THE LAKE MISSOULA FLOODS AND THE CHANNELED SCABLAND[1]

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ABSTRACT

This paper reviews the outstanding evidence for (1) repeated catastrophic outbursts of Montana's glacially dammed Lake Missoula, (2) consequent overwhelming in many places of the preglacial divide along the northern margin of the Columbia Plateau in Washington, (3) remaking of the plateau's preglacial drainage pattern into an anastomosing complex of floodwater channels (Channeled Scabland) locally eroded hundreds of feet into underlying basalt, (4) convergence of these flood-born rivers into the Columbia Valley at least as far as Portland, Oregon, and (5) deposition of a huge delta at Portland. Evidence that the major scabland rivers and the flooded Columbia were hundreds of feet deep exists in (1) gravel and boulder bars more than 100 feet high in mid-channels, (2) subfluvial cataract cliffs, alcoves, and plunge pools hundreds of feet in vertical dimension, (3) back-flooded silts high on slopes of preglacial valleys tributary to the scabland complex, and (4) the delta at Portland. Climatic oscillations of the Cordilleran ice sheet produced a succession of Lake Missoulas. Following studies by the writer, later investigators have correlated the Montana glacial record with recurrent scabland floods by soil profiles and a glacial and loessial stratigraphy, and have approximately dated some events by volcanic ash layers, peat deposits, and an archaeological site. Several unsolved problems are outlined in this paper.

GENERAL STATEMENT

Although paleo-Indians probably were already in North America, no human ear heard the crashing tumult when the Lake Missoula glacial dam (the front of the Pend Oreille lobe of the Cordilleran ice sheet) burst and the nearly 2,000-foot head of impounded water was free to escape from the Clark Fork River valley system of western Montana and across northern Idaho. It catastrophically invaded the loess-covered Columbia Plateau in southeastern Washington (Bretz et al. 1956, fig. 23) and reached Pacific Ocean levels via the Columbia River, 430 miles or more from the glacial dam. So great a flood is unknown at present elsewhere in the world. It has been estimated to have run for 2 weeks. It was 800 feet deep through the Wallula Gap on the Oregon-Washington line.

On the Columbia Plateau in Washington, it transformed a dendritic preglacial drainage pattern into the amazing plexus of the Channeled Scabland (fig. 1). It flooded across stream divides of the plateau, some of which stood 300–400 feet above today's bounding valley bottoms. Closed basins as deep as 135 feet were bitten out of the underlying basalt. Dozens of short-lived cataracts and cascades were born, the greatest of which left a recessional gorge, Upper Grand Coulee, 25 miles long. The greatest cascade was 9 miles wide. The flood rolled boulders many feet in diameter for miles and, subsiding, left river bars now standing as mid-channel hills more than 100 feet high. Current ripples 10 feet and more in height diversify some bar surfaces. A gravel delta 200 square miles in area was built at the junction of Willamette and Columbia river valleys (Bretz 1925, figs. 16, 17). Portland, Oregon, and Vancouver, Washington, now cover some of it. Almost 2,000 square miles of the plateau's basaltic bedrock lost its preflood loessial cover which otherwise is on record in the 100 or more "islands" 40 acres to 40 square miles in area—tracts that stood high enough above, or far enough from, main spillways to have escaped the tremendous erosional attack meted out to the plateau's preglacial valleys. Prevailingly, these "islands" have steep marginal slopes and prow points at their upstream ends (Bretz et al. 1956, fig. 22). Back-flooding left deposits for dozens of miles in nonglacial valleys which entered the

[1] Manuscript received February 6, 1969.

[JOURNAL OF GEOLOGY, 1969, Vol. 77, p. 505–543]

plateau from Idaho on the east (Bretz 1929, fig. 1) and central Washington on the west.

The above statements are generalized, for there probably were at least seven successive burstings of the dam, each (except the last) repaired by later glacial advances to again impound the valley system of the Clark Fork River in western Montana and make another glacial Lake Missoula. Five of these floods could only cross the plateau, because the westward-leading capacious valley of the Columbia River north of the plateau was then blocked by another lobe (Okanogan) of the Cordilleran ice sheet. Two floods found no Okanogan lobe in the way, and most of their water escaped around the north and west sides of the plateau via the preglacial Columbia valley. The earliest flood outlined the anastomosis of the Channeled Scabland. Later ones deepened and widened its main spillways and thus left earlier high-lying and less deeply eroded channels unrefreshed, to become obscured by interflood weathering, rain wash, and wind-made deposits.

The satellite *Nimbus I* has confirmed

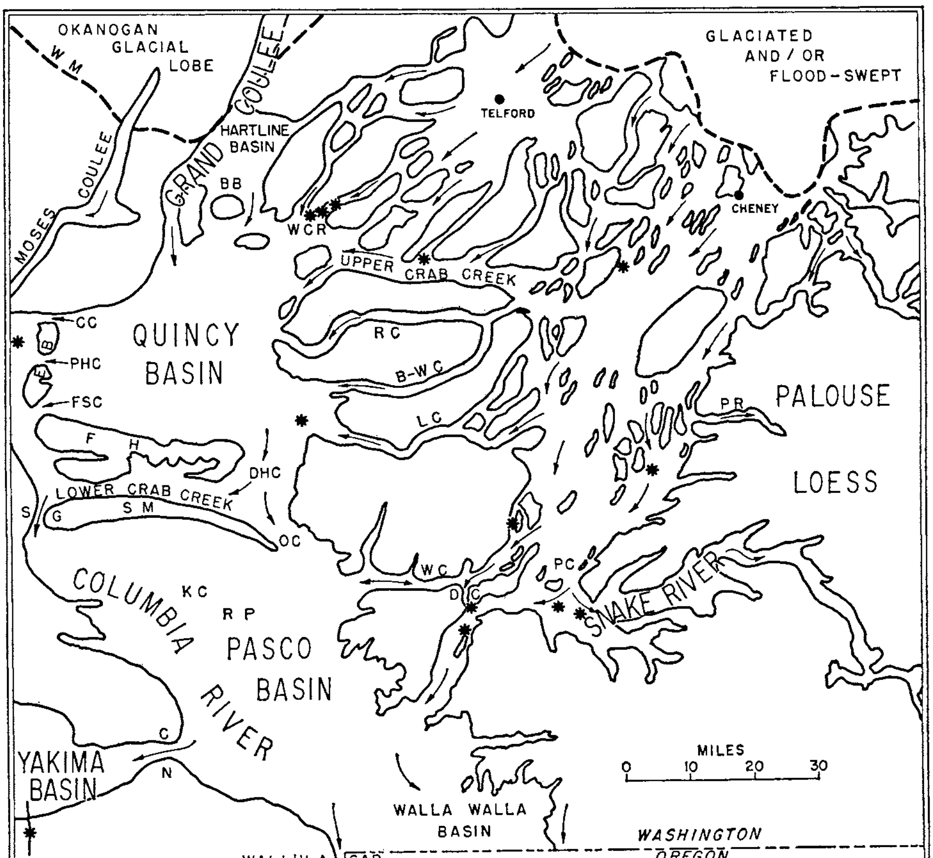


FIG. 1.—Glaciated and flooded areas on the Columbia Plateau in southeastern Washington. Abbreviations: *BB*, Bacon basin; *B-WC*, Bowers-Weber Coulee; *CC*, Crater cataract; *CN*, Chandler Narrows; *DC*, Devils Canyon; *DHC*, Drumheller Channels; *EB*, Evergreen-Babcock ridge; *FH*, Frenchman Hills; *FSC*, Frenchman Springs cataract; *KC*, Koontz Coulee; *LC*, Lind Coulee; *OC*, Othello Channels; *PC*, Palouse Canyon; *PHC*, Potholes cataract; *PR*, Palouse River; *RC*, Rocky Coulee; *RP*, Ringold plain; *SG*, Sentinel Gap; *SM*, Saddle Mountain; *WC*, Washtucna Coulee; *WCR*, Wilson Creek; *WM*, Withrow moraine; *, known occurrences of giant ripples.

this judgment. One of its pictures, made from an altitude of about 500 miles (pl. 1), encompasses almost the whole plateau in Washington and, despite some atmospheric obscuration, has made possible a comparison with the scabland map. The satellite, which "saw" most of the bedrock floors of the anastomosis clearly, failed to record more than 200 miles of high-lying channelways already known as such from their berg-carried erratic boulders, a few gravel deposits, and some scabby channel-bottom basalt outcrops.

HISTORY OF INVESTIGATIONS

The writer's first study of the Washington portion of the Columbia Plateau (Bretz 1923*a*, 1923*b*) dealt in part with Grand Coulee and its origin. But the concept of flood origin of the coulee or the scabland complex waited for another year and was then termed the "Spokane Flood," with no suggestion for the source of the water. A preliminary map of the complex (Bretz 1923*b*, pl. 3) was entitled "Channeled Scabland," the adjective added to the local term for the bare or almost bare rock of the drainageways, which *Nimbus I* "saw" from 500 miles above them. From that time on, the writer has insisted that these spillways were not stream valleys in the ordinary sense, that they had run essentially full during their erosion and were precisely what the name implied—river *channels* superposed on greatly altered preglacial stream valleys (Bretz 1928*b*). Only extraordinary flooding could have crossed the violated preglacial divides, and only extraordinary velocity (born of huge volume) could scarify the bedrocks so tremendously.

More than eyebrows were raised among geologists by this interpretation. Almost a storm of protest arose. Where did that unheard-of quantity of water demanded by the proposed explanation come from in so short a time? Why did not the great, rock-walled Colorado Grand Canyon, with vastly more time and only normal stream volume for its development, supply the correct explanation? Allison (1935) proposed a possible compromise by having numerous iceberg jams along the channels—thus local pondings and divide crossings—with subsequent bursting of such dams to produce repeated local flood conditions. But no one has found field evidence for such dams of floating ice. Flint (1938) was far more conservative. He asked for invading glacial meltwater streams "no larger than the Snake today" and for aggradation of spillways until the violated divides could be crossed. He argued that the scabland was made by "leisurely" streams during *removal* of the fills. The terms "channels," "bars," and "floods" were repugnant to him. Other adverse comments made largely by uniformitarian-minded geologists need not be noted here (see Bretz 1928*c* and Bretz et al. 1956).

In the meantime, the writer continued his field studies and produced nearly a dozen more papers that dealt with (1) specific tracts in the scabland, (2) local scabland making by the Columbia River at The Dalles (Bretz 1924), Oregon-Washington, (3) back-flooding in valleys entering the disputed region from nonglacial drainages, (4) the remarkable erosional and depositional features of the Columbia River valley from the plateau westward across the Cascade Range to the huge delta at Portland, Oregon, and (5) various alternative hypotheses.

Pardee had earlier announced the former existence of glacial Lake Missoula (fig. 2) in mountainous western Montana. He wrote: "As long ago as 1885, Professor T. C. Chamberlin noted a curious phenomenon in the Flathead Lake region that he aptly described as 'a series of parallel watermarks of the nature of slight terraces sweeping around the sides of the valley and encircling the isolated hills within it, like gigantic musical staves' " and that "Chamberlin conceived the idea of a glacial dam and furthermore tentatively suggested that its location was in the Pend Oreille region with outflow by way of Spokane" (Pardee 1910, p. 376–386).

By 1930 the writer had become convinced from a field study that the topographic setting of the lake's ice dam and the altitude of the lake surface had contained the elements for a catastrophic emptying when that dam should weaken (Bretz 1930*a*). Then in 1942 Pardee found, on three low gaps in the crest of a partially submerged, mountainous, peninsular projection of the former lake's irregular outline, that an abrupt lowering had produced great currents headed westward toward the dam 100 miles distant. He estimated the peak discharge at 10 cubic miles per hour and found a descending series of arcuate, asymmetrical ridges of flood-transported debris lying transverse to the slope beyond the downstream end of each narrows. These he interpreted as giant current ripples (fig. 3). Their heights ranged from 15 to 50 feet! Clearly these discoveries were part of the record of a collapsing dam at the north end of the Bitterroot Range. This strongly suggested to the writer that other such giant current ripples must exist along the scabland routes. Their discovery, however, did not come until 1952.

The building of the Grand Coulee Dam across the Columbia near the Coulee's head and the development of the Columbia Basin Irrigation Project provided a superb opportunity to secure new data on the problem. What made the final solution possible was a cooperative field study of these new sources of information by H. T. U. Smith,

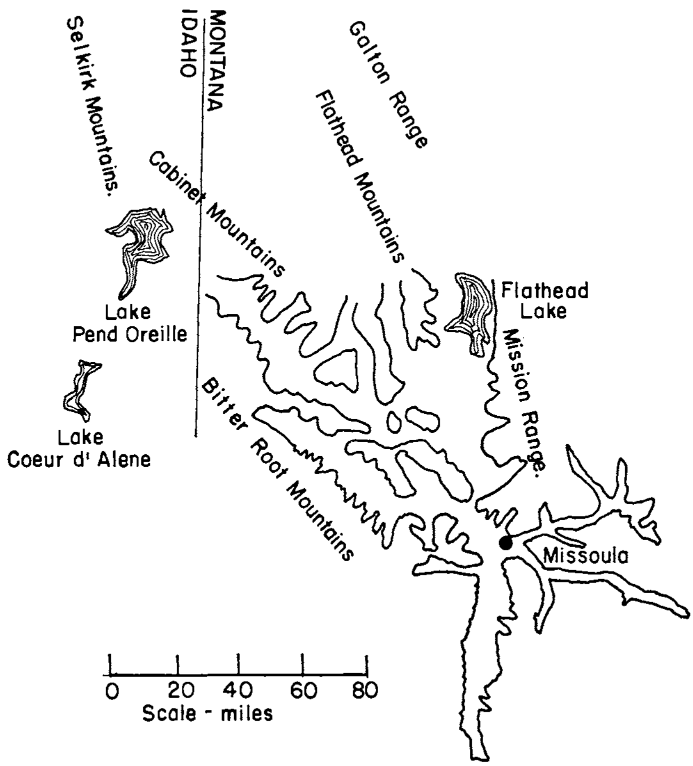
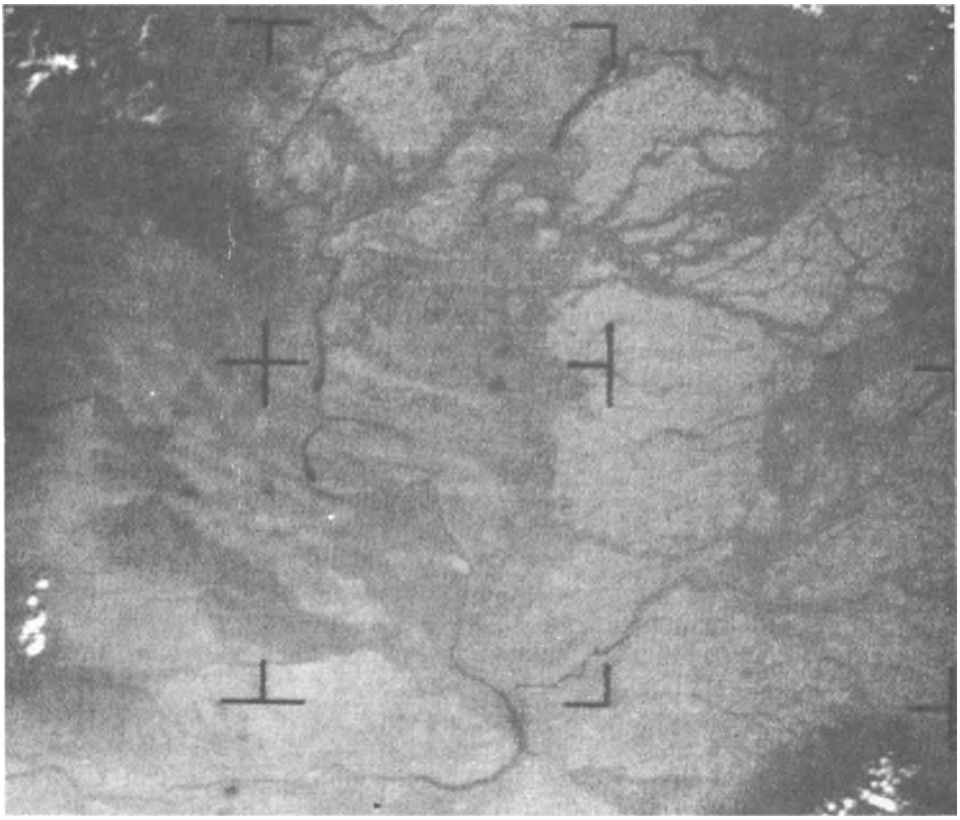


FIG. 2.—Outline map of Lake Missoula. Adapted from Pardee (1910, fig. 4)

PLATE 1.—The Channeled Scabland as "seen" by *Nimbus I* from an altitude of 500 miles. About forty named places can be identified in this depiction. (Nimbus AVCS photograph, Goddard Space Center, September 5, 1964.)



