K-Ar determined ages and the apparent rates of deformation, the average rate of uplift at Wallula Gap is on the order of one foot per 17,500 years. If we assume that the youngest basalt flow may be as recent as 3.5×10^6 years, the average rate of deformation is still only one foot per 7,000 years. The Horse Heaven Hills at Wallula Gap thus appear tectonically less active than other ridges, although it is the site of the so-called Olympic Wallowa lineament and a site of reputed Pleistocene or Recent fault movement. Tectonic activity in the Horse Heaven Hills eastward toward the Blue Mountains and westward toward the Cascades probably is greater as suggested by the rise in height of the hills in those directions.

Tectonic creep on the Hayward fault in California is reported to be eight inches in 55 years (about one foot in 80 years) although rates of

1 1/2 inches in two or three days are recorded⁽⁴⁴⁾. The San Andreas fault similarly is reported moving 0.45 inches per year for seven years⁽⁴⁵⁾ a rate of four feet per 100 years, although earlier reports indicated about two inches per year⁽⁴⁶⁾, about 17 feet per 100 years. Sudden movement and resulting earthquakes can and do occur in areas of low tectonic activity but the lower order of magnitude of rate of deformation at Wallula Gap compared to central California does not suggest a structural lineament of current tectonic importance.

The Glacier Peak Ash and Other Evidence for Recent Folding

The indicator of most recent tectonic activity is the ash bed noted throughout the Pasco Basin and specifically discussed from the Finley quarry. If the 7° dip of the Touchet beds and contained ash bed is in part the result of uplift, tilting and folding, then the age of the ash is important. If the dip is solely depositional, the last tectonic activity is still older and of less concern.

Newcomb in 1953 concluded that the ash bed was deposited in the "last thousand or two years" but cited no evidence for what was an opinion. In 1966⁽⁴⁷⁾ he concluded, as a result of work by Powers and Wilcox⁽⁴⁸⁾, that it was derived from Mount Mazama about 6,600 years ago. However, Powers and Wilcox report no analysis of ash from the Pasco Basin, only beyond the basin to the north. They moreover drew no southern boundary for the Glacier Peak ash. The question is more than academic for if either of Newcomb's dates is valid, the presence of water-deposited Touchet sediments above the ash means that the Pasco Basin was flooded within either literally almost historic times or within the last about 6,000 years in the latter case. Moreover, if the clastic dikes and Skehan's tectonic breccia zones are related to each other and conceivably earthquake-caused, even by very shallow-seated earthquakes, those events then would be so recent as to be of greater concern.

The Touchet beds traditionally are considered to be the result of drainage of glacial Lake Missoula and associated meltwater floods. Fryxell⁽⁴⁹⁾ dated the earliest floods as less than 29,500 years ago and in later work⁽⁵⁰⁾ concluded that the main floods occurred between 18,000 and 20,000 years ago. If the Touchet beds overlying the ash are less than several thousand or even 6,600 years old, then floods must have inundated the Pasco Basin within that period to altitudes higher than 650 feet above sea level. Alternatively, the latest floods may have resulted from other than ice-marginal lake releases. The only other mechanisms for flooding to those levels are the creation of ice jams in narrows such as Wallula Gap as suggested by Allison⁽⁵¹⁾ and the fill-and-cut concept suggested by Flint⁽⁵²⁾. Both are effectively contradicted by Bretz⁽⁵³⁾.

Hansen⁽⁵⁴⁾ determined that the period from about 8,000 to 4,000 years ago was a period of maximum warmth and dryness in the Pacific Northwest. Daugherty⁽⁵⁵⁾ concurred in his work at Lind Coulee; Fryxell⁽⁵⁶⁾ confirmed the same events at Marmes Rock Shelter; and Borden⁽⁵⁷⁾, in the Fraser River Canyon, concurred. It is questionable then whether floods to altitudes of 650 to 700 feet above sea level in the Pasco Basin could have continued to so recent a time and well into the "Thermal Maximum" or Altithermal period.

Fryxell⁽⁵⁸⁾ showed that the ash from Glacier Peak, erupted between 11,000 and 12,000 years ago, blanketed much of eastern Washington. However, distinctions in composition between it and Mazama ash currently appear so fine that ready and positive identification is oftentimes precluded.

