COURSE OF COLUMBIA RIVER IN SOUTHERN CENTRAL WASHINGTON[1]

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ABSTRACT. The Columbia River probably once followed a course now marked by the belt of outcrop of the Hood River conglomerate, southwest from Sentinel Gap in the Saddle Mountains past Sunnyside and Goldendale, Washington, to Hood River, Oregon. This inference is based on the lithology of pebbles, on supposed windgaps in the crests of the two highest ridges along the inferred former course, and on the change from antecedence to structural control of the Columbia and Yakima rivers at points directly related to the inferred former course. This course it occupied at the end of the period of accumulation of the Yakima basalt. The present course from Sentinel Gap to Hood River, crossing the Horse Heaven Hills uplift at a structural low point 80 miles east of the former crossing at Satus Pass, is structurally controlled and must have originated after the beginning of deformation of the basalt. Diversion was probably the result of defeat of the river by the rise of the anticlinal ridge across its course, probably in late Pliocene or early Pleistocene time.

REGIONAL SETTING.

IN Miocene time and possibly continuing into the early Pliocene, successive flows of the Yakima basalt built up an extensive plateau covering much of southeastern Washington. This basalt surface has been deformed so that it varies in elevation from near sea level at Pasco and Hood River to more than 4,000 feet near Satus Pass. The basalt has been so little eroded that over most of its original extent its surface still determines the major topographic features. Thus differences in the deformation of the basalt give rise to distinct topographic divisions. The northern part of the basalt area stands high and is known as the Columbia Plateau, which is inclosed by the "Big Bend" of the Columbia River (Text Fig. 1). The surface slopes gently and rather uniformly southward into a lowland that has been called the Pasco Basin (Flint, 1938B, p. 224). West of the Pasco Basin is an area of asymmetrical anticlinal ridges steep on the north flank, which is that discussed chiefly in this paper.

[1] The second of two papers constituting part of a dissertation presented for the degree of Doctor of Philosophy in Yale University. The acknowledgments are not repeated here.

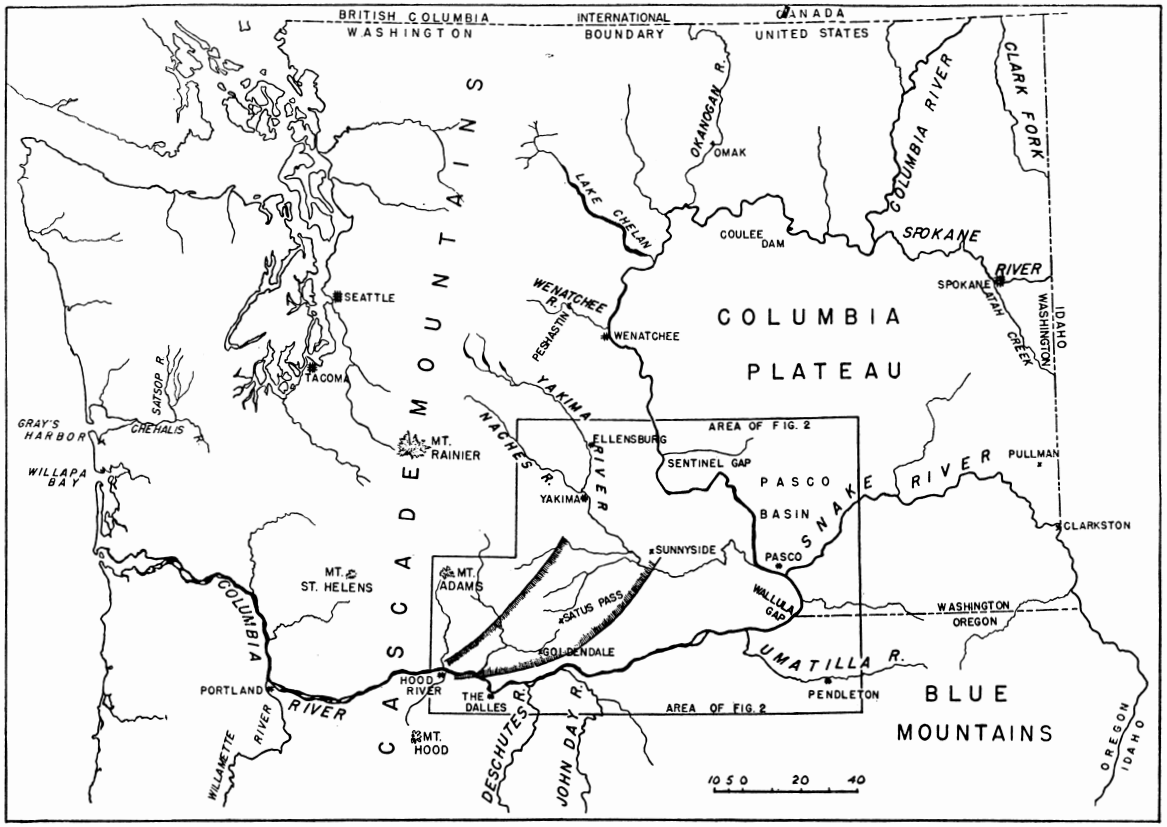

Fig. 1. Map of Washington and northern Oregon showing limits of known distribution of the Hood River conglomerate and boundaries of Text Fig. 2.

Named successively from north to south, the folds include the Saddle Mountains, the Umtanum-Hog Ranch Buttes ridge, Yakima Ridge, the Rattlesnake Hills, Toppenish Ridge, and the Horse Heaven Hills (Text Fig. 2). The Saddle Mountains uplift, through which the Columbia River cuts the spectacular Sentinel Gap, extends westward as Manastash Ridge. West of Union Gap of the Yakima River, the Rattlesnake Hills ridge is called Ahtanum Ridge. The southwestern part of the Horse Heaven Hills uplift, a minor, partially independent anticline, is called Stacker Mountain by Piper (1932, p. 125). The syncline (named *Toppenish Syncline* in Text Fig. 2) between the Rattlesnake Hills and the ridges to the south (Toppenish Ridge and the Horse Heaven Hills) has been called the Yakima basin, although the city of Yakima lies in another basin and the Yakima River flows through a number of synclines.

The trend of these features is generally east-west; the Rattlesnake Hills and the Horse Heaven Hills turn southeast in their eastern portions, parallel with the trend of older structures in the Cascade Mountains to the northwest (Waters, 1939B). The Horse Heaven Hills uplift continues southeast to merge with the Blue Mountains dome in northeastern Oregon, and forms the southern flank of the structurally closed Pasco Basin. The Columbia River escapes from the Pasco Basin through the Wallula Gap cut at a low point in the crest of the ridge.