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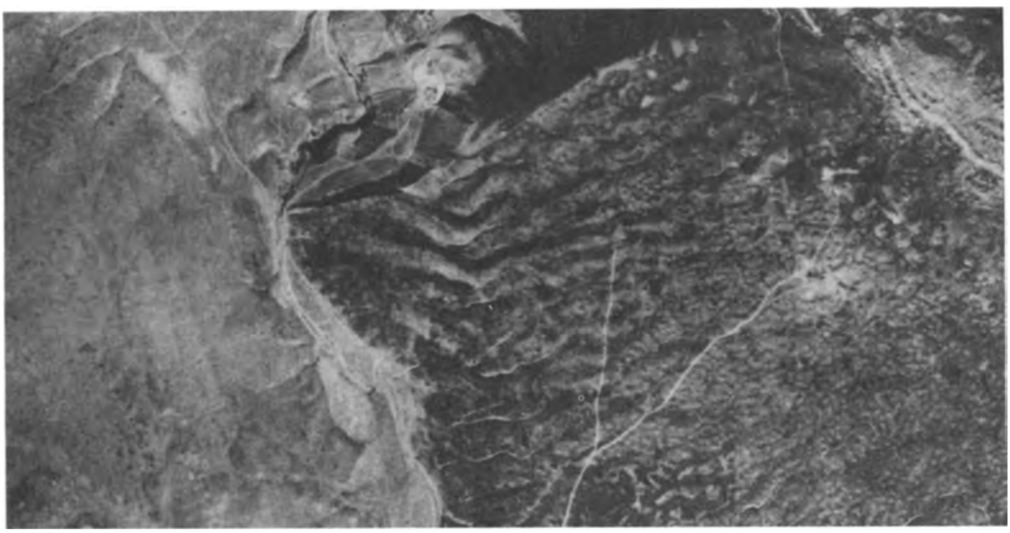

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then of the University of Kansas, G. E. Neff of the U.S. Bureau of Reclamation, and the writer. Their report (1956) finally established the Missoula flood theory and announced that Lake Missoula floods had occurred several times during the Pleistocene. Aerial photographs by the U.S. Department of Agriculture and the U.S. Bureau of Reclamation, supplemented by obliques taken by Smith, disclosed a dozen localities on the plateau scabland where giant current ripples on gravel bars, difficult to identify at ground level under a cover of sage brush, were indubitably present (Bretz et al. 1956, pl. 4, fig. 1).

Since 1957, Richmond has published nearly a dozen papers on the glacial history which he and collaborators have deciphered east of the Lake Missoula region but within the northern Rocky Mountain province. That history involves three different glaciations separated by long intervals

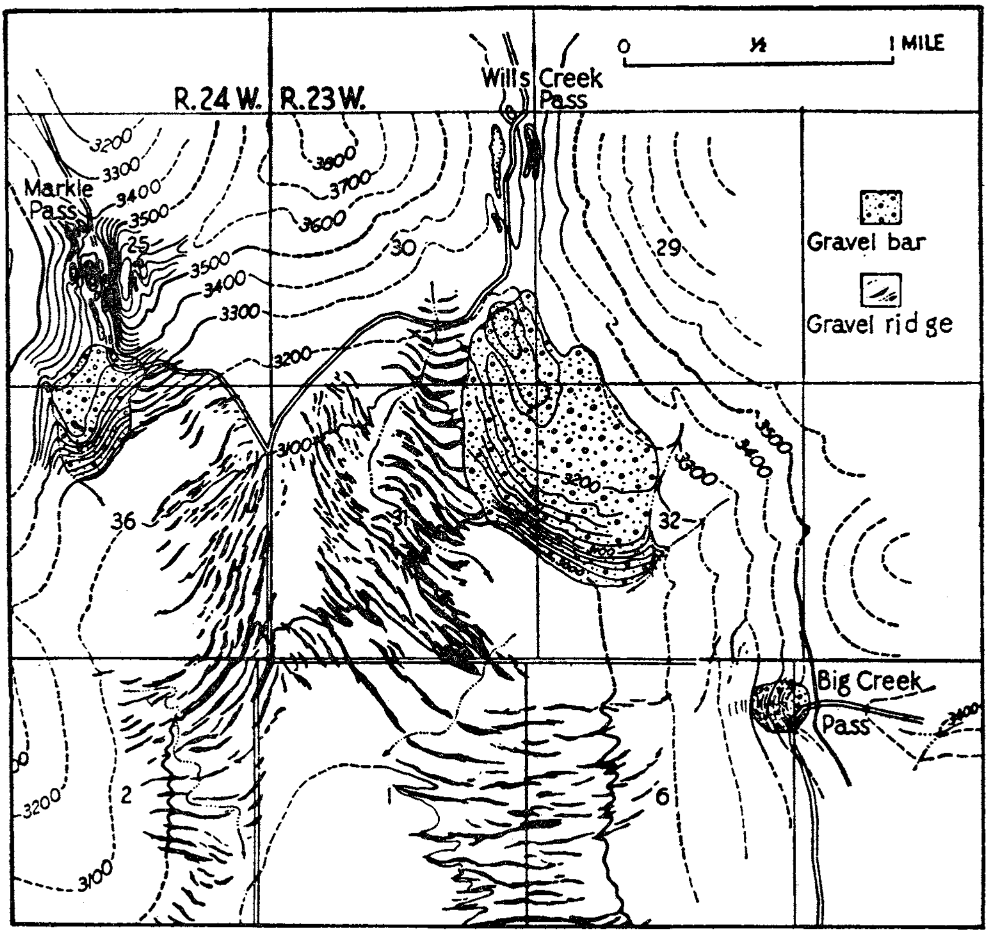


FIG. 3.—Map of giant current ripples north of Plains, Montana. From Pardee (1942)

PLATE 2.—A: Wallula Gap through the Horse Heaven Hills anticline. Seen from Pasco Basin (photograph by Bretz). B: Giant current ripples on summit of shoulder bar, junction of Palouse and Snake canyons. Aerial photo CCH-16-197 from Production and Marketing Administration.

of nonglacial climate when erosion of glacial drift deposits (table 1), accumulation of interglacial sediments, and weathering of soils occurred.

Buried soils of varying development are a vital part of these correlations. The latest paper in the Richmond series (Richmond et al. 1965) traces these old soil markers westward into the Columbia Plateau and identifies the occurrence of three Missoula glaciation and three during the Pinedale (one of them consisting of two episodes). With the three pre-Wisconsin glaciations, he thus has found six "strong" soil-making intervals when glacial ice had retreated from the region and three more times of ice withdrawal in the later record.

From his data, Richmond has deduced the occurrence of three Lake Missoula floods. The earliest occurred at the close of

TABLE 1

GLACIAL STRATIGRAPHY OF THE WIND RIVER MOUNTAINS, WYOMING*

Glaciations and Interglaciations	Stades and Interstades	Soils	Terraces at Bull Lake (Feet above River)
Neoglaciation	Gannett Peak Stade		
	Interstade	Weak azonal	
	Temple Lake Stade		
Altithermal interval		Immature zonal	
Pinedale	Late stade		40
	Interstade	Weak azonal	
	Middle stade		
	Interstade	Weak azonal	
	Early stade		
Nonglacial interval		Mature zonal	
Bull Lake	Late stade		50
	Nonglacial interval	Mature zonal	100
	Early stade		200
Interglaciation		Very strong zonal	
Sacagawea Ridge			380
			500
Interglaciation		Very strong zonal	
Cedar Ridge			660
Interglaciation		Very strong zonal	
Washakie Point			760

* G. M. Richmond (1965) after Wright and Frey (1965).

floods, their times separated by soil-making intervals and by deposition of loess. Two ash layers (Powers and Wilcox 1964) and (Fryxell 1965) have been identified as from Mount Mazama (Crater Lake), Oregon, and from Glacier Peak, Washington, their ages 6,500 years ± B. P. and 12,000 years ± B.P., respectively. From these data, the earliest glaciation (which Richmond has revised to constitute three separate events) is pre-Wisconsin and the following two (Bull Lake and Pinedale) are of Wisconsin age.

Richmond has identified two stades of the Cordilleran ice sheet during the Bull Lake the pre-Wisconsin glaciations, followed by one at the close of the late stade of the Bull Lake glaciation and another at the end of the early stade of the Pinedale glaciation.

If the Pend Oreille ice front reached the site of the Lake Missoula dam in each of these nine advances, as many burstings might be expected in the record. Bretz et al. (1956) believe that the scabland topography records seven such floods, and Neff (unpublished) believes that at least one flood occurred before a heavy caliche, whose fragments are so prominent in flood gravels, had accumulated. If correct, there have been at least eight floods corresponding with the nine glacial retreats in northern Montana, Idaho, and eastern Washington (see table 2).

ESTIMATES ON DURATION, VOLUME, VELOCITIES, AND THE MECHANICS OF EROSION AND TRANSPORTATION OF FLOOD-DERIVED WASTE

The early estimate that a Missoula flood would require 2 weeks to pass through Wallula Gap (fig. 1 and pl. 2*A*) was based on Chezy's formula, where two wetted perimeters and a surface gradient could be obtained (estimate by D. F. Higgins in Bretz 1925, p. 258). The time estimate also considered, incorrectly, that the full 500 cubic miles would be available. The error is obvious when the altitude of the Clark Fork valley floor at the dam site, about 2,000 feet A.T., is compared with the average altitude of scabland channel heads (except for Grand Coulee's later deepening) of 2,500 feet A.T. Only when no Okanogan lobe (see fig. 1) blocked the Columbia west of the head of Grand Coulee, and thus no detour was probable across the plateau, could the entire lake discharge have had free flow down the Columbia Valley. Pardee's estimate of discharge rates along one of the main arms of Lake Missoula much exceeds Higgin's estimate at Wallula Gap.

Nevertheless, the writer is convinced that the narrow Wallula Gap was a bottleneck at some maximum flood or floods, because upper altitudes of back-flooding in the valleys of the Snake, Walla Walla, and Yakima rivers correspond closely with the Wallula's upper limit. Capacious Yakima Valley in particular carries an impressive record of a back-flooding of very dirty, very turbulent water that deposited a cover of silt (mostly rehandled loess) and fine angular basalt granules with plenty of iceberg-transported foreign boulders—surely not the deposit of a static lake, surely that of a strong *up-valley* current (Bretz 1932).

Besides great volume, the scabland rivers owed much of their velocities to the gradients, averaging 20–25 feet per mile, of the preglacial stream valleys they entered on the plateau. Small streams with proportionately large frictional contact with bottoms and sides had found this gradient appropriate, but the great rivers had a far smaller fraction of this retarding factor to deal with, and hence a far greater rate of flow.

Estimation of velocities attained range from Flint's "leisurely" rivers to the high rates implied by the erosion transportation consummated. The use of Chezy's formula by Higgins indicates a velocity through Wallula Gap of between 17.5 and 20.6 feet per second; 20 feet per second is 13.6 miles per hour. The total distance involved was 15 miles, and the gorge thus was refilled almost hourly.

These figures are, of course, speculations, unchecked for several unknown variables such as preflood depth of the Wallula watergap, original width, loss of energy from the erosion that unquestionably resulted and from transportation of debris, possible later uplift in the Horse Heaven Hills anticline, etc. New maps of Wallula (1964) and Umatilla (1962) quandrangles with smaller contour intervals and larger horizontal scales show that the highest flood probably reached almost 1,200 feet A.T.

Some critics have disliked the idea of so much floodwater erosion in so brief a time as the writer has been allowing. This objection was answered by citing the close vertical jointing of the basalt lava flows and the argument that not abrasion but *plucking* of large fragments was inevitable under the high velocity of the huge rivers. Abrasion of large fragments to cobble and pebble sizes occurred largely during transportation. Many boulder deposits lie but short distances downstream from channel-bottom outcrops of large-columned basalt, and many such boulders still possess columnar outlines in part.

Gerard Matthes, eminent authority on river dynamics, has described (1948) the "kolk" in river-bed erosion and has agreed that its mechanics are fully applicable to the scabland rivers. The kolk is a marked

TABLE 2

TENTATIVE CORRELATION OF EVENTS IN THE GRAND COULEE SYSTEM*

Okanogan Lobe	Upper Grand Coulee	Lower Grand Coulee	Columbia Valley below Gr. Coulee Head	Upper Crab Creek	Lower Crab Creek	Hartline Basin	Bacon Basin	Quincy Basin	Bowers-Lind-Rocky†
No dam; no flood		Volcanic ash and shells, Soap Lake		Volcanic ash in peat ±12,000 B.P.					
Dam; no flood	Nespelem formation								
No dam; a flood			Beverly bar		Beverly bar				
Dam; a flood	Steamboat falls reach Columbia Valley; Lake Columbia drained	Dry and Castle falls; Great Blade		Dry Coulee dam, mouth of Upper Crab Creek		Maximum flood across Park Lake and Coulee City quadrangles		Channels in gravel fill; Max. deepening in Drumheller	
Dam; a flood	Isolated Steamboat Rock glaciated; Withrow moraine; Northrup canyon			Lowest Wilson Creek ripples		Initial Hudson and Trail Lake falls	Bar building	Warden falls destroyed	
No dam; a flood			Later Evergreen–Babcock scabland						

* Vertical spacings do not indicate duration of events or intervals.

† Bowers-Lind-Rocky possibly equal Old Maid, Eureka Flat, Ringold summit (see text).

TABLE 2—*Continued*

Okanogan Lobe	Upper Grand Coulee	Lower Grand Coulee	Columbia Valley below Gr. Coulee Head	Upper Crab Creek	Lower Crab Creek	Hartline Basin	Bacon Basin	Quincy Basin	Bowers-Lind-Rocky†
Dam; a flood	Early retreat of Steamboat falls	Deepening of monoclinal canyon		Intermediate Wilson Creek ripples			Excavation of preflood fill	Growing gravel fill; Warden falls	
No dam; a flood			Early Evergreen-Babcock scabland, discharge from Crater notch into Quincy basin (early Pinedale)					Discharge from Columbia Valley into Quincy basin (early Pinedale)	
Dam; a flood	Initial cascade over Coulee monocline	Initial course along Coulee monocline	Three western cataracts	Highest Wilson Creek ripples	Initial Othello Channels and Koontz Coulee			Three western cataracts; Drumheller initiated	Functional initiation of plateau anastomosis
No dam; a flood			Discharge from Columbia Valley into Quincy basin (Bull Lake)					Discharge from Columbia Valley into Quincy basin (Bull Lake)	

turbulence with upward lift and negative pressures which develop at the foot of steep, downstream-facing declivities in the bottoms of stream beds. In effect, it is a subfluvial tornado, an analogy which Matthes approved. He noted that the kolk is "probably the most important macroturbulence phenomenon in natural streams" and "the most powerful form of concentrated energy at work on stream beds." Plucking action thus was greatly augmented wherever submerged basalt ledges with the proper form appeared during flooded regimens. Many low-cataract cliffs and their plunge pools therefore were only "subfluvial cataracts." The comment by an engineer that "basalt is a rock hard to drill but easy to blast" is apropos.

An unusual problem of transportation exists in the gritty silts with mingled weathered and unweathered angular basalt granules and erratic boulders that were carried back up nonglacial valleys which enter the plateau scabland. Only a surface gradient could have produced the up-valley currents. At the bottom, the flow was all uphill! Adequate turbulence for the full affected length of each valley is obviously required, unless some means of flotation existed. For the boulders high on valley slopes, floating masses of ice are indicated. For the fines which blanket gentler slopes, a slurry of excessively muddy water from erosion of loess, perhaps charged with minutely crushed ice, may be envisaged.

With waning of a flood, most such fine debris would settle to the bottom of any back-flood valley, where the bulk of the record is found. Here, also, the excessive turbulence had diminished to a minimum, for such valley-bottom deposits are prevailingly sorted and stratified. In places there is evidence of repetition of the episodes. Yet these back-flood deposits remain, to the writer, the least understood of all the phenomena that record the Missoula floods.

The writer's descriptions of massive erosional and depositional flood effects along the Columbia River Valley from Wallula Gap to Portland, nearly 100 miles (Bretz 1925), were checked by Allison (1933), who agreed in general with the field facts but differed in interpretation. Allison asked for a dam 900–1,100 feet high to account for the high water downstream from Wallula. Flint (1938) also wanted a dam to cause his prescabland aggradation in the plateau valleys. A later study by Lowry and Baldwin (1952), dealing with that part of this stretch across the Cascade Range known as the Columbia Gorge, reported no evidence that damming of any kind (volcanic, tectonic, glacial, landslide) as advocated by Allison and by Flint occurred at any time when the Columbia was carrying glacial meltwater from Canada, Montana, Idaho, or Washington.