Mazama ash has not been positively identified in the Pasco Basin, although it is known near Sentinel Gap. If present, it probably is thoroughly mixed with eolian silts similar to the loessial materials described by Daugherty at

approx.
Years B.P.
(based largely on C¹⁴ Data)

Geologic Units Deposited

Geologic Events
Occurred

Figure 8

Time and Geologic Event Relationships Covering the Last Several
Million Years in the Pasco Basin

Lind Coulee that he felt were laid down during the Altithermal period.

Recognizable deposits of the Mazama ash would be fortuitous and the ash would not blanket the region as does the ash that is exposed in the Finley quarry and elsewhere.

We can conclude that the ash bed originated at Glacier Peak between 11,000 and 12,000 years ago, at which time Fryxell⁽⁵⁰⁾ also records floods to the 650 to 700-foot altitude. The events forming the clastic dikes probably occurred or recurred up to a similar period of time, inasmuch as the ash bed and most recent Touchet sediments are cut by clastic dikes.

If the dip of the Touchet sediments and ash bed is in part due to tilting and uplift, tectonic forces have been active to quite recent time. If the dikes in the Finley quarry be considered as faults or even merely evidence of tectonic activity, there has been insufficient activity to disrupt or offset the Touchet beds and contained ash bed in the 11,000-year period in spite of uplift and folding.

Skehan dates the Wallula fault as Pleistocene or Recent in age, indicating that tectonic activity persisted well through deposition of the Ringold Formation and conceivably past the time of deposition of the Touchet beds and the Glacier Peak ash. He concluded that:

"The present expression is probably for the most part depositional in character with the probable dip of the fault being essentially vertical,"

rather than dipping northward at a high angle. If the fault actually exists and if his conclusion be valid, then no movement has occurred on the fault for a long period of time. Otherwise a vertical or near-vertical scarp, yet unmodified by erosion, would lie at the base of the currently northward-dipping scarp. No vertical or near-vertical scarp exists.

Skehan's conclusion about the dip of the indicated fault may have been based upon the present of the near-vertical breccia zones in the basalt flows behind the scarp. Those zones, however, are common throughout the Pasco Basin in the basalt flows and as suggested may be related to the clastic dikes. They evidently do not relate to the Wallula fault even if the fault exists and is significant.

Waters⁽⁵⁹⁾ states that the Roza Canal, on the north side of Umtanum Ridge at Roza Gap, twice in the last 50 years has lost water over the canal banks north of the tunnel, as a result of grade change. He interprets the change as due to slow and steady anticlinal uplift of the Umtanum Ridge anticline with consequent reversal of grade upstream from the tunnel.

Sudden movement, whether it be uplift of anticlines, movement on faults, or movement of landslides, is not mandatory. Creep is being recognized as an evidently normal situation, particularly on faults⁽⁴⁴⁾. Waters⁽¹⁰⁾ states:

"Part of the adjustment of basalts in anticlinal ridges to folding has been by bedding plane slip, as shown by the local smearing out and slickensiding of thin sedimentary beds and residual soils intercalated between the basalt sheets. Probably most of the movement has been accommodated by minor adjustments between the numerous joint planes of the lava. Columnar joint surfaces are locally slickened where they have been squeezed against one another on the flanks of folds. Many joint columns are broken and displaced along secondary fractures . . . Tilting of columns by rotation and by shear along original platy or secondarily developed joints is visible locally on the limbs of the folds."

In view of the availability of large numbers of sliding planes in contrast to massive or relatively unjointed rocks, slow slippage, creep or adjustment to folding probably occurred during the whole period of folding. Sudden rupture is not necessary nor has any evidence indicated that such rupture, commonly interpreted to be a cause of earthquakes, did indeed occur.

THE OLYMPIC - WALLOWA LINEAMENT

The "Olympic-Wallowa Lineament" was first proposed by Raisz in 1945, when he recognized an alignment of topographic features that appeared to extend from the Straits of Juan de Fuca to the Wallowa Mountains and possibly to the Craters of the Moon in Idaho. He regarded that surface feature as possibly being related to transcurrent faulting. Wise, in a self-styled "outrageous" hypothesis further advanced the fault concept. Watkins, in an attempt to explain paleomagnetic variations, concluded that tectonic rotation of much of the Pacific Northwest had occurred along the lineament. Cantwell discovered a change in crustal resistivity that Skehan related to the lineament and which he indicated was a zone of major tectonic activity. Taubeneck⁽⁶⁰⁾, however, questioned tectonic rotation along the lineament at least following emission of the Columbia River Basalt flows. On the basis of his work in northeastern Oregon he also concluded that the lineament is mostly a topographic feature.