In addition to these, structures exposed by the Columbia Gorge have been named the Ortley, Bingen, and Cascade Locks anticlines. These are less directly reflected in the topography, due in part to the presence of a younger volcanic cover, and their extents are less well known. The Ortley anticline may possibly be the southwestward extension of Stacker Mountain.

Toward the end of the period of extrusion of the Yakima basalt and continuing after its cessation, much of the area which has later been folded into the ridges just described was buried by the Ellensburg and Dalles formations and the Hood River conglomerate, which are preserved, locally to considerable thickness, in the synclines, but are largely stripped from the anticlines. They are late Miocene or early Pliocene in date (Warren, 1941).

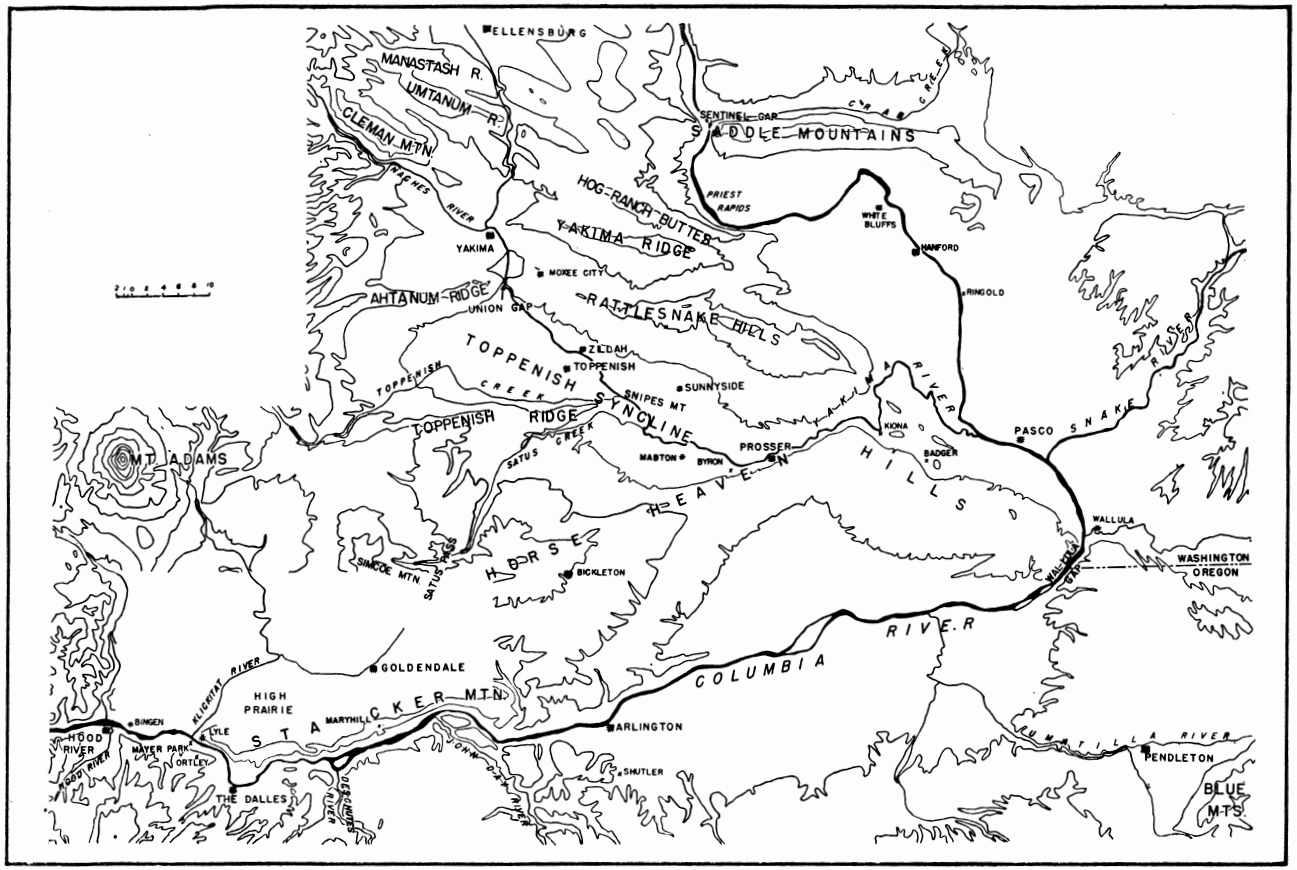

Fig. 2. Topographic map of part of southern central Washington. Contour interval 1,000 feet. Topography generalized from U. S. Geological Survey and E. T. Hodge. The feature here indicated as the *Toppenish Syncline* has been called the *Yakima Basin.*

FORMER COURSE OF THE COLUMBIA RIVER.

In southern central Washington the Hood River conglomerate appears to be confined to a belt extending from the neighborhood of Sentinel Gap, cut by the Columbia River through the Saddle Mountains, southwest past Sunnyside and Goldendale to the type locality of the conglomerate overlooking the Columbia at Hood River, Oregon (Warren, 1941) (Text Fig. 1). Though quartzite is an important component of the conglomerate, it does not crop out in the region, nor has it been found in the Cascade Mountains to the west. The nearest probable source of the quartzite pebbles appears to be the mountains of northeastern Washington and the adjoining parts of Idaho and British Columbia. The Columbia River today carries abundant quartzite pebbles, including types common in the Hood River conglomerate. For these and other reasons, the conglomerate is believed to mark an old course followed by the Columbia River prior to diversion to its present course 50 miles or more farther east. Detailed presentation of the evidence favoring this interpretation follows.

Source of Pebbles in the Hood River Conglomerate.

The quartzite pebbles abundant in the Hood River conglomerate raise the question of the sources from which they can have been derived, for the rock does not occur otherwise in the region. They cannot have been derived from the Columbia Plateau or from the areas of older basalts to the south, for the conglomerate postdates the mass of the basalt. They cannot have been derived from the west, for quartzite is not known in the Cascade Mountains (though this area is not yet adequately studied), and is not present in the contemporaneous Ellensburg formation (Warren, 1941) which was deposited by east-flowing streams (Smith, 1903, p. 18). The similar quartzite-free Dalles formation was probably derived contemporaneously from the southwest, from the Cascade Mountains south of the present Columbia River Gorge. On the other hand, quartzites do occur among the old rocks north and east of the Plateau. Russell (1902, p. 45) mentions quartzites in the basin of the Snake River, and such rocks occur abundantly northeast of the Plateau in the area drained by the upper Columbia. W. A. G. Bennett has collected in Stevens County, northeastern

Washington, specimens of a foliated quartzite which closely resembles a type common in the Hood River conglomerate.