A detailed study of the Portland region (Trimble 1963) accepted the writer's interpretation of the extensive gravel deposit in the broad valley at the junction of Columbia and Willamette rivers as flood-made. The "Portland Delta" (Bretz 1925, figs. 16, 17) is composed dominantly of gravel with foreset bedding that dips westward in most exposures and was originally described as a "subfluvial delta," a "subaqueous deposit" made under perhaps 100 feet of floodwater. It covers at least 200 square miles. (There are no conventional deltas in any scabland gravel deposit. All show that their surfaces were swept by strong, deep currents during accumulation.) Trimble has mapped even larger areas of contemporaneously deposited sand and silt beyond the limits reached by the gravel. They lie southward up the Willamette and Tualatin valleys and northward down the Columbia Valley. His inclusive term is "lacustrine deposits." He wrote of "flood waters of almost unbelievable proportions" and was fully aware of the source. He obtained the ponding, up to 375 feet A.T., by means of a hydraulic damming at a constricted place in the Columbia Valley about 30 miles north of Portland—the same mechanism which the writer used for the backup north of Wallula Gap.

Earlier students of the geology of the

broad lowland between the Cascade and Coast ranges, now containing valleys of the Columbia, Willamette, Tualatin, and other rivers, noted evidence there of widespread ponding with ice-rafted erratic boulders up to 400 feet A.T. (Condon 1871; Diller 1896; Washburne 1915; Allison 1935). The writer earlier (1919) espoused Condon's idea of a "Willamette Sound" at sea level but later abandoned it for the glacial-flood hypothesis. Lowry and Baldwin (1952) have returned to the concept of a eustatic rise in sea level as the cause of the ponding.

A situation closely comparable to that of the Portland Delta appears to have existed at the downstream end of Wallula Gap where the broad Umatilla structural basin was entered by floods from the scabland. Here a rather featureless gravel deposit covers many townships thence for about 30 miles down valley, beyond which the river again encounters a rock-walled course near Arlington, Oregon. A dozen or more scabland-type basalt buttes project through the gravel, and several broad abandoned channels incise it. The topography of the gravel is not that of a deltaic deposit in a body of standing water. It consists of broad, low bars distributed through an altitude range of 300 feet or more and declining in altitude westward. The irregular gorge beyond the Umatilla basin is in places nearly 800 feet deep, and the upland above its walls carries flood channels with floors of 700–800 feet A.T. Here many stranded granite boulders lie above 1,000 feet. Only a few miles farther downstream is a spectacular spillover, southward *out of* the Columbia gorge and *into* the closely adjacent tributary John Day Canyon, its original floor here 950 feet A.T. (Bretz 1928*a*).

CHARACTER OF A FLOOD FRONT

Both Snake River Valley, upstream from the entrance of the easternmost scabland rivers, and Yakima Valley, southwest of the plateau scabland, carry evidence of high-energy back-flooding currents that strongly suggest a steep borelike front of the entering back-flood. But probably the best field evidence to support this view is at "The Narrows" near the junction of John Day and Columbia canyons.

Here the John Day flows parallel to the Columbia for its last 9 miles, separated from it by an asymmetrical, peninsular upland about 2 miles wide and 1,200 feet A.T. Most of this upland drains to the John Day, whose canyon walls are dendritically dissected and nowhere possess cliffs.

In marked contrast, the Columbia canyon wall along the peninsular divide is a continuous cliff for the entire distance and ranges from 660 to 800 feet high. No ravines dissect it. The Columbia's side of the divide has obviously been cut back markedly by widening of the master valley at some geologically recent time.

Both valleys had present depths before any glacial floods arrived. Both had been eroded well down into basalt.

At the east end of the peninsular upland was a low place where a flood in the Columbia Valley spilled a portion of its volume across and made the sharply defined but very limited basalt scabland called The Narrows (fig. 4).

Only a brief life for The Narrows spillover could have been possible before back-flooding up the John Day brought it to an end. Yet in that time the distributary had a cascade down into John Day Canyon that began as a drop of about 500 feet. This cascade eroded the basalt floor of The Narrows to depths as great as 200 feet, making cliffs 100 feet high, a maze of rock basins, and vertically walled castellated buttes, and leaving a huge mid-channel butte whose summit, half a mile long, quarter of a mile wide, and 956 feet A.T., records the preflood surface (Bretz 1928*a*, pl. 23, figs. 1, 2, 15).

Debris from this erosion built a bar on the bottom of John Day Canyon. By the time the back-flooding in the John Day had been consummated, this deposit had spread across the canyon to a depth of 360 feet over an area of nearly half a square mile. It was completed as a great bar, and hence the John Day back-flood had topped it

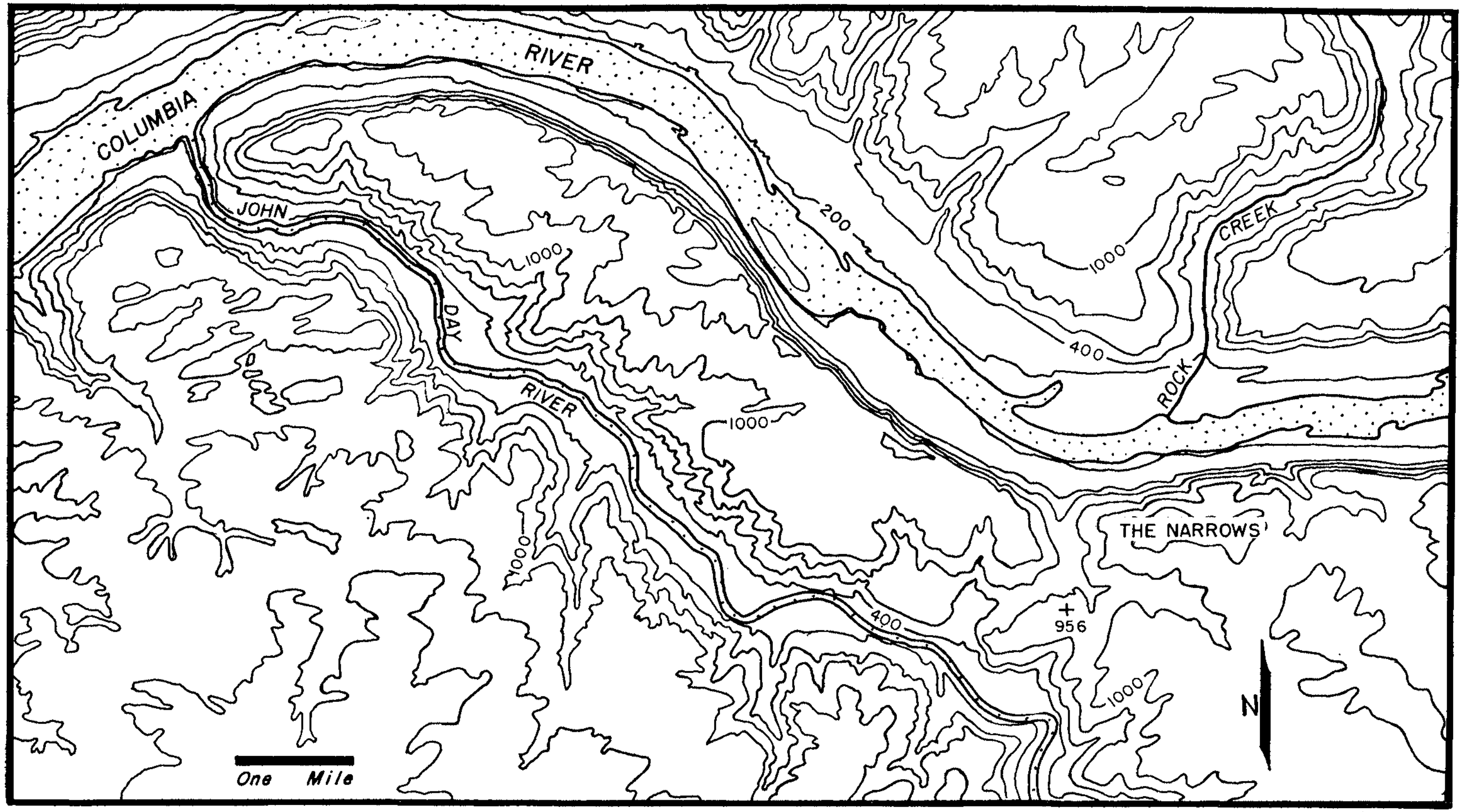


FIG. 4.—Map of The Narrows, Oregon, and environs. The adjoining Arlington and Wasco quadrangle maps, U.S. Geological Survey, on different scales, have been brought to agreement and all contours but the 200-foot contours omitted. Most of The Narrows scabland is on the Arlington quadrangle. Some of the gravel bar lies on the Wasco quadrangle. A marked anticlinical upwarp, the Columbia Hills, on the southern part of the Satus Peak quadrangle just north of the river, has a summit more than 2,000 feet above the valley bottom and is steeply cliffed for most of that vertical distance, apparently in steeply southward dipping basalt flows. The valley wall on the south side is only about half as high. It appears that the river has held an antecedent course essentially along the strike of the steep flank of the structure. Nothing in the relations between structure and valley course has any bearing on the cause of The Narrows spillover.

before The Narrows spillover had ceased to supply detritus.

The figures are simply extraordinary for such a brief episode. The Columbia flood front, after initiating The Narrows spillover, had only 9 miles farther to go before it must have sent a portion back up the John Day to reach the foot of the cascade. Perhaps The Narrows has carried several spillovers, but its initiation required much more than 700 feet of floodwater in the Columbia Valley.

The writer is convinced that no gradual rise in the flooded Columbia can account for these features at The Narrows. The flood arrived catastrophically. It was a great wall of water, its crested front constantly outrunning and overrunning its basal portion. Because of huge volume, its current was essentially unimpeded by channel bottom and side friction.

Because a flood front normally becomes attenuated downstream and no steep front as here interpreted at The Narrows could have been maintained across the broad Umatilla basin farther upstream, an accessory mechanism for regenerating one is required. Such a mechanism probably lies in a hydraulic damming in the encanyoned Columbia (800 feet deep and $1\frac{1}{4}$ miles wide) a few miles upstream from The Narrows spillover (see Arlington quadrangle map, U.S. Geological Survey). This would cause considerable backup in the Umatilla basin, raising flood levels there and reconstructing a steep front in the canyon. Evidence of hydraulic damming with accessory effects is to be expected in all marked narrowings of the preglacial Columbia.

Another demonstration of the character of an arriving flood's front is visible close to the junction of the Yakima and Columbia valleys, which here lie in nearly parallel structural downwards, separated by the strongly expressed Rattlesnake Hills anticline.

The Yakima structural valley is notably constricted some 10 miles upstream from the junction of the two rivers by a minor upfold on the southern slopes of the Rattlesnake Hills anticline that crosses the Yakima Valley mouth to become part of the large Horse Heaven Hills anticline. From average widths of 15 miles, the structural valley narrows at Chandler to 3 miles and the stream-made notch is less than a mile wide (Bretz 1930*b*, figs. 8, 9). The Corral Canyon quadrangle map (fig. 3) shows the anticlinal crest to have a topography wholly unlike anything else in the upfold or on any other surfaces in the district, but is duplicated in thousands of places in the Channeled Scabland complex of the plateau. It is butte-and-basin scabland (Bretz 1930*b*), as isolated as that at The Narrows on the Columbia–John Day divide, and, like the glacial silts and boulders for 50 miles up the Yakima, whose upper limit is 1,100 feet, it also has an upper limit, but here only 950 feet A.T. There are ten rock basins strung along the crest of the little anticline below 950 feet A.T., and hills of tilted basalt 100 feet high stand among them. Total relief is more than 200 feet in a horizontal distance of 500 feet.

Although the Yakima River clearly has never flowed on this crest, stream gravel occurs in several places. A coarse, rubbly basalt gravel with a few granites, quartzites, etc., lies on the western (up-valley) slopes of bedrock eminences and is foreset *up* the Yakima, *away from* the Columbia. This local up-valley current tore loose much bouldery basalt, some of it fresh, some considerably weathered, which came to rest in the foresets.

The writer (Bretz 1930*b*, fig. 6) has indicated that the Yakima Valley upstream from Chandler Narrows and below 1,100 feet A.T. has a capacity of 3.17 cubic miles and could be filled by the Columbia River in maximum flood today up to 1,100 feet A.T. in about $4\frac{1}{2}$ days. However, only tremendous velocity engendered by a steep surface gradient can account for the Chandler Narrows' erosional features (fig. 5). One thinks of repetitions of the catastrophic experience. The record of Missoula floods will provide this!

The scabland torrents were excessively turbid. Relict loessial hills near the north end of the Cheney-Palouse tract are 100 feet high, and loessial scarps overlooking the Palouse-Snake scabland divide are 200 feet high. This denuded tract has lost nearly 1,000 square miles of its former loess cover to these torrents. Furthermore, the back-floods in tributary valleys (Snake, Walla Walla, Yakima, Palouse, etc.) left an almost universal deposit of the rehandled loess, mixed with fresh and decayed basalt grains and granules, up to the limits reached by the floodwaters.

In contrast, any flood that encountered no Okanogan dam followed the open, capacious Columbia Valley around the plateau and found en route very little loess to carry off. Such floods were not only less turbid, but were far less impeded en route to Wallula. They must have arrived in greater initial volume than floods forced to thread the complex of plateau channels.

Wallula's westernmost scabland channel atop the 700-foot cliff summits (fig. 6) is about 60 feet deep and much too wide to be ascribed to its preglacial predecessor. The gravel bar and gravel floor south of the col and the huge gravel spill thence down into Columbia Valley indicate considerable deepening in the channel's headward part and an adequate spill across at the inception of its use, perhaps of the order of 100 feet in depth. The upper flood limit may well have

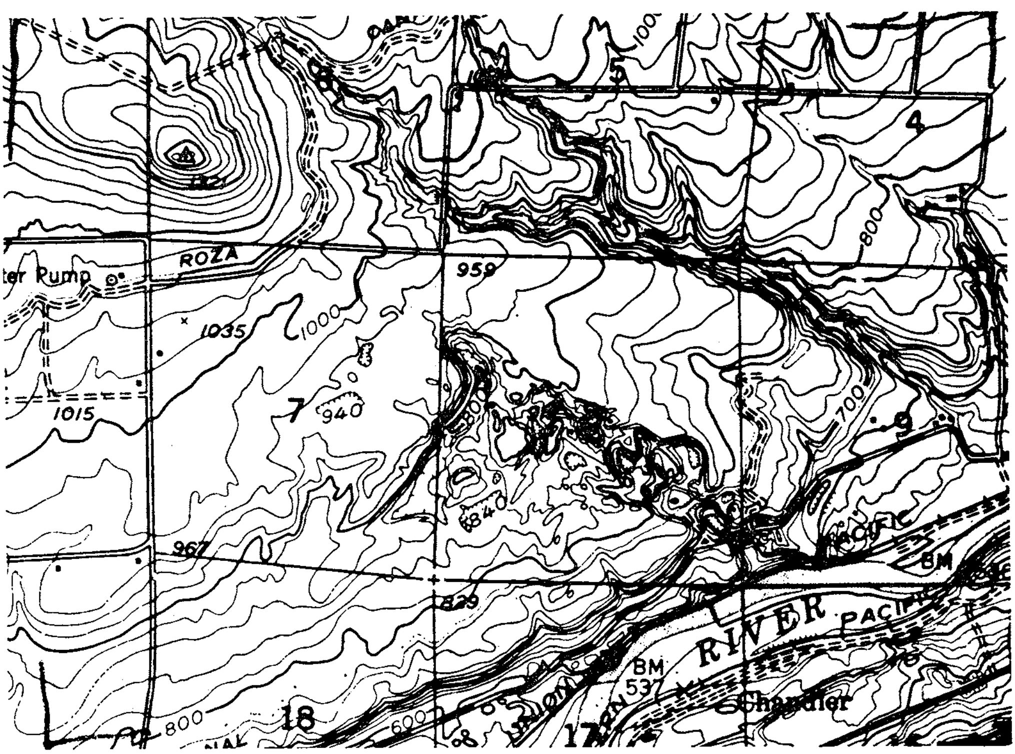


FIG. 5.—Map of Chandler Narrows, Washington. From Corral Canyon quadrangle topographic map, U.S. Geological Survey; contour interval, 20 feet. Although this map of 1951 departs in no significant way from the map of 1917 (Bretz 1930*b*, Fig. 9), it depicts an even more rugged topography of the gutted portions of the minor Chandler anticline, shows a sharper steepening of the anticlinal nose above 1,080–1,100 feet A.T., and reveals the existence of a few undrained depressions on the lee side of the devastated portion of the anticlinal crest. The structure could hardly have been more advantageously placed for receiving the record it carries.