McKee reinterpreted the lineament as a broad zone of fundamental tectonic significance that separates different basement rock types throughout the state of Washington. Yates recognized a similar petrologic and stratigraphic discontinuity but carefully avoided reference to any lineament and, in fact, stated that his discontinuity is not a lineament obvious on maps, air photographs or on the ground. Thus both McKee and Yates recognized what Cantwell's resistivity changes may have reflected but agreed that the changes occurred over a wider zone that Skehan suggested.

No evidence was found that the so-called Olympic-Wallowa lineament exists as a major fault in the Wallula Gap to Rattlesnake Hills segment. Moreover, the Horse Heaven Hills are dominantly a topographic feature where the lineament,

according to Skehan, is supposed to have its greatest tectonic significance. At Wallula Gap, the Horse Heaven Hills structure is nearly absent. To the northwest along the lineament, a line of small unimpressive domes extends for more than 30 miles before the Rattlesnake Hills begin their rise. Thus, with the Blue Mountains segment of the lineament eliminated as a major fault zone by Taubeneck, the lineament for more than 100 miles exists dominantly as topographic features that in some instances at least are genetically unrelated to each other or at most only indirectly.

Skehan emphasizes that the occurrence of earthquakes at three sites along the lineament: (1) the Milton-Freewater and Walla Walla area, (2) the Ellensburg area, and (3) the Puget Sound area further substantiates the presence of the lineament and its tectonic nature, and indicated that additional earthquakes can be there expected. Too little yet is known of the structures along which the earthquakes have originated in those three areas to permit relating them via a surface geologic structure that is non-existent for much of its length. This is particularly the case for the segment from Ellensburg to the Milton-Freewater and Walla Walla areas which lie more than 100 miles apart.

Most workers in south-central Washington concur that some folding, uplift and possible basining are still underway. No evidence has been found indicating that tectonic activity has ceased nor could it necessarily be expected. In support of this concept is the occurrence of eight very minor earthquakes in the general region adjacent to Hanford in the last two years. The epicenters of those quakes were determined, where possible, by the Blue Mountain Observatory and the Newport, Washington Observatory.

July 26, 1965	Two quakes, the first centering nine miles southeast of Prosser, the second evidently in the same area.
August 2, 1965	Epicenter not determinable other than that it was in the general region.
November 9, 1965	Epicenter between Hanford and the Blue Mountain Observatory.
March 7, 1966	Epicenter to the east, probably in the north end of the Blue Mountains.
June 9, 1966	Epicenter between Hanford and the Blue Mountain Observatory.
February 13, 1967	Epicenter near Mabton, Washington.
August 4, 1967	Epicenter near Mabton, Washington.

It is significant that none of the above quakes, nor for that matter any earlier quakes detected at the Hanford Project, were determined to originate in the Saddle Mountains to the north. All quakes occurring in the region and whose epicenters could be determined originated generally to the south, either in the Horse Heaven Hills or the Blue Mountains, in structures that are transverse to or normal to the lineament. The data, although very short-term, suggest that tectonic activity, such as it is, may be greater to the south than elsewhere and is clearly not related to the lineament. This suggestion may be related to the indicated later rise of the Horse Heaven Hills and its possibly greater rate of rise today than other anticlines in the Pasco Basin. It may reflect the greater magnitude of faulting and uplift in the Blue Mountains than in other mountain ridges, or may indicate still more fundamental or deep-seated events.

LANDSLIDES

Landslides often are attributed to earthquakes when the quake exerts a lateral force exceeding the stability of a rock mass. Consequently unstable

rock masses may be set in motion by earthquakes. Prominent landslides were caused in some typical cases by the 1811 earthquake at New Madrid, Missouri; the 1899 Yakutat Bay, Alaska quake; the 1906 San Francisco quake; the Kern County, California quake of 1952; the Anchorage, Alaska quake of 1964; and the Hebgen Lake quake of 1959. Many slides occur along faults where the crushed rock has low strength and stability and is susceptible to movement. Landslides accordingly may be considered a sign of the seismic history of a region and may indicate the time when earthquakes occurred. If, however, the abundance of landslides in the Pasco Basin are considered indicative of earthquake activity, then the absence of large and important faults in the Basin must be explained. Alternatively, the landslides have a less than obvious relationship to earthquakes and well may have developed from other causes.