The streams draining a given area should carry pebbles representing the rock types now important in their respective drainage basins which are resistant enough to persist as stream pebbles. Recent gravels should thus indicate possible sources of pebbles in an ancient gravel. Formations or facies formerly actively eroded might be covered by younger formations, or be so completely eroded that they no longer provided pebbles to streams, but these are probably not important factors in the present problem: there is no important post-basalt cover, and the structural complexity of the pre-Cenozoic rocks precludes the probability of the complete removal of formations formerly widespread. A serious difficulty does arise from important changes believed to have occurred in the courses of the streams of northern Washington during the Pleistocene glaciations (Willis, 1887), as the streams may not now be deriving a considerable part of their load from areas formerly actively eroded. For instance, no gravel is contributed to the Columbia today from the areas drained by the Clark Fork above the settling basin of Pend Oreille Lake.

Nevertheless, the gravels carried today by the various streams in the region surrounding the Columbia Plateau are probably important guides to the bedrock types that have occurred ever since Miocene time in their respective drainage basins. Accordingly, random samples of 100 pebbles between one and three inches in diameter were collected from recent deposits of streams, as follows: the Yakima River above Ellensburg, the Wenatchee River one quarter of a mile south of Peshastin, the Okanogan River at Omak, the Columbia River three miles below Coulee Dam, and the Snake River at Clarkston.

The Yakima River carries chiefly extrusive igneous rocks. Included in the count were one vein quartz, a silicified volcanic, and two sandstones which appear megascopically to be quartzose but which do not resemble types important in the Hood River conglomerate. The Wenatchee River carries intrusive and metamorphic rocks of varied types, including abundant amphibolite schist. Volcanics are also present, but no quartzites were found. The Okanogan, upper Columbia, and Snake rivers, on the other hand, all carry quartzite pebbles of types

present in the Hood River conglomerate. The more abundant types of the Hood River stones find parallels in the gravel of the upper Columbia, but not all of the types are present there; some of the types are present in the Okanogan and Snake rivers.

Thus the study of Recent stream gravels supports the inference from the known distribution of bedrock that the foreign stones in the Hood River conglomerate came from east and north of the Plateau. The conglomerate below the vicinity of Sunnyside was probably deposited by an integrated Columbia River which carried the drainage of the Snake and Okanogan rivers as well.

Windgaps in Crests of Anticlinal Ridges.

Further evidence that the Columbia River formerly took the course marked by the Hood River conglomerate is the presence of probable windgaps in the crests of the two highest ridges along that course. The initial forms of the anticlines in the area are in general well preserved, for the basalt is little eroded, though the weak cover of the Ellensburg formation has been stripped off. Exceptions to the rule that the basalt is little eroded are the watergaps where the transverse streams, whatever their origin, cut through the ridges and expose magnificent sections of the basalt sequence, as at Sentinel Gap (Plate I, Fig. 2), Wallula Gap (Plate I, Fig. 3), and Union Gap. Two other definite gaps which are not only unoccupied by streams but are hanging at both ends will now be described.

Gap north-northeast of Sunnyside. The crest line of the Rattlesnake Hills is undulating (see Pasco, Prosser, Zillah, Hog Ranch Buttes, and Yakima East quadrangles, U. S. Geol. Survey topographic maps), varying only gradually in height except at one point, 11 miles north-northeast of Sunnyside, where there is a steep-sided gap, 1,100 feet deep (followed by the Sunnyside-White Bluffs road near the northwest corner of the Prosser quadrangle). This gap was not formed by processes in action today. Erosion there has been deep, but the floor of the gap is now being aggraded by small piedmont fans deposited by drainage from the sides. Gullies draining the gap to the north and south today carry small, intermittent streams; other streams of comparable size in the region have nowhere

accomplished erosion of any comparable amount since the anticlinal ridges were uplifted.

Satus Pass. The crest of the Horse Heaven Hills, well shown on the Pasco, Prosser, and Zillah topographic maps, is similarly undulating, rising from the Columbia at Wallula Gap to 2,200 feet, then declining gradually to about 1,500 feet at the head of Webber Canyon, thence rising again to 2,046 feet near the eastern edge of the Prosser map, and so forth. But at no point through the mapped distance of 75 miles is there any steep slope not patently due to gullying on the steep north face of the uplift. On the other hand, northeast of Goldendale (unfortunately just outside the area for which topographic maps are available), the condition is very different. At this point a gap known as Satus Pass (Plate I, Fig. 1) is incised more than 1,100 feet below the adjoining portions of the Horse Heaven Hills.[2] West of the gap the similarly steep slope rises to the much higher Simcoe Mountain, with a topographic break in slope at about 4,700 feet. The gap thus appears to have been incised on the flank of an eastward-plunging ridge.

The Satus Pass gap is not the result of present-day erosion. Satus Creek, draining it to the north, does not even head there, but flows east until it turns sharply north almost opposite Satus Pass. Other streams of comparable size have nowhere cut so deeply into the crests of basalt ridges; it appears that the erosion of this gap must antedate the present drainage.

Interpretation of the gaps. The two gaps just described resemble the watergaps elsewhere in this region in that they are notches cut into the crests of anticlines without evident lithologic or structural control; they are steep-sided, each with conspicuous breaks in slope at its shoulders. No other features save the watergaps are incised so deeply into the basalt.[3] But the dry gaps differ from the watergaps in that the slopes are much more nearly graded: the flanks of the gap north-northeast of Sunnyside are reduced to nearly smooth, sage-covered concave-up slopes, although some cliffy basalt is present, and the flanks of Satus Pass are covered with forest. The watergaps, on the other hand, are steeply cliffed, with bare talus

[2] Hills above 4,250 feet; bench mark in Satus Pass, 3,146 feet, is above floor of pass.

[3] A dry coulee extending southeast from Kiona, shown on the Pasco quadrangle, is less deeply incised than these notches. It is interpreted as a former course of the Yakima River.

FIG. 1.

FIG. 2.