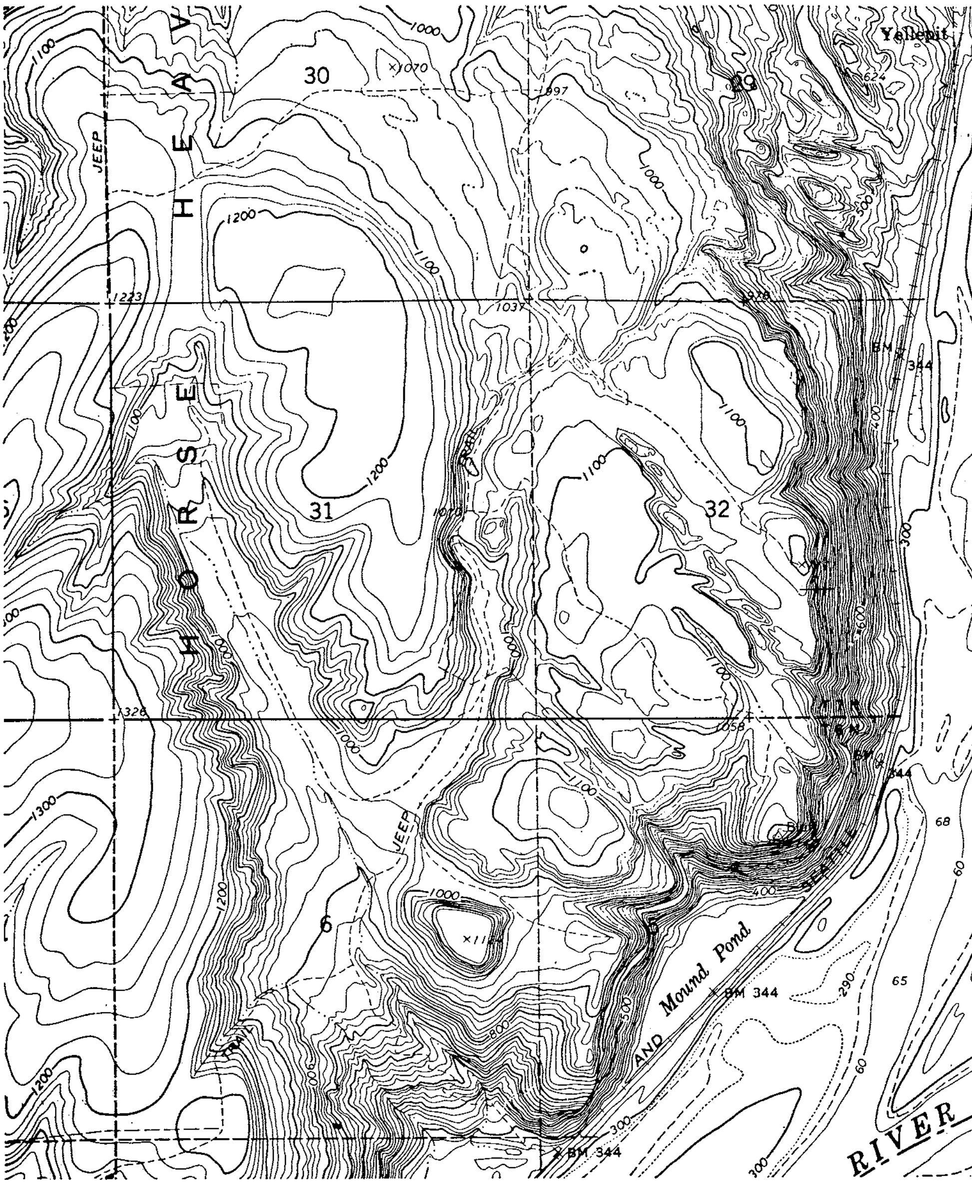


FIG. 6.—Scabland on summit, west side of Wallula Gap. From Wallula quadrangle topographic map, U.S. Geological Survey; contour interval 20 feet. Largely modified preflood topography. Most significant place is in sec. 31, between *R* and *S* in *HORSE*, where a gravel bar just south of the channel entering from the north has detoured the preglacial ravine entering from the southwest which appears to have once continued north along the channeled route. The bar originally dammed local drainage on the east side of the channel, making a depression 25 feet deep, now drained by postflood erosion. Basalt surfaces at this highest record of floodwater are of scabland character. For a mile, this southward-leading channel descends about 175 feet on a gravel floor and there pitches off for 500 feet in less than 2,000 feet of horizontal distance to reach the bottom of the gorge just south of the narrowest place in the Gap. This pitch-off is essentially a delta which is all frontal slope; all of its detritus came from flood erosion in the channel and a tributary scabland-marked channel east of it.

been close to 1,200 feet A.T., 100 feet higher than the upper limits of back-flooded sandy and pebbly silt known on the slopes of Yakima and Walla Walla valleys. Possibly the relatively clear floods that went around the plateau left this high record. But they should have carried berg-borne erratic boulders, but no one has yet specifically noted any lying higher than the upper limits of the pebbly silt. One thinks therefore of the alternative, that a slight post-flood uplift along the axis of the Horse Heaven Hills anticline may account for these aberrantly high channels on the west side of Wallula Gap, and thus abandons the speculation regarding floods around, versus floods across, the plateau.

AGE ESTIMATES AND DETERMINATIONS

Richmond's latest correlation chart (1965) of Quaternary events in the northern Rocky Mountains (table 1) names three glaciations as pre-Wisconsin, two as Wisconsin, and a neoglaciation (Little Ice Age) of valley glacier growth. Blackwelder's pre-Wisconsin Buffalo Gap glaciation becomes the Washakie Point, the Cedar Ridge, and the Sacajawea glaciations, verifying Blackwelder's suspicion that more detailed studies would subdivide Buffalo Gap. Richmond's first Missoula flood is indicated as late in the Sacajawea glaciation, possibly 100,000 years ago.

Friedman (in Richmond 1965), from hydration rims on obsidian pebbles in till of the early stade of Blackwelder's Bull Lake glaciation, suggested that the event occurred 80,000 years B.P. Richmond's earliest flood is indicated as preceding the early stade of this glaciation and was therefore pre-Wisconsin.

Alden (1953) surmised that Lake Missoula had been formed and emptied two or three times and suggested that "lowering of the ice dam might result in floods of great magnitude—even if Lake Missoula were only partially drained. Such may, perhaps, have been the origin of many violent floods that are supposed to have swept over the scablands." However, he could not accept as flood-made Pardee's giant current ripples in the eastern part of the lake or the pronounced scarifying of lower mountain walls and the building of high eddy deposits back in reentrants below the lake's level.

The two stades, one with two episodes, of the Bull Lake glaciation are recorded on the Columbia Plateau in Washington by three definite units in the loess cover, each carrying a caliche record of long exposure before burial. This compound glaciation was followed by another flood at, according to Richmond, about 32,000 years B.P.

Excavation for the Wanapun dam on the Columbia (Fryxell 1962) uncovered a coarse gravel in a flood-eroded rock channel. The gravel was almost wholly of angular, poorly sorted basalt fragments, foreset-bedded with cut-and-fill structures and the debris open-work in part. This was clearly a deposit from the operation of nearby Frenchman Springs cataract and thus a record of Grand Coulee's functioning. In the gravel were fragments of wood and dried peat which were C^{14}-dated as 32,700 $\pm$ 900 years B.P. The organic material was clearly reworked from an interstadial bog back on the plateau. The great coulee therefore operated at least once to make the depression for the bog (probably in the Quincy basin) and once again to tear up the bog accumulation at the time the cataract operated. Only the wood and peat are 32,700 $\pm$ 900 years old.

The identification of two volcanic ash members in the Palouse loesses (Powers and Wilcox 1964; Fryxell 1965) provided two more dates in plateau history. The Glacier Peak eruption occurred 12,000 years B.P., the Mazama eruption 6,500 years B.P. The southern part of Grand Coulee is a closed basin containing alkaline Soap Lake in its deepest part and diatomaceous lake silts on higher slopes (Richmond 1965). In these silts is the dated Glacier Peak ash. Grand Coulee, the greatest and functionally the latest of all flood channels on the plateau, therefore ceased to operate before the Glacier Peak ash was distributed, 12,000 years B.P. A later flood (Bretz et al. 1956, but not noted by Richmond) found an open Columbia. Thus the Okanogan lobe's marked morainic record was made before 12,000 years B.P. Richmond's latest correlation chart shows his last flood as early Pinedale, perhaps 20,000 B.P.

The Telford–Crab Creek scabland tract in the north-central part of the plateau has yielded another controlling date. A bog in a rock basin near Creston (Hansen 1947) contains volcanic ash layers of both Glacier Peak and Mazama ages. This evidence

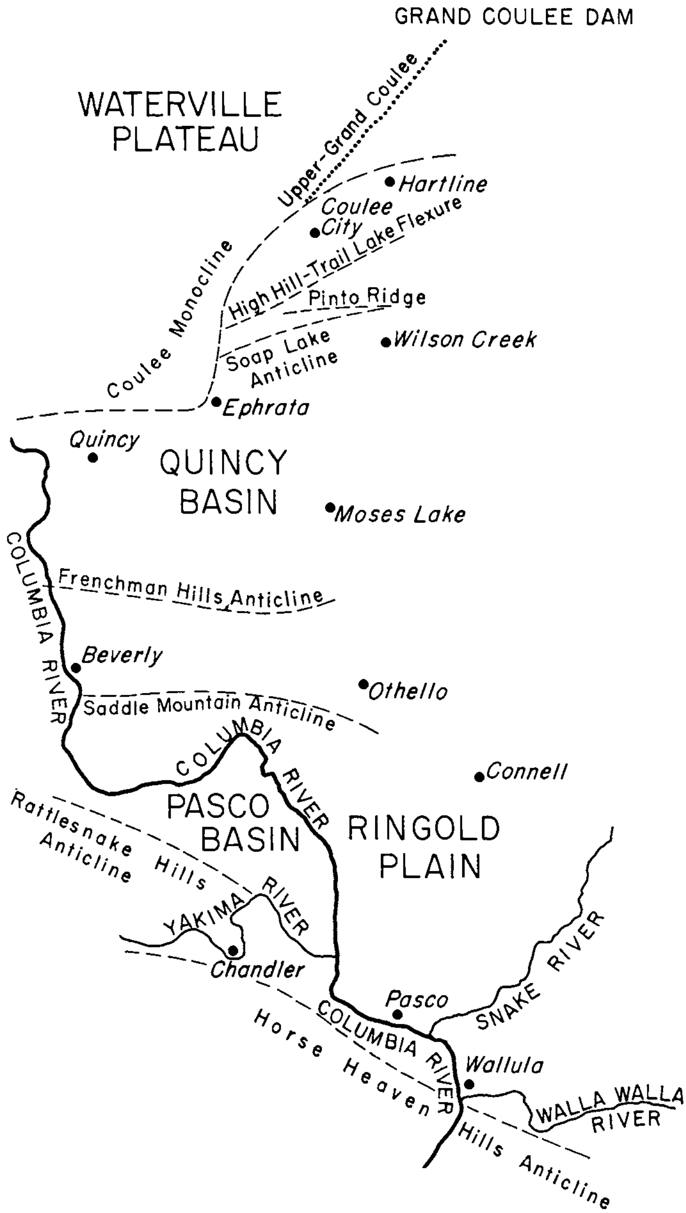


FIG. 7.—Structural features involved in the history of Grand Coulee floods. Data from U.S. Bureau of Reclamation.

agrees with that from Grand Coulee; all the plateau floods must have occurred before 12,000 years B.P.

The largest scabland tract, Cheney-Palouse, also has a contribution to this effort to date the Missoula floods. In the wild, canyoned scabland where the main part of the Cheney-Palouse floods broke across the Palouse-Snake divide (fig. 7), (Fryxell and Daugherty (1962 and 1968 press announcements) have investigated a rock shelter archaeological site (Marmes Ranch). The oldest burials were beneath shell midden with a C^{14} age of 12,000 B.P. ± 100 years, and other burials were under Mazama ash (6,500 years B.P.). Thus no Cheney-Palouse discharge has occurred since about 12,000 years B.P.

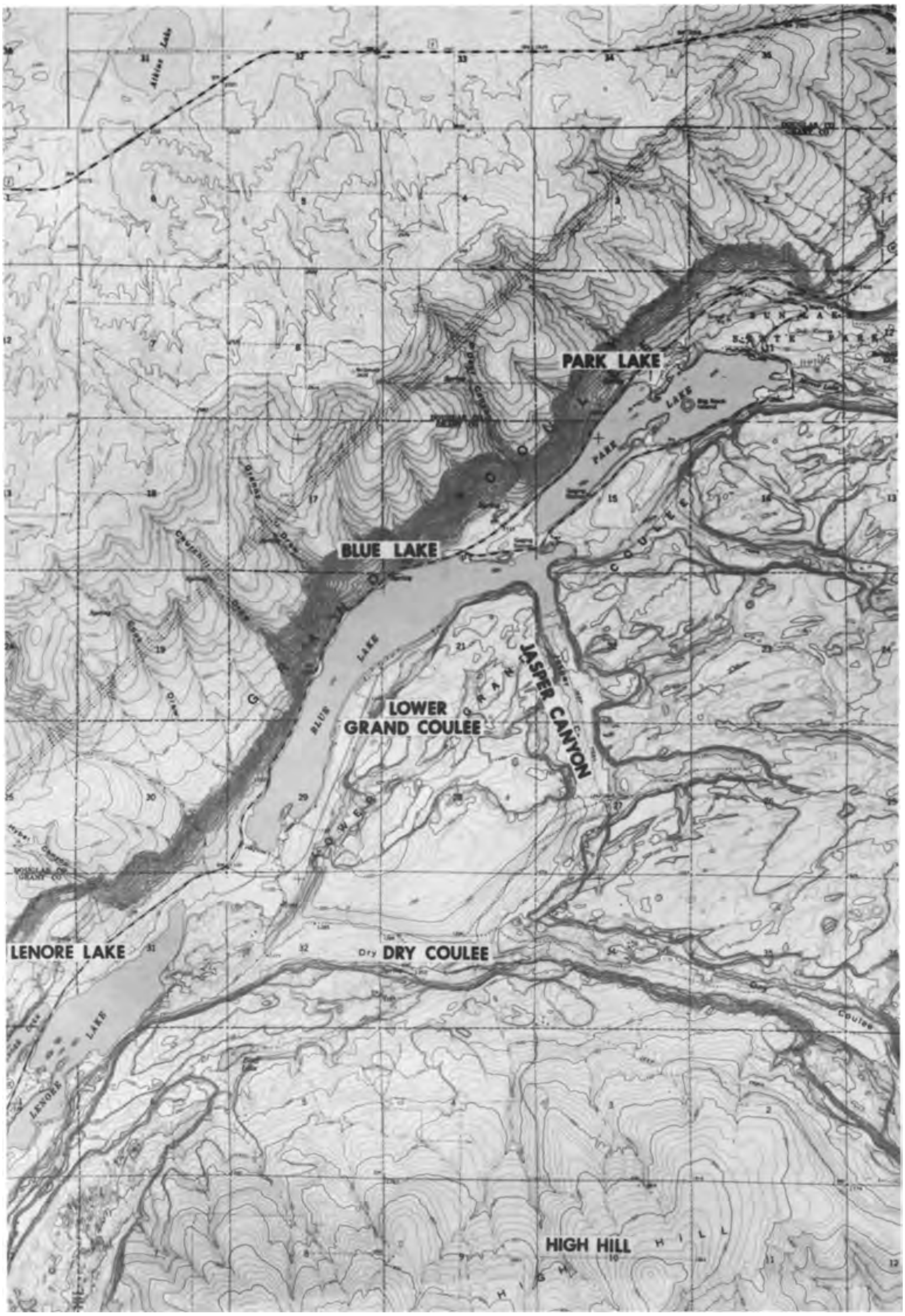
GRAND COULEE SYSTEM

The Grand Coulee system provides the greatest display of flood-made features, although its areal share of the plateau scabland is small. The great coulee is the deepest, longest, and steepest in gradient. Its system possesses the largest number of abandoned cataracts, the widest one, a record of the highest, the greatest cascade, and the largest number of distributary canyons. It is unique in that, at its initiation, it found no preglacial valley head, but crossed 20 miles or so of the northern divide of the plateau before encountering such a valley, and it trenched that divide nearly 1,000 feet deep.

The Columbia Plateau of eastern Washington had earlier suffered local warpings and foldings that produced originally undrained basins and narrow anticlinal uplifts (fig. 8). In the Grand Coulee system, one basin (Quincy) covers more than twenty townships and now is deeply aggraded with basaltic sand and gravel. One great monocline (the Coulee monocline) lifts its high western side about 1,000 feet. The highest of three marked anticlines (Saddle Mountain) rises 2,000 feet above the bottom of its closely parallel synclinal valley (Lower Crab Creek), which served as one of Grand Coulee's distributary routes.