Cedergren⁽⁶¹⁾ emphasizes the importance of saturation of the ground, even when severe earthquakes occur. Morton and Streitz⁽⁶²⁾ point out that landslides in the San Francisco and Los Angeles areas increase in number during seasons of great rainfall, even without earthquakes. Jones⁽⁶³⁾ in his detailed studies in Franklin D. Roosevelt Lake above Grand Coulee Dam, determined that the principal cause of the more than 300 slides he examined, and of the more than 200 which he statistically analyzed, was the weakening of sediments by ground water. Fifty slides, whose dates of sliding were known, were plotted on correlation charts against several influencing factors. Most slides showed relationships to filling of the reservoir and to major reservoir drawdowns and not to other factors. Hence, attributing all slides to earthquakes presents an unrealistic and overly pessimistic view of a region's seismic history.

Dating of landslides at best is precarious. In the Pasco Basin where precipitation and weathering are minimal, slides evidently retain a youthful appearance for thousands of years, and only subtle differences may permit determination of their relative ages. Consequently what may at first glance suggest major earthquakes in historic or near historic time may be indicative only of more normal mass wasting processes over thousands of years. The Thermal Maximum or Altithermal period already discussed further minimized erosion and probably landslide development from 8,000 to 4,000 years ago, as demonstrated by Fryxell at Marmes Rock Shelter.

Region-wide and detailed study of landslides in south-central Washington has never been made because of the difficulty in positively ascribing an origin and in dating them. Most workers in the region have described slides but few have more than identified them. Grolier evidently was the first to geologically date slides, and then only the Corfu slide and a few in the White Bluffs. Most recently, Stradling⁽⁶⁴⁾ thoroughly appraised the slides of the Yakima folds. Jones made probably the most detailed study of landslides, but only along the Columbia River Valley in northeastern Washington.

Most landslides occur on the steep north slopes of the anticlinal ridges where sharp folding opened the joints in the rocks, permitted moisture penetration, lubrication of sliding planes, additions to the static load, a decrease in the shearing strength of the sedimentary rocks (including those lying between basalt flows) and decreasing stability. North-facing slopes in addition retain moisture longer than south-facing slopes and consequently accumulate more. Slopes oftentimes are steepened by erosion to greater instability. We can expect, therefore, that most landslides should occur where slopes are steepest and clay-rich interbeds thicker and more abundant. This occurs in the western part of the Pasco Basin, where landslides are far more abundant than to the east.

Landslides appear on the basis of their topographic features to have formed in roughly two main periods of time. The older slides are characterized by deeper soil development and more extensive vegetation, similar rounding of hummocky-topography, and a general lack of open fissures, precariously perched rocks and unmodified hanging valleys. Younger ones, including current slides in the White Bluffs, appear markedly different. Stradling also recognizes that the Simcoe and Toppenish slides are younger than those in the Horse Heaven Hills on the same bases, but dates the Simcoe and Toppenish slides only as Recent.

Grolier theorized that a late Pleistocene period of flooding of the Pasco Basin may have caused the Corfu slide. The slide cuts across well-defined scarplets bordering wave-cut terraces that mark successive levels of glacial Lake Lewis. The slide post-dates the earliest flooding and may have been related to Grolier's Lake Lewis II, of unestablished age. If the maximum flood, presumably Lake Lewis I, were 18,000 to 20,000 years ago, and if successive floods were to progressively lower altitudes, Lake Lewis II may have existed sometime between 12,000 and 18,000 years ago. Further work is needed to establish those events.

Grolier also recognized that the Corfu slide lies where flood waters from glacial Lake Missoula impacted the Saddle Mountains as they divided to flow down Crab Creek and the Othello Channels. Erosion of the mountain toe steepened the already steep slopes. Saturation of the rock to an altitude of 1250 feet once, to lower levels probably several other times, and subsequent lowering of the water level must have caused sliding. Grolier suggests that movement along faults to the west or minor earthquakes may have helped induce sliding. Perhaps the quakes were those that possibly helped form the clastic dikes. Earthquakes or fault movement do not appear necessary, however, because of the floods that inundated the region.

Because of indicated channelling of landslide blocks in the White Bluffs, Grolier felt that sliding there may have begun prior to Recent times. The slides then would be comparable in age to the Corfu slide, and perhaps related to flooding of the basin.