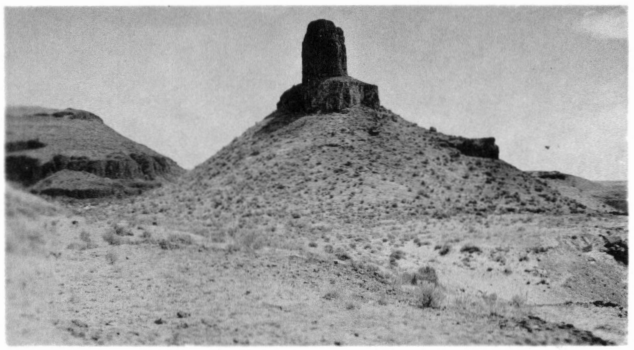

FIG. 3.

FIG. 1. View north-northeast at Satus Pass, showing abandoned notch in Simcoe Mountain—Horse Heaven Hills ridge, from summit of Stacker Mountain northeast of Maryhill.

FIG. 2. View northwest across Columbia River at west wall of Sentinel Gap. Note ungraded cliffs and steep talus slopes.

FIG. 3. Detail in Wallula Gap showing isolated basalt remnant. Contrast Figs. 2 and 3 with Fig. 1.

between successive tiers of columnar basalt (Plate I, Figs. 2, 3). It seems probable that the dry gaps have the same origin as the watergaps, but that the stream or streams which cut them ceased to flow through them after part but not all of the folding had occurred.

Absence of windgap south of Priest Rapids. The Columbia River, flowing south from Sentinel Gap in the Saddle Mountains, turns sharply east at Priest Rapids along the base of the Umtanum-Hog Ranch Buttes ridge. The lack of a windgap in the ridge south of this turn might be cited as evidence that the Columbia did not cut the windgaps in the Rattlesnake Hills and Horse Heaven Hills to the south, but the ridge, though high at Priest Rapids, plunges eastward, and disappears within ten miles (Priest Rapids and Coyote Rapids quadrangles, U. S. Geol. Survey topog. maps). If, at the initiation of uplift, the Columbia below Sentinel Gap chanced to be flowing but a few miles east of its present course, it would not have encountered the rising basalt ridge.

The broad terraced flats in the Ringold formation east and northeast of Priest Rapids are erosional rather than constructional features, for they are well below the elevation up to which the Ringold formation was built. They cannot have been eroded by local runoff, for their distribution is not that of terraces cut by lateral planation by small streams, and the lower and hence younger terraces preserve channels and bars which could not have beeen formed by small streams. They must have been cut by the Columbia, which has therefore shifted laterally over a wide area and may have been far east of Priest Rapids at the beginning of the deformation. In that case no windgap is to be expected in the Umtanum-Hog Ranch Buttes ridge.

Summary of windgap evidence. It thus appears that if at the beginning of the deformation the Columbia River took a course within the belt of the Hood River conglomerate, it would have crossed two anticlines but perhaps no others. Both anticlinal ridges carry within the area of Hood River conglomerate deeply eroded gaps that are not due to present stream erosion and are unexplained unless they were cut by a major stream or streams subsequently diverted. The inference is made that the Columbia did take a course through the gaps, and that it was diverted from that course after a part but not all of the

deformation. A rough estimate suggests that between a third and a half of the uplift antedates the diversion, for the incision amounts to about 1,100 feet, and the windgaps hang some 1,500 and 2,400 feet respectively above the floor of the Yakima Basin today.

Change in Control of Columbia River Below Sentinel Gap.

At and upstream from Sentinel Gap, the course of the Columbia is indifferent to structure and is probably antecedent. Thus Chappell (1936, p. 385) infers antecedence where the Columbia enters the area of the Yakima basalt, ten miles below Wenatchee, because the lavas dip gently northeast and the river flows southeast. Sentinel Gap is a striking example of discordance, for the Columbia could have found a much lower structural and topographic passage around the eastern end of the Saddle Mountains. This eastern course, indeed, was taken by glacial meltwater which poured across the Plateau from its northern edge (Bretz, 1928, Plate V).

Downstream from Sentinel Gap, on the contrary, the Columbia River does not cut through the ridges, but instead detours far eastward down a structural depression around the ends of the Umtanum-Hog Ranch Buttes ridge, Yakima Ridge, and the Rattlesnake Hills. Where it finally reënters a canyon and cuts Wallula Gap through the Horse Heaven Hills uplift, it does so at a structural low point in the crest of that ridge. The plunge of the basalt ridge from both directions toward Wallula Gap distinguishes the latter from the other gaps characteristic of the region (e. g. Satus Pass, Sentinel Gap, Union Gap). From Wallula Gap westward to The Dalles the Columbia follows approximately the axis of a synclinal depression. Thus the course from Priest Rapids all the way to The Dalles appears to be controlled by the structures in the basalt, and therefore probably was initiated after the inception of the deformation of the basalt.

If the belt of outcrop of the Hood River conglomerate marks a former course of the Columbia River, that course is antecedent to present structures, as shown by the probable conformity of the conglomerate on the basalt and by the anticlinal ridges it crosses. It diverges from the present course below Sentinel Gap, just where the stream turns eastward and changes from independence of structure to complete structural

control. This coincidence supports the belief that the present structurally controlled course originated, after deformation had blocked out present structures, by diversion from a former antecedent course, and that that antecedent course is the one marked by the Hood River conglomerate.

Similar Change of Control of Yakima River.

Smith (1903, p. 32) believed that the Yakima River at Union Gap is antecedent to the Ahtanum Ridge-Rattlesnake Hills anticline. It must also be antecedent to Yakima Ridge at Selah Gap, immediately north of Yakima, for the Naches River cuts an independent gap to a point south of the axis of the anticline, and there joins the Yakima, though there is no evidence of any post-deformational cover thick enough to have superposed the streams on the ridge. Moreover, if the Yakima had ever escaped eastward down the syncline from the Selah Valley north of the gap, traces of the valley would be recognizable today, but there are none. North of the Selah Valley and extending to the Kittitas Valley in which the town of Ellensburg lies, is an uplifted area consisting of Manastash Ridge, Umtanum Ridge, the Cleman Mountain anticline, and the intervening synclines. The Yakima River is incised throughout this part of its course; the resulting canyon preserves an incised meander-pattern which strikingly demonstrates the antecedent origin of this portion of the course of the Yakima River.