Grand Coulee is a tandem canyon that heads in a notch in the south wall of the preglacial Columbia Valley with a floor 650 feet above that valley bottom. Its northern 25 miles, about 900 feet in depth and ranging from 1 to 5 miles wide, cross the high side of the Coulee monocline. The glacial stream, on encountering the downwarp slope of the monocline, descended in a cascade that very shortly became a cataract

FIG. 8.—Park Lake quadrangle topographic map, U.S. Geological Survey. The 10-foot contour intervals show that the summit of the Coulee monocline is actually a minor anticline standing about 200 feet higher than semiparallel U.S. Highway 2 less than 2 miles distant to the northwest and nearly 1,600 feet above Blue and Park lakes. The brink of the great cliff ranges between 800 and 1,100 feet above the lakes in the coulee bottom. The five named draws which head on the southeastern flank of this anticlinal divide show very little rejuvenation since the great wall was made. Knickpoints in them are very obvious. The great oversteepened wall paralleling the strike of the monocline ends north of Park Lake by turning a right angle to follow down the dip of the structure and there leads into the lower cliffs of the Dry Falls recessional gorge. North of this, the monoclinal slope into the Hartline basin is only a smooth structural slope with the preflood draws uninterrupted by knickpoints down almost to the Dry Falls platform. East of the coulee lakes and of all tilted basalt flows, this map shows, north of Dry Coulee, a terribly scarified scabland anastomosis of canyoned coulees 100–400 feet deep with four subfluvial cataract alcoves and recessional gorges 100–150 feet deep. This tract was flood river bottom throughout, eroded *before* the lake-occupied deep gash along the monocline had been gouged out and Dry Falls initiated. High Hill anticline, in the southern part of the map, stood a few hundred feet above the highest flood. A subfluvial cataract alcove and its recessional gorge at the truncated western end of High Hill are separated from the main coulee by a remarkable bladed ridge. Where narrowest (extreme southwest corner of the map) it rises more than 100 feet above the bottom of the recessional gorge on the east and more than 450 feet above Lake Lenore in the main coulee on the west. This bladelike ridge is the attenuated toe of all that survives of the monoclinal slope before it was gutted by Grand Coulee floods. The recessional gorge with its cataract east of the Blade is the record of a preflood streamway between the Coulee monocline and the High Hill anticline. Lake Lenore basin occupies most of the width of the steep toe of the moncoline as its hogback islands testify.


PARK LAKE
BLUE LAKE
LOWER
GRAND COULEE
JASPER CANYON
LENORE LAKE
DRY COULEE
HIGH HILL


COULEE CITY
DRY FALLS
CASTLE LAKE
TRAIL LAKE
COULEE
HUDSON
COULEE
LONG LAKE

which receded back into horizontal basalt flows of the high side of the monocline. This recession eventually lengthened the canyon all the way across to the Columbia Valley's southern wall and thus destroyed itself. An imposing mid-coulee butte, Steamboat Rock (Bretz 1932, figs. 20, 21), about a square mile in summit area and as high as the bounding Coulee cliffs, for a time was a "Goat Island" in the receding cataract.

Further evidence for this interpretation is the existence under the present detrital floor, at least as far north as Steamboat Rock, of a debris-filled trench in the basalt more than 200 feet deep, a greatly elongated plunge pool of the vanished great cataract. Just downstream from the site of the original cascade, the coulee floor is of untrenched basalt with a typical scabland river-bottom topography (Bretz, 1932 fig. 6). This is the Upper Coulee.

For a few miles beyond, the glacial river spread widely in a broad synclinal valley (Hartline basin), burying most of it in basaltic waste. But a lower upwarp, the High Hill–Trail Lake anticline at the southern margin of the basin, was shortly encountered and the widened flood plunged across that relief feature in several cataracts on its way to the lowest structural feature it encountered (Quincy basin). One of these abandoned cataracts, 165 feet high, is today utilized by the main canal that leads from the equalizing reservoir on the Upper Coulee floor to the same depression (Quincy) where the Columbia Basin Irrigation Project's largest present development exists. Thus the Lower Coulee is bypassed by man's puny river from Grand Coulee Dam to the fertile but arid region of the Quincy basin. The need for the bypassing is obvious, for the Lower Coulee is a closed depression dammed by its own huge bar deposits in the basin.

For about 15 miles, the Lower Coulee's course is superposed directly *on* the Coulee monocline with consequent erosional features unknown elsewhere in the scabland complex. The shattered rock in the steep limb (45°–60°) of the monocline yielded so readily to the flood from the Upper Coulee that a small preglacial stream valley closely parallel but two miles or so farther east was left with only relatively minor alteration. The flood channel moved over into the shattered belt, leaving a string of deep lakes on subsidence.

The western wall of this monoclinal course rises, 1,000 feet above the lakes, and its crest line is gabled in appearance from

FIG. 9.—Coulee City quadrangle topographic map, U.S. Geological Survey; contour interval, 10 feet. All but about a square mile of this quadrangle has been swept by Missoula floodwater. What is probably the world's largest abandoned cataract lies in its northern half, and two large, compound subfluvial cataracts with recessional alcoves lie near midlength. Structural control is evident in (1) a small portion of the Coulee monocline's flank in the northwest (largely above flood levels), (2) a part of the gravel-filled Hartline basin along the eastern side of the quadrangle, and (3) the Trail Lake and a part of the High Hill anticlines (with Dry, Hudson, and Trail Lake coulees) which trend northeast from the southwest corner of the quadrangle. The nearly 500 feet of relief in the canyoned tracts south of the great cataract is all the product of flood erosion before that cataract (Dry Falls–Castle Lake Falls) was made. The Dry Falls cliff is about 400 feet high, and the complex of recessional gorges dominated by Castle Lake Falls totals about 300 feet in height above Deep Lake. Before the Lower Coulee's great gash was made in the flank of the Coulee monocline (Park Lake quadrangle) and the great cataract was eroded, earlier floods had traversed essentially the whole of the quadrangle and had given origin to Dry, Hudson, and Trail Lake erosional gashes. The highest surviving basalt of the scabland stands just west of the Hudson Coulee cataract alcoves and suffered but little. Its altitude corresponds closely with the easternmost scabland on the southern part of the Hartline basin fill and thus indicates a relief of nearly 500 feet before the great cataract was born. The Bacon syncline once carried a prescabland gravel fill comparable to that in the Hartline basin. Stream-lined, attenuated remnants lie southeast and east of Hudson Coulee. As far as shown on the map, the only human uses of this desolate area south of Coulee City are transverses (highways, dirt roads, jeep trails, and abandoned railroad), gravel pits, springs, the main irrigation canal, and perhaps jackrabbit hunting. Recorded only by name are the tragic attempts by two brothers to farm a portion of Hudson Coulee and the location of a particular (Deadman) spring. The total vertical range of flood-eroded scabland on this quadrangle is at least 650 feet.

truncation of the now-hanging little ravines that originally descended the monoclinal slope (Bretz 1959, fig. 6). But the outstanding erosional form of the Lower Coulee is at the head and in the broad uncanyoned area (part of the Hartline basin) which separates the two canyoned portions of Grand Coulee. It is Dry Falls–Castle Lake, an abandoned compound cataract with maximum height of 400 feet and a width of $3\frac{1}{2}$ miles (fig. 9). It had taken origin and been maintained only because it was initiated a little north of the coulee's entrance into the shattered belt. Plunge pool lakes in alcoves at the base of the cliff mark several more concentrated strands of the floodwater (Bretz 1932, fig. 50).

The distributary system of cataracts and canyons which took much of the spill across Hartline basin's southern rim and out of the east side of the Lower Coulee all returned to the northeastern corner of Quincy basin a few miles east of the major coulee's mouth. This large basin also received several distributary rivers from the upper stretches of the Cheney-Palouse tract and from all of the Telford–Crab Creek tract (see fig. 1). Seven of these were converged into one (Upper Crab Creek) before reaching Quincy basin.

The debouchure of the main Grand Coulee discharge out of its rock-walled course into Quincy basin involved a great slackening of flood current and the consequent deposition of a known maximum of 186 feet of gravel and sand over the twenty townships involved. The topography of the deposit is that of great, broad bars with separating channels (Bretz et al. 1956, fig. 4) which lead southward toward the Drumheller cascade (Bretz et al. 1956, pls. 7, 10, fig. 1). Drumheller is 9 miles wide and has a maximum depth of 300 feet in basalt.

The gradient of the water escaping from the basin at Drumheller was 15 feet per mile. That water entered the synclinal valley (Lower Crab Creek) between the Frenchman Hills and Saddle Mountain anticlines, and much of it there turned west along that valley to reach the Columbia 20 miles distant. But the volume was so great that a portion rose to overflow southward past the eastern nose of Saddle Mountain anticline by way of Othello Channels (Bretz et al. 1956, fig. 12), a small edition of Drumheller. In both the Othello and Drumheller cascades, a residual hill of sedimentary rock survived the tremendous erosion the basalt received. Othello has a plucked rock basin 135 feet deep (Eagle or Scootenay Lake) on the summit of the preglacial divide.

Drumheller did not carry all the flood overlow from Quincy basin. On the west side of this basin is a broad, low, north-south ridge (Evergreen-Babcock) separating it from the closely adjacent Columbia Valley. In three places, saddles in the ridge took some of the floodwater, and three cataracts (Bretz 1959, figs. 13,14,15,16,17) were born as their take fell over the Columbia Valley cliffs. Both Frenchman Springs cataract and Potholes cataract were 400 feet high above the bottom of their plunge pools. Both were double falls with a narrow dividing septum. The total width of Potholes cataract was $1\frac{1}{2}$ miles. Crater cataract was 200 feet high. All three had the same upper limit and must have operated simultaneously.

A startling fact that spurred critics of the early "Spokane Flood" to propose even more startling alternatives (Bretz 1928*c*) was that the upper limits reached initially by discharge over these three cataracts were identical with Drumheller's upper limit, 1,300 feet A.T., although 30 miles distant. It was the relative altitudes of bars and channels in Quincy basin and of the cataract upper limits which led to the concept of a succession of floods down Grand Coulee. Another startling fact is that at some time during Lake Missoula's repeated outbursts, flooding *back from Columbia Valley into Quincy basin* occurred through the saddles used by the westward cataract discharge *to* the Columbia. At such times there could have been no Okanogan dam and no scabland rivers, not even in Grand Coulee.

At Beverly, where Lower Crab Creek's glacial river from Drumheller Channels joined the Columbia River valley, a well-marked bar almost 100 feet high and $1\frac{1}{2}$ miles long has been built *across the mouth* of the synclinal valley by a Columbia flood. This bar is double, its structure well shown in cuts along Chicago, Milwaukee, and Saint Paul Railroad (Bretz et al. 1956, figs. 1, 11, pl. 12). A flooded Columbia rolled this bouldery gravel 125 feet above river level of today and back into the tributary glacial river's mouth after Grand Coulee had completely ceased to function. The last Missoula flood *thus was later than* the last Okanogan lobe's invasion of the plateau.

Pardee (1918) has described an extensive deposit of white silt, the Nespelem formation, in the Columbia Valley upstream from the head of Grand Coulee and on much of the floor of the Upper Coulee itself, but unknown farther down either drainage course. Only quiet water could have provided for the deposition of this silt, and only an empty coulee from that time on can explain its survival on the floor. The last Missoula flood was over by this time, but an Okanogan lobe dam must have held up this latest (and local) ponding in the Columbia Valley.

If these conclusions are correct, the flood that built Beverly bar (clearly later than the last of Grand Coulee's discharges and clearly a record of an open Columbia Valley around the northwestern part of the plateau) preceded the last advance of the Okanogan lobe.

The damming for the Nespelem silt episode may well have been only a partial reclaiming of that lobe's maximum stand and certainly was not the one which pushed over into Grand Coulee's head portion. Yet its failure as a dam may have released the very last flood down Columbia Valley, and not a maximum flood at that.

Most of Othello's discharge went southwest across a plain determined by the flat-lying Ringold superbasalt sedimentary formation in the Pasco basin. The several distributary channels (Koontz Channels) all hang at varying altitudes above the present Columbia. They entered the broad lowland of the Columbia River in the Pasco basin, which must have been semiponded at different times up to the varying levels of these hanging channels.

Pasco basin contained the major part of the flood backed up by the hydraulic damming at Wallula Gap 30–35 miles south of the Koontz Channels. This also was the ponding which backed up Yakima Valley and which left the great flock of icebergs stranded on the eastern lower slopes of Rattlesnake Hills. The Koontz Channels continued to be deepened while the Pasco basin water level was being lowered as much as 250 feet. Their relations to a range of 250 feet in the level of the Pasco pool are evidence of perhaps three different Missoula floods, during each of which Grand Coulee functioned.

EVERGREEN-BABCOCK RIDGE

The west side of this broad ridge has a pronounced structural bench which slopes southward 30 feet per mile from Crater to Potholes and has a maximum width of 1 mile (Bretz et al. 1956, pl. 11, figs. 1 and 2, pl. 13, fig. 2). For 4 miles north of The Potholes the bench surface is scabland and the 100-foot cliff above it is clean-cut. But north of the 1,300-foot contour crossing, the bench is much dissected and has no scabland or cliffs. The rise here to the summit of Babcock is over a completely soil-covered surface much less steep than the cliff, although held up by the same basalt flow.

Floodwater in the Columbia Valley has clearly swept over that part of the bench below 1,300 feet A.T. But both cliff and scabland record two different times of such flooding. North of about 1,250 feet A.T. on the bench, the cliff is talus-covered almost to the summit and has a mantle of soil with sage and grass cover. The terrace surface below this subdued cliff, although definitely scabland, has few bare rock outcrops and, like the cliff, is mantled by coarse, weathered debris and soil. Farther south and below that altitude, the cliff is vertical bare rock with an actively growing talus and the structural bench carries strongly expressed scabland. Clearly, here is scabland of two different ages, a record of two floods down the Columbia, widely separated in time, and the earlier one the greater.

FLOOD CROSSINGS OF THE PALOUSE SNAKE DIVIDE

Palouse River in preflood time crossed from east to west what later became the Cheney-Palouse scabland tract. Here its valley, most of its loessial uplands, and its lower western extension, the now-empty Washtucna Coulee, were severely altered but proved far from adequate to carry the discharge coming over the plateau's northern edge and the Cheney region.

When Washtucna Coulee could not contain the great surge, floodwaters rose to make one of the most significant records on the entire plateau. In two places, they topped the divide between the nearly parallel preglacial Palouse and Snake valleys, crossing it to enter the Snake Canyon. They swept away a loessial cover more than 100 feet thick from 80 square miles of summit area and scored the basalt thus exposed into a congeries of canyons, cataracts, and rock basin (Bretz et al. 1956, fig. 19). One canyon was cut down so deeply that the postflood Palouse abandoned Washtucna and now reaches the Snake through a 400-foot deep narrow gorge that still possesses two waterfalls in its course. A state park includes the larger fall, 196 feet high.

Two rock basins on the very summit of the divide (Bretz et al. 1956, fig. 20) are 80 and 120 feet deep, and the H.U. Ranch abandoned cataract is 280 feet from its lowest lip to the bottom of its plunge pool basin. Striking joint control of the recessional gorges which this and other cataracts left has been noted by Trimble (1950) and is obvious on the topographic maps.

The writer's original interpretation (Bretz 1928*a*) asked for a flood from the north across the ravaged divide that swept its debris *across* and 500 vertical feet *up* on the far (south) side of the Snake Canyon, picking up well-worn cobbles from the Snake riverbed to be mingled with the rubbly, coarse gravel yielded in the divide summit's erosion.

Fryxell reports that the enormous gravel deposits made here in Snake Canyon constituted a dam for some time afterward, upstream from which the terrace record of the postflood Snake is "completely different" from the terrace system downstream.

A semi-isolated basalt hill here had its lee slopes and most of its summit buried in this flood gravel. The southbound deluge was turned westward by higher hills to go down the Snake. The gravel-buried lee slopes of the semi-isolated hill show strikingly long foreset stratification dipping back (northward) toward the Snake (Bretz et al 1956, pl. 15, figs. 1, 2, 3). The square mile of gravel flat on this hilltop has a splendid display of great current ripples (Bretz et al. 1956, pl. 13, fig. 1) 500 feet above the river of today. This original interpretation has stood the test of detailed ground-level mapping, aerial photography, and inspection by critics.

Rounded Snake River cobbles and pebbles in this gravel deposit and similar flood deposits in the canyon show percussion flaking and fracturing to make forms called "broken-rounds" (Bretz 1929). Sharply angular fractured faces and edges have clearly been superposed on originally continuous smooth surfaces, and the associated fine material just as clearly contains the angular chips and splinters broken off in some violent experience just before deposition. The percentage of these broken-rounds is far higher than in the Snake River gravel now in transit.