The mechanism of repeated flooding of the Pasco Basin for an unknown number of times between 20,000 and 10,000 years ago evidently is an excellent mechanism for inducing sliding. Earthquakes and fault movement may not have been necessary or even present. Detailed study of soil development and detailing of many minor features may suggest a contemporaneity of landslides and indicate whether the flood mechanism is generally applicable.

Newcomb and Strand in 1953 mapped a slide which covers about 13.5 square miles or three times the area of the Corfu slide. Newcomb subsequently expressed doubt about the slide extent, however, a recent (1966) draft report⁽⁴⁷⁾ shows the slide agreeing in detail to his 1953 report. The area centering on Snively Ranch was studied. It lies northeast of the Rattlesnake No. 1 well where the Rattlesnake Hills turn from a northwest to a west trend. Workers⁽⁶⁵⁾ earlier than Newcomb postulated a thrust fault to account for the change in trend of the hills. Determination of the structure obviously was necessary in either case.

Two major anticlinal axes were traced into the area, one from the west, called the Rattlesnake Hills Anticline West, the other from the southeast, called the Rattlesnake Hills Anticline Southeast. The latter passes north of the one from the west and dies out west of Snively Ranch on the lower slope of the hills. A plateau, centering in the "slide" area, slopes gently northward between the two anticlines and includes a small intervening syncline. The (1) continuity of the northernmost anticline and adjacent syncline across the

Figure 9

Generalized Geologic Cross Section
Through the Snively Ranch Area of the Rattlesnake Hills

"slide," (2) generally gentle dips, (3) continuity of specific basalt flows, and (4) lack of rotated blocks, abundant breccia and true hummocky landslide topography in the main part of the area demonstrate that it is not a large slide. What appears to be hummocky topography is largely the normal erosional form of the Elephant Mountain flow that forms dip slopes on the plateau.

Numerous small slides, areas of Touchet sediments and colluvium lie along the steeply dipping north limb of the Rattlesnake Hills Anticline Southeast along Cold Creek Valley. They there obscure the structural details. The thrust fault earlier mapped by Hammer⁽⁶⁵⁾ does not exist as demonstrated by continuity of the basalt flows and the two anticlines across the fault trace without offset.

The idea that some previously mapped "slide" areas, such as the Snively Ranch area, are the result of similar overlap and offset position of anticlinal axes was confirmed by Stradling in the Horse Heaven Hills. Numerous bona-fide slides there are present, but the number is less than earlier thought. The number of possible earthquakes, based on "geologic indicators" similarly is less than earlier thought.

Landslides are occurring today in the Pasco Basin without triggering earthquakes. Evidence is increasingly abundant that most current slides result from ground saturation. Thus slides occur in all stages of development in the White Bluffs, particularly where the Columbia River undercuts the bluffs and where elevated or perched ground waters from the Columbia Basin Irrigation Project increase the instability of the Ringold Formation sediments. Excellent examples are in sec. 25, T.12N., R. 29 E.; in sec. 1, T.11.N, R. 28 E. where a U. S. Bureau of Reclamation concrete wasteway is threatened by renewal of movement on an old slide; and in sec. 32, T.13N., R. 27 E. subsequent to the 1967 high water stage of the Columbia River.

An attempt was made to determine the number of slides that have occurred in the White Bluffs in recent years. The geologic maps by Newcomb and Strand (1953) were examined. They show extensive landslides south of Wiehl Ranch (the east landing of the White Bluffs ferry) but none north of that. Inspection by boat showed, however, numerous landslides of several different ages, many expressed by the mapped topography. We can conclude that they did not study that portion of the bluffs.

Sliding also is reported by the Roadmaster of the Northern Pacific Railway Co. at Pasco⁽⁶⁶⁾ to require periodic regrading of the roadbeds of the railroad and U. S. Highway 410 three miles east of Prosser. Irrigation on Taunton Bench also causes continual sliding that requires routine maintenance of the Chicago, Milwaukee, St. Paul and Pacific Railroad there. Moreover, multiple lines of power poles that cross the Corfu slide show abundant evidence of tilting downslope. The Corfu slide continues to move, probably thousands of years following its formation.

Evidence strongly suggests that landslides in the Pasco Basin are fundamentally not related to earthquake activity. The primary cause appears to be saturation of the ground, probably in two main periods: (1) flooding of the basin by glacial melt and floodwaters between 10,000 and 20,000 years ago, and (2) excessive precipitation and irrigation subsequent to the Altithermal period.

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