Below Union Gap, however, the Yakima is apparently so weak as to have been diverted from the axis of the valley by a fan that it built during the Wisconsin glaciation. As far as Snipes Mountain it follows the crease where this fan abuts against the older higher surface to the northeast. Below that point it follows the axis of the syncline to Kiona, and appears to be consequent on the folded surface of the basalt. At Kiona, the Yakima turns north across the axis of the Rattlesnake Hills ridge, but the watergap is shallow, because it occurs at a structural low point in that axis where it converges with the Horse Heaven Hills. It might well have originated by superposition from the Ringold formation, remnants of which occur up to higher elevations today.

This striking change in the control of the Yakima, from antecedent to consequent, occurs at the very point where it crosses

the former course of the Columbia as that is inferred from the distribution of the Hood River conglomerate. Union Gap, the farthest downstream of the antecedent gaps, is cut in the last ridge that would have been crossed by an antecedent Yakima River tributary to a Columbia following the course indicated by the windgaps and the conglomerate. This supports the inference that the Columbia River did actually follow such a course at the time of the inception of the deformation of the basalt that gave rise to the watergaps.

Summary of Evidence of Former Course of Columbia.

Thus three lines of evidence indicate that the Hood River conglomerate marks the former course of the Columbia River from the vicinity of Sentinel Gap southwest past Sunnyside and Goldendale to Lyle and Hood River. These are:

(1) The lithology of the conglomerate itself and the possible bedrock sources whence the pebbles in it can have come,

(2) Deep gaps, probably cut by a major stream or streams, now dry and hanging in the crests of the two highest anticlinal ridges along the belt of outcrop of the conglomerate, and

(3) Change of both the Columbia and Yakima rivers from antecedent streams to structurally controlled streams at points closely related to the belt of outcrop of the Hood River conglomerate.

DEFEAT AND DIVERSION OF THE COLUMBIA RIVER.

The evidence that the Columbia River formerly flowed southwest from Sentinel Gap in the Saddle Mountains raises the question as to how the stream was diverted from this former course into its present course 50 miles or more farther east. The former course is unrelated to present structures and appears to be antecedent to them, whereas the present course, being structurally controlled, was probably assumed after the beginning of the deformation. The fact that the windgaps hang high above the structural valleys suggests that the diversion occurred before the deformation had progressed very far. It seems probable that diversion may have been due to defeat by the rising of the anticlines across its path.

As the anticlines started to rise across the former path of the Columbia, the steepened gradient downstream from each would stimulate downcutting, forming gaps such as Sentinel

Gap and Satus Pass. Correlatively, the gradient upstream from a rising ridge would be decreased, and the stream would aggrade and might even be ponded. If the hydraulic gradient were thus raised sufficiently to permit the water to spill over into a lower channel around the end of the ridge, the antecedent course would be abandoned in favor of the easier consequent one.

The rising obstacle of the broad and high Horse Heaven Hills uplift would have formed an important local baselevel that might readily have raised the stream profile progressively until the water finally spilled over at the low point in the rim of the newly-forming Pasco Basin, namely at Wallula. If this occurred, the diverted course could readily have been established in the course followed by the Columbia today. No other date or manner of diversion to such a structurally controlled course is evident, and it seems probable that the present course originated in this manner.

Ringold Deposition During Defeat.

Before the Columbia was diverted, it and its chief tributary the Snake River must have dropped abundant alluvial or lacustrine deposits north of the rising anticlines. Remnants of these should be preserved today, for such an extensive deposit could scarcely have been completely removed by erosion in a period of time insufficient to permit more erosion in the basalt ridges than is found today. Though the deposits of the Yakima Basin and Pasco Basin areas have not yet been studied in sufficient detail, it seems unlikely that important undescribed formations exist. The only known formation younger than the Ellensburg, except for glacial deposits believed to postdate the deformation (Flint, 1938A, pp. 516-519), is the Ringold formation. This, then, probably represents the body of detritus accumulated during the defeat of the Columbia River just prior to the diversion.

Ringold formation. The Ringold formation is a body of sedimentary beds partly filling the Pasco Basin. Merriam and Buwalda (1917), who first described the formation, believed it to be undeformed, but Culver (1937) states that "While both [the Ellensburg and Ringold] formations have been deformed by warping, only the Ellensburg beds have suffered marked deformation." This is entirely compatible with the inference

that the Ringold was deposited during and as a result of the warping. No other adequate explanation has been offered for the cause of the accumulation of the deposit, more than 500 feet thick in a single exposure (Merriam and Buwalda, 1917, p. 261), and perhaps originally more than 1,000 feet thick (Flint, 1938B, p. 226; Waters, 1939B).

Extent of the Ringold. Culver (1937) believes that the Ringold formation occurs widely over the area north of the Horse Heaven Hills, though paleontological evidence will be necessary to establish this belief. He also reports "exposures of Ringold-like sediments, even on the south slopes of the Horseheaven Hills," and infers that the Ringold was formerly continuous across the ridge. However, no Ringold remnants have yet been described on the Horse Heaven Hills, and pending study of their sedimentary petrology, there is no proof that the beds on the south side of that ridge were ever continuous with the type Ringold north of the ridge. They may belong to the Shutler (†Arlington) formation of Hodge, which may very possibly have been deposited in a distinct basin inferred to have formed in northern Oregon contemporaneously with the formation of the Pasco Basin, as is discussed below.

Fluvial or lacustrine origin of the Ringold. The early students of the type Ringold beds considered them to be largely or wholly lacustrine (Russell, 1893, p. 23; Smith, 1903, p. 18; Calkins, 1905, p. 36), but Merriam and Buwalda (1917, p. 263) believe the formation is probably "largely of floodplain origin." The lower part of the formation must be fluvial, as shown by asymmetric ripple marks (Plate II, Fig. 3) and by the localized occurrence of the terrestrial vertebrate fossils. One may walk for miles along the bluffs north and south of Ringold without finding a single fossil, and then come on a spot with a great abundance of material derived from a variety of species. This distribution is hardly to be expected if the animals were floated out into a lake as Russell suggests (1893, p. 99), but can readily be explained as due to the presence of localized quicksand in an aggrading fluvial plain. If aggradation continued to keep the basin filled as fast as it deepened, the Columbia may never have been ponded.

Summary. Thus the Ringold formation was probably deposited within the closure of the Pasco Basin north of the Horse Heaven Hills during the defeat of the Columbia River just prior to the diversion from the former course via Sunny-

side and Goldendale to the present course via Pasco and Wallula. The deformation causing the defeat was probably slow, for the Columbia was probably not ponded during the deposition of at least the lower part of the Ringold.