Equally significant is the record of an enormous back-rush eastward *up* the Snake. In addition to a pebbly, sandy silt veneer on gentle slopes up to the altitude of the ripple-marked hill summit and stranded glacial erratics reaching the same upper limit, this back-rush rehandled gravel in the bottom of Snake Canyon and redeposited it with foresets dipping *upstream* all the way to Lewiston, Idaho, 70 miles distant.

A smaller spill across the Palouse-Snake preglacial divide, 15 miles farther west, made a single scabland canyon (Bretz 1923*b*, fig. 13) almost as deep as Washtucna itself. If Washtucna in flood was only a distributary of the main Cheney-Palouse discharge, Devils Canyon, cut de novo 400 feet deep in basalt, was only a distributary of a distributary!

THE SUCCESSION OF FLOODS

The head region of Grand Coulee has been noted as involving both flooding and glaciation. A single flood could hardly produce the 25-mile length of the Upper Coulee's recessional gorge. Its sill at the head is about 1,000 feet lower than all other scabland channel heads, and therefore, if an Okanogan dam then existed, Grand Coulee must have carried virtually all floods arriving after its great cataract had breached the Columbia Valley wall it so deeply notches. Therefore, there could have been no plateau flood farther east after the recessional gorge was completed and the great Steamboat Falls was destroyed. One caveat, however, should be considered.

The plateau summit where crossed by the Upper Coulee has approximately the same altitude as those eastern channel heads, and on both sides of the Coulee head, such altitudes (2,500–2,550 feet A.T.) are typical scabland. These rugose surfaces, which were made before the great cataract had migrated that far north, are contemporaneous with the Telford–Crab Creek and Cheney-Palouse channel heads.

But after completion of the Upper Coulee gash, the Okanogan lobe's last advance pushed glacial ice across or nearly across to the east wall. If it was complete, the Coulee's discharge was forced again to traverse the summit scabland on the east side.

On this side are two short, semiparallel cataract gorges and alcoves which join the Coulee in the latitude of Steamboat Rock. Northrup Canyon (Bretz 1932, figs. 24, 25, 26), three times as deep as Niagara gorge, and its unnamed mate are quite out of harmony with the rest of this upper scabland and could not have originated until the great cataract had retreated this far north. It seems very likely that they record the same time that the summit of Steamboat Rock was glaciated and that Okanogan ice was then crowding well across to the Coulee's eastern wall. Such a sequence would mean that the Telford–Crab Creek and Cheney-Palouse channels, which had been abandoned because of completion of the big notch in the Columbia Valley wall, were again functioning briefly. This is the caveat noted.

The summit of Steamboat Rock has a scabland channel across it (Bretz 1932, fig. 21); therefore, the rock had become isolated before the glacial record was superposed. But whether or not the causal cataract had already reached the Columbia Valley wall, a large ice-dammed lake (Lake Columbia of Richmond) existed in that valley upstream from the Coulee head. Waters (1933) has interpreted a hummocky, kettly topography in gravel deposits on the south wall of Columbia Valley, opposite the mouth of Okanogan Valley, as a record of a breakup of the Okanogan lobe's dam. If a Lake Columbia then existed, that is, if Steamboat Falls still fell short of reaching Grand Coulee's head, a flood of respectable magnitude down the Columbia could result. If the breakup was triggered by the arrival of a Lake Missoula flood, a back-flooding (eastward) through saddles in Evergreen-Babcock Ridge would be almost inevitable. When the cataract did recede through the valley's wall, this lake must have emptied catastrophically. If the emptying of Lake Columbia coincided with another failure of the Lake Missoula dam, the stage was set for by far the greatest flood that the Coulee has ever known.

It seems probable that the flooding over into Hartline basin, across Trail Lake anticline and down Dry and Long Lake coulee to the northeastern corner of Quincy basin, occurred when Grand Coulee was taking such a flood. Evidence for this is found in a bar at the entrance of Dry Coulee into the basin, built back into the mouth of the Upper Crab Creek scabland channel. It was a complete dam originally, and foreset bedding in it dips east *up-valley*. The modern creek has cut a narrow gulch through the bars but, for a long period in the past, it retained a lake to the east, which is recorded by silts on the scabland valley floor. Therefore no flood ever came down any of the seven distributary channels from Cheney-Palouse or the five channels which lead from the Telford region during or after the time Dry Coulee functioned for the last time. This seems to show that the caveat should be accepted, that is, that there never was a renewed functioning of the eastern spillways after Grand Coulee's great gash was completed.

But there had been three different floods across the Telford tract before the Dry Coulee bar dammed Crab Creek. The evidence is in three different levels of gravel deposits in the scabland channel of Wilson Creek, westernmost of all Telford distributary routes (Bretz et al. 1956, pl. 9, fig 1). Here the gravel bar on the channel floor carries excellently shown ripple marks with wavelengths of about 300 feet, the work of the last flood to use this route. Two higher deposits, ranging up to 150 feet above the rippled floor, have been scarped by later floods. Each carries giant current ripples above its scarped drop-off. Those on the uppermost and oldest bar have an amplitude of nearly 20 feet. The series can hardly be interpreted as anything other than the record of three successive floods.

Just downstream from the spillways over the Trail Lake anticline and the resultant canyoning and cataract alcove-making in its southern limb, there are gravel deposits at three different levels that seem to record three different discharges. The highest is an isolated hill. Later flood erosion has left it scarped on all sides and thus exposed a preflood loess with a caliche cap beneath the gravels. On the west side, the discharge from Hudson Coulee cataract (150 feet high) left two bars at successively lower levels as the floodwaters escaping from the Bacon syncline deepened its two outlets, Dry Coulee and Long Lake Coulee. Here, three discharges apparently occurred out of Hartline basin across Trail Lake anticline.

However, the high gravel flat which buries a caliche-capped loess is apparently only an erosional remnant of a once-complete fill in an early Bacon synclinal depression. It does not have the equilibrium profiles that elsewhere mark subfluvial gravel accumulations. Thus, only two floods can safely be read from this place. Preflood gravel is also known beneath the glacial flood gravel in Hartline basin (Kirk Bryan, personal communication). There it suffered burial instead of erosion.

Summarizing, the maximum discharge down Grand Coulee came after its great cataract had receded across the plateau divide and all the eastern spillways had gone dry. It flooded back into Hartline basin, thence southward over Trail Lake anticline, perhaps three times. Its Dry Coulee discharge, late in this episode, blocked Upper Crab Creek channel. But Wilson Creek had already left a record of three floods. Thus the plateau scabland complex involves three floods before the Grand Coulee obtained complete control of all plateau floodwater and left a record of at least two later floods.

Quincy basin's great spread of gravel has bar profiles almost throughout. Areally, there are two groups bounded and separated by three channels almost entirely in gravel (Bretz et al. 1956, fig. 4). Channel depths and bar altitudes suggest three times of channel erosion initiated on an unchanneled earlier fill. The highest parts of this fill now stand 290 feet higher than the rock bottom of Soap Lake at the mouth of Grand Coulee. The three channels, however, functioned late in the basin's history, and the head of the lowest is hardly 100 feet above Soap Lake rock bottom. Nevertheless, the deepest part of Coulee discharge flowed *up* this 100 feet.

Why the channels? Their different altitudes suggest a sequence in operation. They must be read, however, as three originally contemporaneous channels, and the reason for the deepening of two is the deepening of Drumheller that presumably was continued with each flood out of the coulee. Drumheller's marginal scarps, cut in a superbasalt sedimentary rock (Ringold formation?), record the highest and earliest flood, 1,300 feet A.T., the same flood that initiated the three cataracts on the west side of Quincy basin. Drumheller outran the cataracts and finally reached a depth in basalt of about 950 feet A.T.

In the deepening of Drumheller is a record of perhaps two Grand Coulee floods. On both eastern and western margins are minor, high-level basalt channels in the sedimentary rock, each once a cataract and each partially cut away later by the deepening of Drumheller. In themselves, they do not establish a sequence in floods. Taken with the Quincy basin channels in gravel and the cataracts of Evergreen-Babcock ridge, a sequence is clear. Add to this the existence of three faintly shown scabland rivers (Rocky, Bowers-Weber, and Lind) entering Quincy basin from the Cheney-Palouse region (Bretz et al., 1956, pl. 7) but lying south of the group that discharged to Upper Crab Creek. They were abandoned so early in flood sequences that, as shown in the *Nimbus I* depiction (pl. 1), they became obscure before the plateau floods had ceased.

Uncertainties and complexities in the Grand Coulee system's record do not justify the concept of more than two floods, but the suspicion remains, and from Neff's later, unpublished research, the number, still uncertain, probably is more than two. Neff has demonstrated that two floods *out of* the Columbia Valley *into* the Quincy basin have occurred, the first one before the strongly marked caliche was made. His sections, near the head of Crater Notch, contain long, poorly sorted, southeast-dipping beds of slightly bruised basaltic columns, boulders of soft siltstone, and angular masses of an older caliche and of calcareously cemented loess. From consultation with Richmond, Neff dates the earlier flood as Bull Lake and the second (the one noted in this account) as early Pinedale.

The discharge through Drumheller Channels across the nose of the Frenchman Hills anticline could not all be accommodated by the westward-leading synclinal valley (Lower Crab Creek) between the Frenchman Hills and Saddle Mountain anticlines, and a considerable portion spilled southward across the eastern nose of the Saddle Mountain anticline. This produced the Othello group of deeply bitten channels and rock basins and a mile-wide channel in the sedimentary cover on the preglacial divide summit there. The entire group is 3 miles wide.

Fully as significant as this channeled divide summit is the 8-mile channel from Drumheller to Othello (Bretz et al. 1956, fig. 12); broad, rudely terraced, and strewn with huge boulders, some of which had to be blasted for excavation of an irrigation canal. Yet there is no continuous gradient for this distance. Only a steep surface gradient of a large volume of floodwater, arriving with adequate depth, can account for this channel leading to Othello.

No sequence in floods through Othello can yet be read with confidence. But the farther course of Othello water across the Ringold plain, 10 miles or more to the south in the Pasco basin, left a record of what appears to have been three floods. The Koontz Coulee channel group on this plain consists of two sets of channels in the soft rock. The heads of the highest set hang 200 feet higher than, and are truncated by, the scarfs of those of the lower set. As previously noted, all Koontz Coulee channels hang in notches in the White Bluffs summits along the Columbia River.

A third flood (actually the first of three) is postulated from the existence of a mantle of glacially derived gravel with basalt and caliche fragments lying higher on the Ringold plain than any of the channels and 500 feet above the Columbia.

A fourth and last flood, limited to the Columbia Valley, is unquestionably recorded in the Beverly bar which blocked the mouth of the synclinal valley of Lower Crab Creek and must postdate all Grand Coulee discharge.

Successive floods down the great Cheney-Palouse spillway doubtless occurred to correspond with those in the Grand Coulee system before the Upper Coulee's 25-mile-long 900-foot gash had been made. But the record is not as detailed or as trustworthy. One early flood is definitely established, however, from the obscuration that the Rocky, Bowers-Weber, and Lind coulees have suffered. Neff would date this flood as Bull Lake. To serve these three distributary coulees, its magnitude must have been adequate to carry it also down Washtucna and across the Palouse-Snake divide. Later floods failed to reach the heads of the three obscured coulees, because clearing away of the loess and enlargement of the preglacial valleys in the broad Cheney-Palouse tract had provided adequate capacity for them.

The number of floods on the Columbia Plateau and in its master valley is one less than the number of interstadials and intra-episodes in the northern Rockies. A complete correspondence is not required by our main thesis that Missoula burstings were the source of scabland rivers. Nor is it required that Missoula filled each time to its uppermost shoreline before its dam burst. Indeed, Pardee (1942) recognized that in Flathead Valley, Montana, there had been two different fillings, the later one less extensive than the earlier.

The writer feels that the back-flood deposits in preglacial valleys tributary to what became scabland routes will yield more knowledge and possibly a firmer chronology of successive floods. These deposits appear to record a repetition of deposition under currents of varying strength alternating with erosion into deposits already laid down. Some of the erosion was clearly subfluvial under up-valley currents, but some may have been subaerial and thus may record fairly long intervals of exposure before another back-flooding occurred. This subject has not yet attracted any investigator's close attention.

THE LAKE BONNEVILLE FLOOD

Another great Pleistocene lake's outburst is to be noted in this account—the breaking of the lowest (earthen) rim of Lake Bonneville, the ancestor of the Great Salt Lake in Utah, and the funneling of the uppermost part of its volume into the Snake River at a point nearly 600 miles upstream from the entrance of Lake Missoula water at the Palouse-Snake divide.

Gilbert (1878) was the first to discover the breakout at the extreme northern end of that pluvial, but nonglacial, great lake's basin. The rimrock which constituted the divide was poorly consolidated, deeply weathered alluvial waste between the lake basin and a north-draining valley that led to Port Neuf River, a tributary of the Snake River. According to Gilbert (1890), the overflow from Bonneville's previously closed basin (the Bonneville level of the lake) trenched into this divide for 375 feet before encountering more resistant rock that determined a new and lower (Provo) level. Gilbert estimated that 482 cubic miles of water (cf. Missoula's 500) escaped down this trench, and thought that the lowering continued for about 25 years. Yet he called it a "debacle."

Field evidence that this discharge across the Snake River plain had been vastly increased for a brief episode is credited to Malde (1960, 1965, 1968). His detailed study of that basalt plain has found a complex of abandoned high-level channels and cataracts and a number of river bars comparable in magnitude, structure, and composition to those along the Missoula flood routes. Some are more than 100 feet high, some block mouths of tributary valleys, some are separated from adjacent canyon walls by "marginal troughs" 150 feet deep. Down-valley foresets are consistently shown. According to Malde (1968) they are similar to the gravel bars in the channeled scabland of eastern Washington. Like the scabland bars, they can be accounted for by the passage of a catastrophic flood. Malde's estimate of the time involved in this Bonneville overflow is much less than Gilbert's.

He also states (1968, p. 10) that the catastrophic overflow of Lake Bonneville was "about 30,000 years ago." This would place it between the Bull Lake and Pinedale glaciations as dated by Richmond. He adds that "the Missoula Flood far exceeded the Bonneville Flood in violence although it was only a little greater in volume."

Malde's latest contribution on the Lake Bonneville flood revises Gilbert's opinion that the prism of water involved is indicated by the vertical distance between the Bonneville (highest) shoreline and the succeeding Provo shoreline. Malde and his associates, Bright and Rubin, are confident that the lake, prior to the flood episode, was much lower than the Bonneville shoreline and that lava flows in the drainage of the Bear River, by diverting that large source of water to the Bonneville basin, caused a rise in lake level perhaps 100 feet higher than the level marked by the later Bonneville shoreline. It was this influx which reached the summit of Red Rock Pass and initiated the debacle down Port Neuf River.

However, these students hold that the catastrophic erosion in the pass deepened it only to the Bonneville level, where sufficiently resistant rock was encountered, and flood discharge down Port Neuf River was succeeded by an erosional deepening rate consonant with the stabilized outlet river. The flood was over. Thus Malde and the others hold that a lowering of only about 100 feet yielded floodwater of about 380 cubic miles. The time estimated for this rapid deepening and lowering of outlet lake level may have been at least 6 weeks and less than 1 year. Malde's Professional Pazer 596 contains these and other quantitative estimates made by associated students of the Bonneville field evidence.

All this briefly discharged volume went westward down the Snake to the Oregon-Idaho line. There it turned northward through the Snake River's Seven Devils Canyon, emerged into the Lewiston downwarp, turned westward again, and entered that 70-mile-long portion of the Snake's canyon which has herein been described as the scene of a great up-valley back-rush from the Cheney-Palouse flood.

Here is a challenging situation for the historically minded geomorphologist. The flood record in this last 70-mile stretch is, as far as is known, all back-rush! It suggests that the last great up-valley invasion was later than, and erased any record of, the earlier Bonneville flood.

Altitudes of the pebbly, gritty silt and floated erratic boulders in the Snake Canyon upstream from the Palouse-Snake divide transsection indicate that the back-rush must have reached at least 1,300 feet A.T. Its effects in the broad, downwarped region of Clarkston, Washington, and Lewiston, Idaho, are complicated by other stream-gravel deposits of various ages but cannot be expected much farther up the Snake.

A gravel deposit in the valley of the Snake a few miles south of Lewiston, built across the mouth of Tammany Creek Valley, is certainly a great river bar made under very exceptional conditions. In the light of present data, it may be assigned either to a scabland flood's backwash or to a northbound Bonneville flood emerging from the Snake Canyon south of Lewiston.

The deposit is a broad ridge nearly 100 feet higher than the creek's valley floor, 250 feet above the Snake and nearly 1,050 feet A.T. (Bretz 1929). It slopes gently toward the Snake but steeply toward the blocked valley. Its long delta-type foresets which dip out of the Snake Valley determine this steep slope.

The bar is a plum pudding of unsorted boulders and cobbles in a matrix of fine gravel. From several samplings, the fines average 89 percent angular and subangular, 9 percent broken-rounds, and 2 percent well-rounded particles. The 89 percent angular fine gravel can hardly be distinguished from the product of a rock crusher.

Percussion scars on the edges of disk-shaped but otherwise smoothly worn cobbles and boulders record tremendous pounding. Commonly, the scars are 2–3 inches across. One basalt boulder carried a scar 1 inch deep and 15 inches in diameter.

Basalt is by far the dominant constituent of the deposit, but the previously smoothed large fragments are in large part former Snake River cobbles picked up locally by the flood. Dominance of basalt and the altitude of this debris argue for derivation in a scabland back-flooding. But until further field study, the suspicion remains that the Tammany bar may be a Bonneville flood product.

Only one Bonneville flood of catastrophic proportions is to be contemplated, and some older gravel locally exposed may also be of Missoula flood origin. By Richmond's chronology, Lake Missoula had a later flood than the Bonneville debacle. Any Bonneville flood must have gone all the way down the Columbia to reach Pacific Ocean levels. But we must conclude that its record is probably limited to Utah and Idaho. No evidence for it has yet been found in Washington or Oregon.

THE BACK-FLOODED GLACIAL SILTS

The intimate mixture of tiny basalt granules in the back-flooded silts on the lower, gentler slopes of all nonglaciated valleys tributary to the Cheney-Palouse tract of the Snake canyon above the Palouse River junction, of the Walla Walla River basin, and of the lower valley of the Yakima River may be ascribed, in part, to soil creep. Some intimate mixing, however, exists in flat-lying valley-bottom deposits, and there it must be an original structure.

Lenses and pockets, even thin strata, of silt-free basaltic sand may lie in and between usually thicker beds of essentially granule-free silt, originally loess. The almost omnipresent foreign rock pebbles, cobbles, and boulders prove that these materials were introduced by glacial water. Their upper limits in the eastern tributary valleys make a southward-descending series in accordance with the Cheney-Palouse spillway gradient (Bretz 1929). The absence of any such deposits on spillway bars seems to mean that when these bars were growing, no fines could come to rest on channel floors.

Surges are a necessary part of the picture of these back-floods, because only great turbulence could have maintained suspension for the many miles traveled up some valleys.

Another necessary part of the picture is slower down-valley draining away that left largely intact the slope mantles and the valley-floor deposits made at the intervening pause in reversing the circulation. Flushing-in occurred, flushing-out did not.

The great thickness of some valley-floor accumulations may have required recurrent episodes of floodwater filling and emptying. The long distances traveled in these up-valley floods is one of the most incredible items of the Missoula flood story. The towns of Arrow and Juliatta in the lower Clearwater Valley mark the maximum known distance this material was carried back up-valley, nearly 100 miles from the Palouse-Snake junction. Fresh highway cuts near Arrow afford a series of sections totaling 1 mile with depths of 30 feet maximum in rude, terracelike shoulders of the bottom slopes of this valley. The sections are dominantly of silt and fine sand, stratified with the familiar undulatory bedding and variations in thicknesses and in contacts of members. Multitudes of pockets, seams, and indistinct strata of coarse basaltic sand are well distributed along with foreign pebbles and cobbles.

Freshly made highway sections in the bottom of the lower Tucannon river valley, a few miles up the Snake from the Palouse River junction, were described by Bretz et al. (1956, p. 1034) with the comment that "perhaps two kinds of backwater episodes are recorded in these deposits, both with up-valley currents. The well-sorted, well-stratified valley bottom deposits may be the consequence of melt-water incursions from normal valley train building along the main scabland routes. Because, however, floods have all but destroyed any record of valley trains, survival of such valley bottom sediments seems anomalous. Furthermore, their existence in Snake tributaries above the Palouse junction would require a Palouse canyon, an Allison ice dam, or a Flint fill in order to cross the divide."

In the Yakima structural valley, silt with foreign rock fragments extends for 50 miles upstream from Chandler Narrows and in numerous places has a definite topographic and stratigraphic relation to younger features. Two postsilt terraces flank the present floodplain, each with a volcanic ash which dates each deposit. The glacial silt higher up the slopes has a maximum thickness of 30 feet near the head of the structural valley. Its stratification shows some graded bedding —repeated couples of sand grading up into silt. Graded bedding also occurs in a number of Walla Walla Valley exposures. There are altogether too many in one section, and they are too thin to assign each couple to a separate flood influx. Thicknesses of the total deposit seem too great, however, to assign to one flood. Thus far, no marker for identification and separation of successive silt- and berg-laden floods, here or elsewhere, has been recognized.

GLACIAL LAKE MISSOULA

While Lake Bonneville lay for many centuries in a broad basin among mountainous uplifts and never had an outlet until its rising level topped the divide at Red Rock Pass, Lake Missoula occupied free-draining river valleys that only a very few times were briefly blocked by glacial ice. Bonneville's shorelines (Bonneville, Provo, and Stansbury) are strongly expressed features of the landscape; Missoula's are of the faintest character. Bonneville's advantages in this item were a broad expanse for wave fetch and a long-continued balance between precipitation and evaporation. It never had an experience with glacial ice like that of Missoula, where growth and wastage of the Cordilleran ice sheet was the climatic factor.

Missoula's numerous shorelines are so faint and close set that there is little hope of determining the total number or of correlating from valley to valley. No long-continued pauses in the changing lake level are on record. Probably the series is the aggregate result of several fillings and emptyings, not a strictly chronological series as Eakin and Honkala (1952) have conceived.

Richmond (1965) has found glacial stream gravel at 4,200 feet A.T. on the northern nose of the Bitterroot Range, against which the Pend Oreille lobe impinged. Presumably this outlet stream flowed between rock on one side and glacial ice on the other. Probably Missoula discharged its constantly rising levels between rock and ice during whatever time was involved in rising to 4,200 feet A.T. and, had the Pend Oreille lobe crowded farther south before the dam broke, Missoula would have risen to spill across the lowest notch that does exist in the Bitterroot crestline.

For years after Pardee's 1910 paper, the evidence for Lake Missoula was predicated on the faint shorelines etched out in the mountainside mantle waste and on certain deposits banked up in minor ravine mouths at appropriate altitudes. These were called eddy deposits by Pardee. Davis (1921) doubted this and hypothesized that tongues of glacial ice in such valleys left fragmentary lateral moraines.

But Pardee established his interpretation when, in 1942, he reported the spillway gorges and giant current ripples already noted (see p. 1569-1600) and the severely scrubbed and largely bare rock salients along that particular flooded valley (Flathead-Clark Fork River). These strongly eroded surfaces are below the lake's upper limit, while the same slopes above have a cover of soil and colluvium. Only Alden (1953), admitting the probability of catastrophic emptying, remained dubious about the "unusual currents in Lake Missoula."

Bonneville's lacustrine sediments have had the attention of several investigators since Gilbert's classic study, but any record in Missoula's bottom deposits is only in the early stages of deciphering. Probably the lake arm occupying the broad Rocky Mountain trench will yield the most detailed record.

Nobles (1952) and Bretz et al. (1956) have been concerned with the relations of Lake Missoula to the frontal moraine of the latest advance of the Flathead lobe in the Rocky Mountain trench. At the south end of Flathead Lake, the Polson moraine has Missoula shorelines inscribed on its strongly expressed, subaerially built forms, and therefore must be older. On the west side of the lake, the Elmo moraine, a continuation of the Polson, also has the shorelines, though faintly developed. But west of and beyond the Elmo moraine, valley slopes carry much more definite scorings of a premoraine stand of Lake Missoula, and outwash from this moraine lies in a trench cut into lake silts. Thus an early lake level here was drained away before the last ice advance occurred, and only after that reached its maximum did the lake level come back. Richmond, the most likely student to pursue this theme, has already established criteria for differentiating deposits of Bull Lake age from those of the later Pinedale age.

GLACIAL LAKES COEUR D'ALENE AND SPOKANE

The Pend Oreille lobe which dammed the Clark Fork River valley approximately at the north end of Lake Pend Oreille also pushed 40 miles farther southward along the western side of the Bitterroot Range in the now-streamless valley called Rathdrum Prairie. Here it blocked another northwest-draining river system and made another glacial lake, the predecessor of modern Lake Coeur d'Alene. Its water backed up for miles to the southeast, drowning preglacial river valleys which had drained the western slope of the Bitterroots and the Coeur d'Alene mining region. Water rose at one time high enough to spill briefly from its western side across unglaciated country well south of the dam and to discharge into the head portion of the Cheney-Palouse tract. Because this outlet traversed loess of Bull Lake age with a strong soil profile and because the moraine which retains the modern lake is of Bull Lake age, Richmond (1965) thinks that the berg-floated erratic boulders reported by several observers since Hershey (1912) and the outlet channel in loess record a back-flushing—a great surge from the bursting of Lake Missoula's dam in early Pinedale time. During Bull Lake glaciation, the lake had been at a lower level and had discharged from its northern end, the overflow escaping westward between glacial ice on the north and mountains on the south (Bretz et al. 1956, p. 1040).

This water entered another glacial lake, Lake Spokane, whose area, originally defined by Large (1922), has been extended considerably north of the city of Spokane by Richmond. Lake Spokane, thus defined, was dammed on the west by the Colville lobe of Bull Lake age. Its overflow was probably southward into the Cheney-Palouse scabland tract.

SOME INTERRELATED QUESTIONS AND PROBLEMS WHICH PRESENTLY LACK ANSWERS AND SOLUTIONS

Correlations of and by back-flood silts.—The number of Missoula outbursts is still tentative, and correlations among widely separated scabland spillways remain unsettled. A promising approach appears to lie in the flood deposits on the bottoms of back-flushed valleys. There may have been two kinds of experiences involved: (1) the flooding-back of Missoula discharges and (2) backwater from normal glacial drainage between floods. If such occurred, differentiation is yet to be found, and records of the second kind of event can be expected only in the lower reaches of the tributaries involved. Transportation of the flood silts is a problem for which the writer has only vague solutions. A hydraulic engineer conversant in the field could well improve on them.

Walla Walla basin sediments.—The basin drained by the Walla Walla River is a district of backwater sedimentation from a greatly swollen Columbia River. Except for the Ringold formation, no tract in the entire plateau carries a thicker deposit of fine-textured, well-sorted, and stratified quiet-water sediments. Some of it is surely of glacial origin. Is it all from glacial water? Are the graded beds here and in the Yakima Valley annual records? What chronology can be found in the exposures? Are the Glacier Peak and Mazama ash beds present? What relation is there between the Ringold formation, apparently from nonglacial water, and the Walla Walla deposits?

If successive floods are on record in this basin's sediments, alternating with records of interflood intervals, a sequence will be established when calichified or weathered horizons, berg-transported erratic material, up-basin erosion, transportation or deposition, volcanic ash layers, peat deposits, etc., are found.

Lake Lewis and Touchet silts.—Dating from Symons's report (1882) is the concept employed by several later investigators that the finer sediments in the Pasco downwarped region record a glacial "Lake Lewis." Both Allison and Flint imagined a dam in the Columbia Gorge across the Cascade Range as the cause of such a lake, and Flint gave a formational name—Touchet silts—to such deposits.

The writer's concept of hydraulic damming at Wallula Gap provides a ponding of the Pasco basin for each Missoula flood, sees the fine sediments as deposited irregularly in both time and space, and questions the Lake Lewis concept.

The name Touchet silts is still used (Richmond et al. 1965) for rhythmically bedded silts in the lower Snake Canyon. The implication that such deposits are correlative with what are here termed backwater silts should be investigated as should also their relations with the Walla Walla Valley deposits.

Lake Ringold and Wallula Gap.—No Ringold-type sediments have ever been reported beyond Wallula Gap. Is this extensive deposit, believed by some to be of Pleistocene age, due simply to a damming of the Columbia by the rising Horse Heaven Hills anticline as late as the Pleistocene?

Origin of Wallula Gap.—If, following Newcomb (1958), we date the uplift of the Horse Heaven Hills anticline at Wallula Gap as mid-Pleistocene, we can have no considerable gap during the life of his Lake Ringold. How much of a gap was there when the first Missoula flood arrived? How much of the Gap's present depth is the erosional consequence of all floods? One begins to wonder if that highest scabland just west of the Gap might be the oldest scabland now surviving. It certainly is not as old as the Old Maid record (see Prescabland Floods below).

An answer lies in the gravel spill from the highest Wallula scabland channels down more than 400 feet in a horizontal distance of less than 2,000 feet. It could hardly lie more steeply. It reaches essentially to the bottom of the gorge, just downstream from the narrowest part. The gorge downstream from the gap itself therefore was as deep as it is today when the first flood (pre-Wisconsin according to Richmond) arrived.

The mid-Pleistocene uplift at Wallula and the draining of Lake Ringold (cutting of the Gap) could hardly have been many millennia apart; yet by our argument, time sufficient for the transection of the anticline to the present depth must have elapsed.

The nearly flat top of the Ringold deposit is undoubtedly original with completion of this fill in the Pasco basin and is scarcely higher than the cliff summits along Wallula Gap. It seems very probable that the 500+ feet of this lake sediment accumulated during the uplifting of the Horse Heaven Hills anticline and that only an initial gap was eroded during the life of the lake.

Considering the depth of the Umatilla structural basin immediately downstream from the Gap and the short gorge of the

Gap, it may be postulated that transection of the anticline was accomplished by headward stoping of a marked series of rapids, falls, and cascades. If so, the draining of Lake Ringold was very rapid, because most of the gorge length was already excavated by the time recession of such high-gradient cascades finally reached completely across the tectonic barrier.

Predeformation course of the Columbia River.—Waterworn quartzite pebbles are strewn over a northeast-by-southwest area of the Horse Heaven Hills uplift south of the Yakima Valley, also on gentler slopes of the western parts of the Saddle Mountain and Frenchman Hills anticlines. They therefore are older than the folding. They also occur as strata in downfolded sedimentary rock in the Yakima Valley, generally considered to be the Miocene Ellensburg formation. They are clearly from a far-traveled river gravel and appear to record a Columbia course from the Beltian terrains of Montana, British Columbia, or Idaho. Are they the record of a Miocene river? Do they record the Columbia's course just before the foldings of the anticlines, that is, just preceding the shift of that river to the site of Wallula Gap? The undeformed Ringold occupies the broad Pasco structural basin, which almost certainly dates from the time of the Horse Heaven Hills uplift.

Columbia Valley between Okanogan Valley and Moses Coulee.—This stretch of 85 miles traversed by at least two Missoula floods has never been critically examined. In the last few miles, it receives Wenatchee River, below which junction is an area that the writer has described as glaciated (Bretz 1930*b*). But Page (1939) has found no evidence in the tributary valley that glacial ice ever reached its mouth (see Bretz et al. 1956, p. 990). Much landslide topography exists here, and the suspicion is justified that the writer has misinterpreted the tract. The entire stretch of 85 miles should yield new data on the late Pleistocene history of the Columbia Valley.

Chandler Narrows flood front.—Because of the large capacity of the Pasco basin, floodwaters from the Cheney-Palouse and Grand Coulee systems can hardly be expected to have produced in it the crested flood front deduced from Chandler Narrows and The Narrows of Oregon while Wallula Gap was open. Yet the Chandler scabland demands a very vigorous back-flooding up the Yakima structural valley. It seems logical, therefore, to assume that enough large berg ice arrived at Wallula to make a temporary blocking (an Allison ice jam) and thus the head necessary at Chandler and at the less spectacular back-rush into the Walla Walla depression which, like Chandler, is at the far end of the basin. But no field evidence for this is yet known.

Upper limits in Yakima Valley and on Wallula summit.—Disparity on the upper limits reached by floods back up the Yakima Valley (1100 feet A.T.) and at Wallula Gap 1,200 feet A.T.) may be due to inadequate field study in the structural valley. But the upper limit at Chandler Narrows is explicable by the much greater cross section of the valley above 960 feet A.T.

Recalculation of Wallula's discharge rate.—With remapping of the northwest corner of the Pendleton quadrangle on a larger scale will come an opportunity to recompute the discharge rate at Wallula Gap. Hydraulic damming also seems probable at the west end of the Umatilla depression, and this suggestion can be verified or disproved when the old Arlington quadrangle map is topographically resurveyed.