Consequent Course Below Wallula.

When the Columbia was diverted by spilling over the Horse Heaven Hills ridge at Wallula, it must have taken a consequent course on the previously developed topography of the basin south of that ridge. The Umatilla, John Day, and Deschutes rivers, entering that basin, carry too great a discharge to permit postulating a basin of interior drainage; their waters must have escaped in some manner to the sea, and the Columbia must have followed the course of this previous drainage. Inasmuch as the present course of the Columbia is independent of the inferred old one as far downstream as Lyle (11 miles east of Hood River), the Oregon drainage must at that time have been integrated into a single stream that must have crossed the Ortley anticline at the site of the present Gorge to join the Columbia at Lyle.

The diverted course of the Columbia follows approximately the axis of a syncline from Wallula Gap to The Dalles. This suggests that just before the diversion of the Columbia, the Oregon drainage must have followed a course determined after the beginning of deformation. The still earlier, pre-deformation drainage may have entered the Snake-Columbia with normal acute-angled junctions, but may have been defeated by the uplift of the Horse Heaven Hills. The defeated streams must have united and crossed the Ortley anticline at a low point which may have been localized by a fault.

The Columbia River would have intrenched itself rapidly in the gap at Wallula, for the structural slope was steep and in this distance of less than ten miles it concentrated much of the fall previously distributed over more than 50 miles of its inferred former diagonal course across a wider part of the uplift. Furthermore, the stream did less work in removing debris derived from the sides of the shallower canyon, and was thus freer to work at downcutting. As trenching progressed, however, it would have begun to re-excavate the Ringold material previously deposited upstream from Wallula, and the increased load thus acquired would have retarded downcutting.

Similar trenching into the Ortley anticline may be reflected by the incised meander-pattern in the middle portions of the courses of the John Day and Deschutes rivers (Hodge, 1931, pp. 978, 981, 983). Possibly the latter were meandering sluggishly northward, tributary to a lake or aggrading fluvial plain, held up by the rising Ortley anticline, which may be recorded by the Shutler (†Arlington) formation of Hodge (1930, p. 407; 1931, p. 964; 1932, p. 6; 1938, pp. 869-871). The increased discharge passing through the Ortley anticline as soon as the Columbia spilled over at Wallula would have rapidly deepened the gap. The streams from the south would thus have been rejuvenated and intrenched, but they would not develop meanders in their lower courses. A somewhat similar hypothesis was suggested by Hodge (1931, pp. 978-984).

In summary, the Columbia must have taken a consequent course on the surface south of the Horse Heaven Hills uplift. This surface was partly initial and probably partly constructional, but was probably almost unmodified by erosion except for some trenching at the Ortley anticline. The Columbia became intrenched in this new course, at first rapidly and then more gradually.

Repeated Diversion of the Columbia River.

The Ringold formation in the Pasco Basin occurs today up to elevations considerably higher than the crest of the east end of the Rattlesnake Hills where that ridge converges with the Horse Heaven Hills west of Pasco. Both the Snake and the Columbia (which presumably jointly deposited the formation) must therefore have been flowing on a profile so high that the Columbia must have been detoured around the east end of the Rattlesnake Hills. Though the Columbia cut the gap in the Rattlesnake Hills 11 miles north-northeast of Sunnyside to a depth of 1,100 feet, it must have been diverted from that gap some time before the final diversion at Wallula, because that diversion ended the deposition of the Ringold and initiated the erosion that still continues. Thus the Columbia must for a time have reached Satus Pass by flowing down the structural slope from Kiona to Sunnyside. The Yakima River now follows the same valley in the opposite direction, against the plunge of the syncline.

Date of the Diversion.

If the Ringold formation was deposited during the deformation prior to the diversion at Wallula, its date defines approximately that of the diversion. Merriam and Buwalda (1917) describe two collections of vertebrate fossils from the formation and conclude (p. 260) that "The evidence on the whole favors Pleistocene rather than the latest Pliocene" for its date.

A priori reasoning might lead to the supposition that the folding of the basalt was incidental to collapse following the removal of subjacent magma (Hodge, 1938, p. 849), though basalt accumulation was doubtless slow enough to permit isostatic adjustment and the surface was probably never as high as the present ridge crests as Hodge suggests (1938, p. 849). It might then be assumed that folding followed hard on the heels of the cessation of basalt extrusion (Hodge, 1938, p. 869), but the evidence of the Ringold formation seems more trustworthy than such hypothesis as to the origin of deforming stresses, especially in the Pacific Coast region which has elsewhere been tectonically active repeatedly through the Cenozoic.

Hood River conglomerate occurs east of the course shown by the windgaps to have been that occupied by the Columbia at the beginning of uplift of the anticlines. Moreover, if beds described by Twiss (1933) and Culver (1937) on the summit of the Saddle Mountains are derived from the west, the Columbia must have been east of its present course at the time they were deposited. If they prove to belong to the Ellensburg formation, the river must have shifted westward after the deposition of the Ellensburg but before the deformation. Such westward shifting would shorten the course of the Columbia, and would be favored by the difference in resistance to erosion between the hard basalt of the east bank and the weak sedimentary beds of the west bank.

The preserved meander pattern of the Yakima River in the uplifted area south of Ellensburg, its southerly course, and the normal drainage pattern suggested by the acute-angled junctions of the Naches with the Yakima (preserved in Selah Gap) and of the Yakima with the inferred former Columbia (near Sunnyside) point to a pre-deformational interval of stability during which the streams were free to cut laterally in the Ellensburg formation, for the drainage pattern on the

Ellensburg fan at the end of its accumulation should have been radially eastward. This period of stability following the extrusion of the Yakima basalt agrees with the evidence that the Columbia shifted laterally westward in the Ellensburg formation, and implies that the deformation did not immediately follow the cessation of basalt extrusion.

The evidence corroborates the inference from the Ringold formation that there was an interval between the accumulation of the basalt and its deformation. If the Columbia was diverted when the deformation had reached roughly a third or a half of its present amount, and if the Ringold formation was deposited in response to the pre-diversion part of the deformation, the deformation may have started in the late Pliocene but was probably chiefly Pleistocene in date.

Possible Discontinuous Deformation.