Berg deposits on Rattlesnake Mountain.—The writer noted (1930*b*) that the berg mounds on the northeast slope of Rattlesnake Hills (Iowa Flat) are abundant below an altitude of 850 feet but that only scattered berg-carried boulders lie between that altitude and the upper limit of glacial silt, 1,100 feet A.T., on this slope. Bretz et al. (1956) suggested that perhaps two different floods are on record here. If the berg abundance and berg load differed as much as indicated, this criterion should find support in further field studies in the district. The larger problem is the lack of a comparable berg population elsewhere in the semiponded tracts of the scabland or the Columbia Valley.

Tammany bar.—Solution of the Tammany bar problem will depend in part on a detailed field study of various gravel deposits in the Lewiston-Clarkston basin. The oldest gravel should date back to early downwarping and accompanying incision of the Snake River canyon thence downstream.

Glaciation at channel heads.—The writer believed that till deposits and subdued morainelike forms on that part of the Columbia Plateau between the Spokane and Columbia rivers on the north and the heads of Cheney-Palouse and Telford-Crab Creek channels on the south recorded glaciation almost up to the channel heads. Flint also saw this area as glaciated. Richmond has dismissed this view and sees the tract as flood-swept. But the total lack of isolated, residual hills of loess, so prominent a feature of flood erosion elsewhere on the plateau, seems to argue for glacial, rather than flood, removal. Perhaps both events occurred, glaciation before flooding.

Correlations of western cataracts.—Successive events in the life of the three western cataracts are not yet clear. Certainly at some time all fell from brink to plunge pool bottom. But such time could not coincide with the high level of floodwater in the Columbia Valley. When the Evergreen-Babcock bench, the high Wallula scabland, or the Beverly bar were under floodwater, none of the three cataracts could have functioned to the full depth of their recessional gorges.

Sequential operation of Palouse and Devils canyons.—The mouth of Devils Canyon is blocked by a gravel deposit nearly 300 feet thick. On the opposite side of the Snake River, this deposit extends about a mile downstream. Both remnants carry well-developed giant ripple marks oriented for discharge from Devils Canyon (Bretz et al. 1956, pl. 9, fig. 3). The mounded surfaces are 200 feet or more higher than any terrace or bar down the Snake or upstream as far as the great gravel bars at the mouth of Palouse Canyon. The deposit cannot be older than those bars and have survived the huge river they record. Was it made in that great stream or is it younger?

Bretz et al. (1956, p. 1005) describe a probable distributary discharge from Othello Channels eastward *up* Washtucna Coulee but say nothing of its farther course. The altitudes involved permit the idea that, if a Devils Canyon was already well incised and the distributary had adequate volume, it could have followed the canyon to the Snake and made the deposit. This would date it as after Grand Coulee had captured all plateau floodwater, when Othello was operating with a maximum flood and Cheney-Palouse had ceased to flow. This interpretation is based almost entirely on maps and aerial photographs. A field study would verify or disprove it.

Sentinel Gap.—A deep hole in the rock bottom of Sentinel Gap where the Columbia River crosses the Saddle Mountain anticline seems to indicate that kolk action has occurred in this constricted place. Was hydraulic damming here a part of the cause? If backup of a Columbia flood did occur here, did it initiate Othello Channels, flood Evergreen-Babcock bench, or discharge eastward through the cataract notches in the Evergreen-Babcock ridge?

Prescabland floods.—Alden (1953) details scattered evidences for possible Illinoian glacial ice in Clark Fork drainage south of the definitely Wisconsin moraines. The question of a pre-Wisconsin Lake Missoula immediately rises. Richmond finds three glaciations recorded in Flathead Valley and indicates the first of his three Missoula floods as immediately pre-Wisconsin.

Two features of the southwestern part of the plateau strongly suggest floods earlier than those in Rocky, Bowers-Weber, and Lind coulees. One is Old Maid's Coulee, shown on the Connell quadrangle topographic map. It contains remnants of a bouldery gravel, mostly decayed basalt with pebble fragments of caliche, all under a marked caliche cap. The southwest-draining coulee is described (Bretz et al. 1956) as having no scabland and no notch at the head for entrance of floodwater from Washtucna. Richmond suspects that it is pre-Bull Lake in age.

The other feature is elongated Eureka Flat, most of it on the Walla Walla quadrangle, where it is 2 miles wide. It is parallel to the nearby Snake for its full length, 12 miles or so, and is bounded by strikingly narrow, linear loessial hills in alignment with the flat. Drainage enters it from these hills but, beyond a few miles, leaves it to reenter the loessial hills. No bedrock and no gravel are known, but its form, proportions, and parallelism with the Snake and the loessial hills surely are not simply fortuitous.

Possibly both valleys functioned as very early precaliche flood channels. If the Old Maid gravel records an older caliche broken up in an early flood with its fragments incorporated in a later flood gravel which lies under a later caliche, the suspicion arises that some caliche horizons in the loess of the Palouse region, thought to be correlative with interstades (nonflood episodes), may indeed be correlative with very early (pre-Wisconsin) Missoula floods. Neff's earliest known flood, from the Columbia Valley back into Quincy basin, disrupted a caliche that may be older than the one herein inferred to be immediately prescabland. Neff has also found, on the undissected summit plane of the Ringold formation, a gravel containing caliche fragments. Where does this belong chronologically?

Bacon basin.—Age and origin of the gravel beneath a caliche-capped loess in the Bacon basin are uncertain. It may be a preflood deposit of local origin, like the old gravel noted by Bryan in the Hartline basin. But if found to contain erratic material and large, sporadically distributed basalt boulders, it must be assigned to the earliest Missoula flood ever to cross the Trail Lake flexure and thus to early stages of cataract retreat in Upper Grand Coulee.

Repeated floods at Portland.—Trimble (1963) did not report any field evidence for successive floods in his "lacustrine deposits" of the Portland region. But if multiple floods (including a Bonneville flood) came down the Columbia, some record of intervals between them should be expected, at least in the silt and sand beyond the "Portland Delta" gravel. Trimble's investigation was detailed. Exposures made since may, however, reveal such records. They are worth looking for.

Rocky Butte.—In the eastern part of the Portland Delta gravel deposit, Rocky Butte (fig. 10) rises to 607 ft. A.T., while the gravel flat east of it is 300 ft. A.T. and a long train of gravel depending westward has nearly the same altitude. The eastern gravel flat fails to reach the cliffed face of the butte. Instead, there is a "hole" in the delta surface, a hole in gravel on the east but with a craggy rock wall on the west. This fosse is a basin more than a mile long (north-south) and less than a quarter of a mile wide. Along the face of the butte, it is a closed depression 10-25 feet deep whose bottom is approximately 100 feet lower than the delta surface just to the east, that is, upstream.

The flood which made the gravel flat had a huge downward-directed eddy when it encountered the butte, an eddy that either maintained a bottom hole here or eroded it. In the scablands, this would be a rock basin, here it is partly in gravel.

The north end of the hole opens to the Columbia's immediate valley slopes. The south end becomes two curvilinear troughs which lead westward alongside the gravel flat and gradually shallow and taper out. All this bespeaks, in Trimble's phrase, the "almost incredible" discharge from the Cascade Gorge into the broad Willamette-Columbia depression, as proposed by the writer in 1925. But the unanswered question of today is the proper place for this particular flood in the presently known series of floods.

Richmond indicates his Pinedale flood as the greatest of the three he identifies. The Rocky Butte fosse could well be a part of its record. However, the flood that Neff has identified as discharging *from* Columbia Valley through Crater Cataract notch *into*

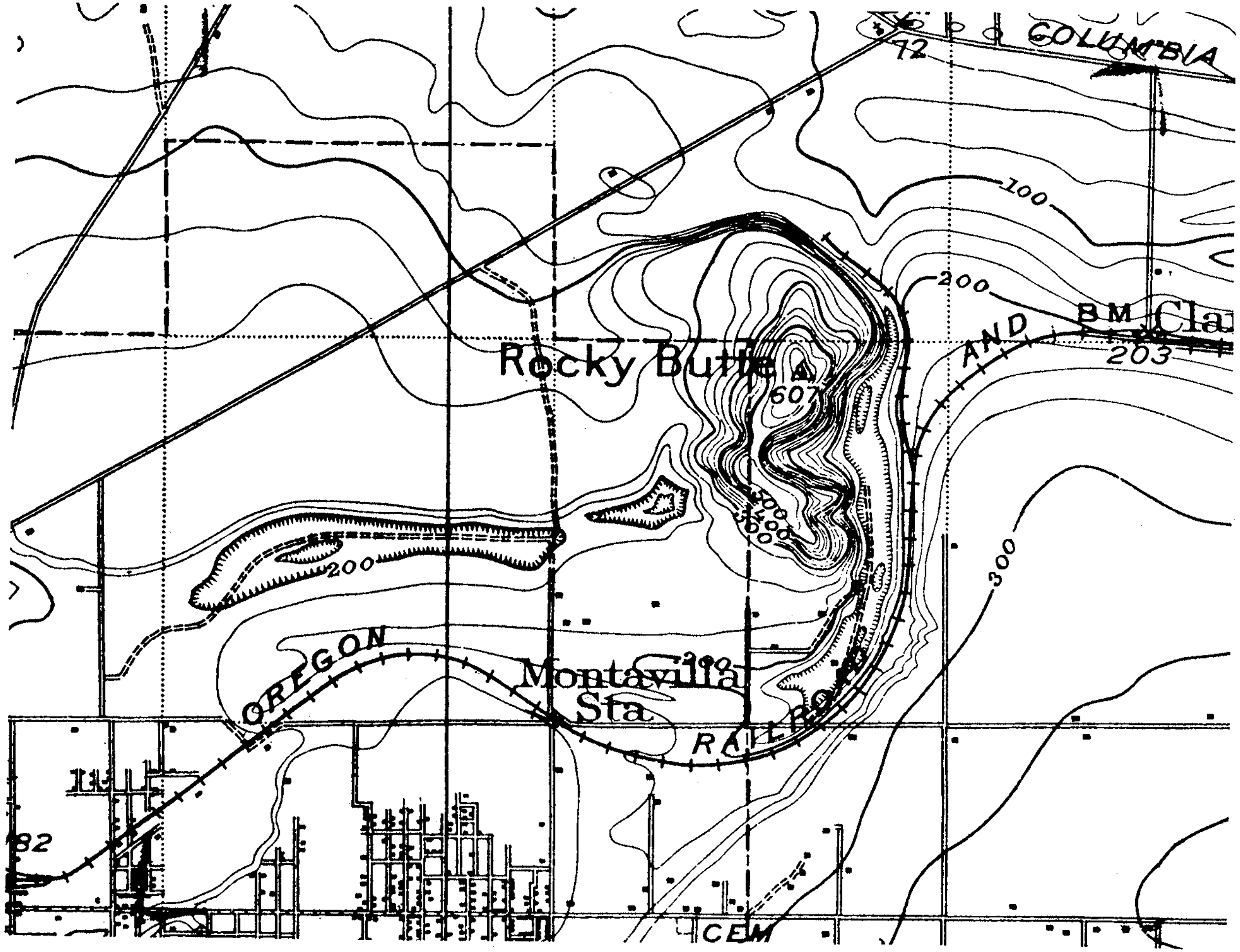


FIG. 10.—Rocky Butte, from Portland, Oregon, topographic quadrangle map, U.S. Geological Survey; contour interval, 20 feet

Quincy basin and the probably contemporaneous eastward discharge through the Potholes notch (Bretz et al. 1956) both demand that Drumheller and Lower Crab Creek channels then function, even without any Grand Coulee contribution. Was this the Pinedale flood with no Okanogan dam then existing?

Then one recalls Beverly bar, built after the last operation of the Lower Crab Creek channel. It would have to be post-Pinedale and would also be a post-Okanogan affair, and therefore a smaller flood.

It is fair to assume that the Rocky Butte fosse is a maximum flood record, along with the ice-floated erratic boulders known up the Willamette Valley to altitudes of 450 ft. A.T. How was the fosse modified by floods? If they were only 125 feet deep in the Columbia thalweg, they did not reach the fosse through its open north end. Such an interpretation would perhaps take care of the Beverly bar flood, especially if it were not adequate for Trimble's hydraulic damming. But the Crater and Potholes reverse discharge into the Quincy basin seems to demand a major flood and, hence, a record of back-flooding in the Rocky Butte fosse if it then existed. Dating the fosse constitutes a neat little problem for further study.

Flood sources other than Missoula.—There is tacit acceptance throughout this paper that collapse of the Missoula dam provided the floods on record. However, an Okanogan dam burst could release a huge quantity of water without any Missoula flood, although minor in comparison. There are at present unexplored possibilities of other glacially dammed lakes in the northern Cascades and the Okanogan Valley from which sudden release could leave some of the flood records known in the Columbia Valley from the Big Bend all the way to Portland.

Relations of the Nespelem formation to Walla Walla sediments.—Note has been made of Lake Columbia's white silts on the Upper Grand Coulee floor, considered by Richmond as late Pinedale in age. Can this Nespelem silt formation be dated by organic remains (C^{14})? Neff reports that it is older than the volcanic ash layers. If no correlations can be made between any part of the Walla Walla sediments and the Ringold formation, the latter will prove to be the older. But both the Walla Walla and the lower Yakima structural basins logically must be considered as contemporaneous with the Pasco basin, and altitudes of these two basin bottoms are well below the Ringold's flattish summit levels. Why then should not at least the lower portions of the Walla Walla beds prove to date from Lake Ringold? A more challenging situation exists in the Yakima Valley, where no Ringold or Walla Walla sediments have yet been reported. The Yakima's later meandering can hardly be held responsible for cleaning out that wide structure of any such sediments.

Sediments of Lake Missoula.—As far as is now known, the glacial lake's sediments are varved and contain randomly distributed, ice-floated rock fragments.

Future studies will begin with sections in postglacial stream trenches in floors of various lake-occupied valleys. The shallower bays will have had complete emptying with each dam burst and may record flood currents. All parts of the lake must have been emptied whenever retreat of the Cordilleran ice sheet reestablished the preglacial Clark Fork and Columbia River drainage system and thus provided for nonflood erosion on the lake bottom. If, however, an Okanogan lobe still blocks the Columbia, a shrunken remnant of Lake Missoula will linger in the deeper valleys near the site of the dam, and if Upper Grand Coulee's cataract has not yet breached the Columbia Valley's southern wall, a Lake Columbia will extend eastward, possibly past the Colville lobe to join the shrunken Missoula.

Reconstruction of the Pend Oreille dam will produce another Lake Missoula and another varved clay deposit. Unconformities will separate every two such sedimentary units.

During an episode of glacial retreat and lake drainage, bogs and forests will invade the exposed floors. Return of lacustrine conditions will bury peat beds and tree stumps along the unconformities. Leaching and oxidation will be added to the record of erosion and plant invasion.

Carbon-14 dating of woody material will be the only reliable method of correlation among areally separated records of drainage intervals. Exceptionally complete local records may correlate with the glacial record in the northern Rocky Mountains and the loessial sequence on the Columbia Plateau, but it will fall short of the scabland record as outlined in this paper.

Astoria deep-sea fan.—Two different causes for the ponding recorded by the Portland Delta are hydraulic damming (Trimble 1963) and a higher sea level (Lowry and Baldwin 1952). Evidence bearing on this conflict of interpretations can probably be found when the Columbia Valley beyond Trimble's dam site is studied in detail.

With more data than presently announced (Nelson and Byrne 1968), the deep-sea fan at the mouth of the Columbia River may conceivably yield information on the arrival of various catastrophic floods. The summit portion of the fan possesses "poorly sorted gravel, sand and silt members" in "coarse layers of irregular thickness with sharp upper contacts and poorly developed clay interbeds" which are considered to be of glacial age buried by postglacial clay.

Q.E.D.?

The International Association for Quaternary Research (INQUA) held its 1965 meeting in the United States. Among the many field excursions it organized was one in the northern Rockies and the Columbia Plateau in Washington. The party of thirty-two participants representing nineteen countries, led by Richmond, saw the Polson moraine and Lake Missoula shorelines in the Rocky Mountain trench, Pardee's gigantic current ripples and the strongly scoured valley shoulders and eddy deposits in the Clark Fork Valley in Montana, and the site of the Pend Oreille glacial dam for Lake Missoula in Idaho, and spent a day on the Columbia Plateau in Washington. The party crossed the head portions of the Cheney-Palouse and Telford-Crab Creek tracts, traversed the full length of the Grand Coulee, part of the Quincy basin and much of the Palouse-Snake scabland divide, and the great flood gravel deposits in the Snake Canyon. The writer, unable to attend, received the next day a telegram of "greetings and salutations" which closed with the sentence, "We are now all catastrophists."

ACKNOWLEDGMENTS.—Roald Fryxell, Harold Malde, George Neff, Gerald Richmond, and Donald Trimble have been consulted on various items in this paper and have contributed suggestions and criticisms. They have the writer's lively appreciation.

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