There is little to suggest any pre- or post-diversion halts in the rise of the ridges in the area here discussed. The only undoubted second-cycle erosion form I have seen is on the north side of Yakima Ridge northeast of Yakima, where the flat-topped interfluves are parallel to the present stream profiles but are not parallel to the structure of the weak Ellensburg beds on which they are cut. The feature may well correlate with that described in Kelley Hollow (see Waters, 1939A, p. 644); it appears to be a sort of pediment graded by the streams draining Yakima Ridge when the Yakima River was flowing on a profile higher than the present one. The inferred rejuvenation of the Yakima River does not necessarily imply recent deformation, however, for it might result from the diversion of the river from a possible former course through resistant basalt southeast of Kiona, or it might be of purely climatic origin as has been suggested for similar features elsewhere in the arid West. The probability of such a climatic change has been suggested by Russell (1897, p. 28).

All other evidence suggests that the ridges rose continuously. The summit of Toppenish Ridge at the triangulation station south of Toppenish is capped by the uppermost basalt flow exposed on the flanks of the ridge, showing that there has been no peneplanation truncating slightly uplifted ridges there such as Smith (1903, p. 34) infers in the Ellensburg quadrangle. The windgaps at Satus Pass and north-northeast of Sunny-

side do not have compound cross-profiles. Any important phase of uplift should have retarded the streams and should be marked by deposits today, but the Ringold formation is the only known formation in the region intermediate in date between the Ellensburg, which is comformable on the basalt, and glacial deposits believed to postdate all of the deformation. Thus, although there may have been more than one deformation here as in John Day basin to the southeast, it seems possible that most if not all of the deformation recorded by the attitude of the basalt today may have occurred during a single period of warping.

Summary of Defeat and Diversion.

The Columbia River was probably diverted from an antecedent course from Sentinel Gap southwest past Sunnyside by defeat during the rise of the broad and high Horse Heaven Hills uplift across its path. The stream aggraded, and whether it was eventually ponded or not, the water rose high enough to spill around the east end of the Rattlesnake Hills and later to spill over the crest of the Horse Heaven Hills at a structural low point at Wallula. The course from Wallula to Hood River is consequent on the previous topography of the basin south of the divide. The Ringold formation probably represents the deposits formed north of the rising barrier before the final diversion, and probably dates the principal deformation in the area studied as early Pleistocene. The bearing of this conclusion on the date of uplift of the Cascade Mountains is not known; the rise of the greater north-south mountain mass need not have coincided with that of the east-west Horse Heaven Hills.

ORIGIN OF FORMER COURSE OF THE COLUMBIA RIVER.

According to the above interpretations, at the end of the period of basalt accumulation the Columbia River followed a course from Wenatchee past Sentinel Gap, Sunnyside, and Goldendale to Hood River (Text Fig. 1). The whole describes a single wide arc on the map of the State of Washington, and probably forms a single unit whose origin may be discussed as such, though later diversion from part of the course has divided it into two segments. The course lies within the basalt area, and differs in this respect from that above Wenatchee.

From the junction of the Spokane River, where the Columbia

first encounters the Yakima basalt, to Wenatchee, the stream follows approximately the contact between the basalt and the older crystalline rocks to the north. This has been interpreted (Willis, 1887, p. 7; Pardee, 1918, p. 46; Waters, 1930, p.252) as indicating that this portion of its course was diverted by the accumulating lavas. The previous drainage was centripetal toward what is now the Plateau, but the lava dam caused the various streams to spill over the divides between adjacent drainage basins, and eventually to become integrated as a new consequent stream following the crease between the initial north slopes of the lavas and the old south-sloping surface.

At Wenatchee, the Columbia River abandons the basalt margin and plunges boldly into the basalt area. The cause of this change in the habit of the stream is discussed by Chappell (1936). He rejects (p. 385) the hypothesis that rise of the Wenatchee Mountains anticline diverted the river from a former continuation of the basalt marginal course westward from Wenatchee, because he finds no indication of any pre-diversion valley. Study of the Hood River conglomerate has shown that the Columbia followed the course across the basalt long prior to the deformation and supports Chappell's conclusion. Alternative hypotheses of antecedence for the origin of the Wenatchee-Goldendale course will therefore be discussed.

Control by Hypothetical Volcanoes.

Chappell (1936, p. 386) believes that

> ". . . the southeastward deflection of the Columbia River into the Plateau at Wenatchee was in direct response to floods of basalt, the river following the junction line between the easterly advancing lavas erupted from the vicinity of the western margin and the main body of the basalt series from within the plateau."

The difference between the basalt in the Toppenish syncline region and that of the Plateau proper (Warren, 1941) suggests that the basalts were derived from different sources, lending support to Chappell's hypothesis that the river followed the topographic low point between two large-scale volcanoes.

Superposition from the Ringold Formation.

Twiss (1933) and Culver (1937) report sediments of Ringold age on the summit of the Saddle Mountains east of the

Columbia River. As these are not considered to have been deposited at their present elevation, it might be contended that the rise of the Saddle Mountains anticline postdated that of the Rattlesnake Hills, and that aggradation upstream from the gap north-northeast of Sunnyside may have been extended headward up to Wenatchee. The Columbia, no longer confined to its previous channel, may have shifted widely over the surface of the Ringold and may have been superposed on the underlying basalt when the uplift caused it to be incised. Some of the curves of the river between Wenatchee and Vantage resemble incised meanders that might record such an episode.

However, no paleontological evidence has been advanced in support of lithologic correlation between the deposits in question and the Ringold. If, as seems likely, the beds prove to be of Ellensburg date, the above hypothesis fails. In any case, the quartzite-bearing conglomerate interbedded in the basalt at Sentinel Gap seems unlikely to be much younger than the Ellensburg formation; it indicates that the Columbia River followed a course similar to its present one long before the Ringold formation was built.

Obstruction by the Ellensburg Formation.

The presence of Hood River conglomerate interbedded with the basal portion of the Ellensburg formation (Warren, 1941) suggests that the Ellensburg fan (known to have been derived from the west: Smith, 1903, p. 18) may have caused the ancestral Columbia to shift successively farther eastward. The course from Wenatchee via Sentinel Gap and Sunnyside to Satus Pass would then be fan-marginal, consequent on the crease between a great piedmont fan and the initial westward slopes of the plateau basalt. The wide belt of occurrence of the Hood River conglomerate in the latitude of the Rattlesnake Hills may reflect shifting of the Columbia as the Ellensburg fan was built.

It thus seems probable that the inferred Pliocene course of the Columbia from Wenatchee via Sentinel Gap, Sunnyside, and Goldendale to Hood River may have been consequent on the crease between the Ellensburg fan and the initial northwest slopes of the plateau basalt, although it may also have been determined (perhaps in part) by a large low basaltic volcano west of the main mass of the basalt.

CHRONOLOGICAL SUMMARY.

In summary, the drainage changes inferred above to have taken place in southern central Washington will be described in chronological order.

1. The accumulation of the Yakima basalt (Miocene and perhaps in part early Pliocene) diverted streams previously converging from the north and northwest. The streams became integrated as a new Spokane-Columbia River marginal to the basalt as far as Wenatchee. There it turned to enter the basalt area, following the crease between the plateau basalt and either local basalt flows from the west or the fan of the Ellensburg formation or both. This crease led it past Sentinel Gap, Sunnyside, and Goldendale to Hood River. Drainage on the Ellensburg fan was presumably radial. The Snake River crossed the basalt plateau from its eastern edge (Flint, 1938B, p. 225), perhaps joining the Columbia near Sunnyside.

2. The deposition of the Ellensburg continued for a time and probably forced the fan-marginal Columbia progressively eastward.

3. Erosion dominated for much of the Pliocene, and the land was probably stable. The Columbia shortened its course by planing westward again in the weak Ellensburg beds. Streams formerly radial eastward on the Ellensburg fan became integrated into the Yakima River meandering south to join the Columbia with normal acute angle near Sunnyside. The Umatilla, John Day, and Deschutes rivers of northern Oregon may have entered the Snake-Columbia independently of each other.

4. The basalt folds that control the present topography began to rise in late Pliocene or early Pleistocene time. The Umatilla, John Day, and Deschutes rivers were soon defeated by the Horse Heaven Hills uplift, and became integrated into a single stream crossing the Ortley anticline at the site of the present Columbia Gorge.

5. The Horse Heaven Hills rose faster than the Columbia could erode Satus Pass. The river therefore began to deposit the Ringold formation upstream, and was diverted into a course from Sentinel Gap around the east end of the Rattlesnake Hills, perhaps joining the Snake near Kiona and following the syncline westward to Sunnyside. The Oregon rivers simultane-

ously aggraded in the basin south of the Horse Heaven Hills, developing meander patterns in parts of their courses.

6. The hydraulic profile of the Snake-Columbia rose so high that the water spilled over the Horse Heaven Hills at the structural low point at Wallula. The diverted stream established a consequent course on the surface of the basin south of the uplift, crossing the Ortley anticline where its own former tributary had crossed.

7. The diversion of the Columbia left the Yakima River to cut Satus Pass unassisted. Unequal to the task, the Yakima was defeated and diverted to a structurally controlled course east from Sunnyside, joining the Columbia not far above the new Wallula Gap.

8. The trenching of the streams in their new courses was at first rapid, and meanders of the John Day and Deschutes rivers were caught and preserved. Subsequent changes in the locations of the streams include migration of the Columbia by lateral planation in the Ringold formation between Sentinel and Wallula gaps, a possible diversion of the Yakima below Kiona, and minor changes due to aggradation during glacial periods.

WORKS TO WHICH REFERENCE IS MADE.

Bretz, J Harlen: The channeled scabland of eastern Washington, Geogr. Rev., Vol. 18, pp. 446-477, 1928.

Calkins, Frank C.: Geology and water resources of a portion of east-central Washington, U. S. Geol. Survey Water-Supply and Irrigation Paper No. 118, 1905.

Chappell, Walter M.: The effect of Miocene lavas on the course of Columbia River in central Washington, Jour. Geol., Vol. 44, pp. 379-386, 1936.

Culver, Harold E.: Extensions of the Ringold formation, Northwest Science, Vol. XI, pp. 57-60, 1937.

Flint, Richard Foster: Origin of the Cheney-Palouse scabland tract, Washington, Bull. Geol. Soc. Am., Vol. 49, pp. 461-524, 1938A.

————: Summary of late-Cenozoic geology of southeastern Washington, Amer. Jour. Sci., Vol. 35, pp. 223-230, 1938B.

Hodge, Edwin T.: Late Tertiary climatic changes in Oregon, Monthly Weather Review, Vol. 58, pp. 405-411, 1930.

————: Columbia River Fault, Bull. Geol. Soc. Am., Vol. 42, pp. 923-984, 1931.

————: Geological map of north central Oregon [text accompanying map], Univ. Oreg. Pub., Suppl. to Geol. Ser., Vol. 1, No. 5, 1932.

————: Geology of the Lower Columbia River, Bull. Geol. Soc. Am., Vol. 49, pp. 831-930, 1938.

Merriam, John C., and Buwalda, John P.: Age of strata referred to the Ellensburg formation in the White Bluffs of the Columbia River, Univ. Cal. Pub., Bull. Dept. Geol., Vol. 10, No. 15, pp. 255-266, 1917.

Pardee, J. T.: Geology and mineral resources of the Colville Indian Reservation, Washington, U. S. Geol. Survey Bull. 677, 1918.

Piper, Arthur M.: Geology and ground-water resources of The Dalles region, Oregon, U. S. Geol. Survey Water-Supply Paper 659-B, 1932.

Russell, Israel C.: A geological reconnoissance in central Washington, U. S. Geol. Survey Bull. 108, 1893.

————: A reconnoissance in southeastern Washington, U. S. Geol. Survey Water-Supply and Irrigation Paper No. 4, 1897.

————: Geology and water resources of the Snake River Plains of Idaho, U. S. Geol. Survey Bull. 199, 1902.

Smith, George Otis: Geology and physiography of central Washington, U. S. Geol. Survey Prof. Paper 19, pp. 3-39, 1903.

Twiss, Stuart Nelson: Stratigraphy of Saddle Mountains, Unpublished master's thesis, State Coll. of Wash. Library, Pullman, Wash., 1933.

Warren, Charles R.: The Hood River conglomerate in Washington. Amer. Jour. Sci., Vol. 239, pp. 106-127, 1941.

Waters, Aaron C.: Geology of the southern half of the Chelan quadrangle, Washington, unpublished doctor's thesis, Yale University Library, New Haven, Conn., 1930.

————: Resurrected erosion surface in central Washington, Bull. Geol. Soc. Am., Vol. 50, pp. 635-660, 1939A.

————: Cascade Mountains and Columbia Plateaus, (Manuscript in preparation), 1939B.

Willis, Bailey: Changes in river courses in Washington Territory due to glaciation, U. S. Geol. Survey Bull. 40, 1887.

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