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CHANNELED SCABLAND OF WASHINGTON: NEW DATA AND INTERPRETATIONS

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ABSTRACT

The existence of four different interpretations of that extraordinary assemblage of erosional and depositional land forms of eastern Washington, the "Channeled Scabland", indicates that rigorously definitive diagnostic characters had not been found. This study, dealing with new data, largely from extensive excavations and detailed topographic maps made by the U. S. Bureau of Reclamation in developing the great Columbia Basin Irrigation Project, returns to the earliest of the four interpretations: that channeled scabland is almost wholly the consequence of catastrophic flooding of glacial water across this part of the Columbia Plateau which remade preglacial valleys into an anastomosing complex of great river channels with huge cataracts, deep rock basins, and bars attaining magnitudes unknown elsewhere on earth.

The new evidence is held to establish firmly the following points:

(1) Some structural basins of the region did not have exterior drainage prior to arrival of glacial water.

(2) The gravel hills called bars by Bretz (1928a) have the shapes, surface markings, structures, and topographic situations possible only for subfluvial constructional deposits. In magnitudes and bouldery composition, they are *sui generis*.

(3) Several episodes of catastrophic discharge have occurred across this part of the Columbia Plateau.

(4) The Columbia Valley skirting the plateau has had comparable floods in which the scabland complex did not share.

(5) Successive floods have been differentiated only by topographic relations of their records, not by differential weathering and erosion.

(6) Bretz did not overestimate the magnitude of the erosion by glacial waters.

(7) The existing scabland features contradict the three later interpretations.

CONTENTS

TEXT

	Page
Introduction	958
Acknowledgments	961
Previous investigations	961
General discussion	961
Summary of original interpretations	965
Advance summary of new evidence and interpretations	966
Grand Coulee and Quincy basin	967
Grand Coulee	967
Trail Lake anticline and Bacon syncline	967
Soap Lake	969
Quincy basin	969
Drumheller Channels	975
Upper Crab Creek	977
General statement	977
Comparison with Yakima Valley gravel deposits	979
Bars in Wilson Creek valley	980
Black Rock Coulee	980
Rocky, Bowers-Weber, and Lind coulees	982
Western part of Quincy basin and adjacent Columbia River valley	984
Moses Coulee	988
Correlation of events and sequences thus far presented	990
Lower Crab Creek	990
Othello and Koontz Coulee channels	995
Earlier flooding in Quincy and Othello basins	999
Washtucna Coulee	999
Drainage	999
Staircase Rapids and its bar	1000
Other deposits	1003
Esquatzel Coulee	1005
Pasco basin	1009
Palouse-Snake divide and environs	1015
General	1015
Scabland features on the divide	1016
Bars in Snake Canyon	1020
Prescabland Fields Gulch	1024
Flint's Riparia Lake	1024
Devil's Canyon	1026

Page
Flint's derivation and disposition of scabland debris 1027
Repetition of floods 1028
Cheney-Palouse tract north of Palouse-Snake divide 1030
Multiple scarps 1030
Meander scars 1031
Willow Creek bar 1031
Slackwater silts near Palouse-Snake junction 1033
Glacial Lakes Missoula and Coeur d'Alene ... 1034
Summary 1043
Bretz's flood hypothesis 1043
Allison's ice-jam hypothesis 1043
Flint's fill hypothesis 1044
Character of new evidence 1045
Flood correlations 1045
Recapitulation of inferred history 1047
References cited 1048

ILLUSTRATIONS

Figure Page
1. U. S. Geological Survey index map for most of the quadrangles referred to in this paper 960
2. Physiographic diagram of Channeled Scablands and environs 962
3. Profile of gravel deposits on south slope of Trail Lake anticline 968
4. Main portion of Quincy Basin 970
5. Northern end of Quincy Basin 972
6. Moses Lake and vicinity 973
7. Profiles across Drumheller Channels 976
8. Summit of upper Crab Creek-Quincy basin divide 981
9. Sequence in channel operation, Quincy basin and environs 989
10. Lower Crab Creek and Jericho Coulee ... 992
11. Beverly bar 993
12. Map of Othello Channels 995
13. Profiles across Othello Channels 996
14. Staircase Rapids and environs 1001
15. Bar north of Mesa 1008
16. Cold Creek bar 1011
17. Central part of Pasco basin 1013
18. Profiles of scabland on Palouse-Snake divide 1017
19. Vicinity of H U Ranch cataract 1018
20. Rock basins on summit of Palouse-Snake divide 1019
21. Scabland features on south side of Snake River at confluence of Palouse River. 1021
22. Lower Willow Creek and vicinity 1032
23. Map of Glacial Lake Missoula and Channeled Scablands 1036
24. Region between Lake Missoula and Channeled Scablands 1038
25. Scabland channel heads northwest of Cheney 1041

Plate Facing page
1. Map of Channeled Scabland of Eastern Washington 957
2. Map of Trail Lake anticline and vicinity. 968

Following page
3. Unnamed Coulee and associated gravel deposits 974
4. Giant current-ripple marks 974
5. Bars in Upper Crab Creek Valley 974
6. Bars in Upper Crab Valley 974
7. Map of Drumheller Channels 978
8. Map of bars in Upper Crab Creek Valley 984
9. Giant current-ripple marks 986
10. Drumheller and Potholes dischargeways 986
11. Bench between Babcock Ridge and Columbia River 986
12. Scabland bars 986
13. Scabland details 986
14. Bars near Mesa 1006
15. Gravel bars south of Snake River 1006
16. Scabland features in mid-width and mid-length of Cheney-Palouse tract 1006

Introduction

The plateau character of eastern Washington is determined by the Miocene Columbia River basalt flows. In northern and eastern marginal portions, islandlike hills of much older crystalline rocks project above the general plane surface. Locally, folding and faulting of the basalt have made strongly expressed corrugations, uplifted little-eroded linear tracts, and depressed areas of only incomplete filling. All relief features, whether diastrophic, erosional or depositional, are interruptions of a regional southwestward slope of the plateau basalt flows.

The original low-lying basalt plain received fluviatile and lacustrine sediments—Ellensburg, Latah, early Ringold (?)—before recorded deformation or erosion. After folding and some weathering and erosion, similarly derived sediments were deposited in structural basins and are still flat-lying. The Ringold formation in the Pasco basin is the outstanding record of this time. Considered to be of Pleistocene age solely from its scanty vertebrate remains, it shows no evidence of contemporaneous glaciation.

Overlying all these older formations is an extensive, thick silt mantle, the "Palouse soil." Most of it is clearly of loessial origin, but a detailed history has not yet been deciphered. A rolling to hilly topography, made mostly by stream erosion but some by wind, appears to have existed on this mantle during the time of accumulation of the dust and has subsequently become much more marked. Calcified and reddened zones, even caliche layers, are known deep in the loess. A widespread sub-

SHINGTON[9]

Page
...annels..... 996
...environs..... 1001
...ia..... 1008
..... 1011
...asco basin..... 1013
...nd on Palouse-Snake di-
..... 1017
Ranch cataract..... 1018
...summit of Palouse-Snake
..... 1019
...s on south side of Snake
...ence of Palouse River.. 1021
...reek and vicinity..... 1032
...al.e Missoula and Chan-
...s..... 1036
Lake Missoula and Chan-
...s..... 1038
...el heads northwest of
..... 1041
Facing page
...led Scabland of Eastern
..... 957
...ce anticline and vicinity. 968
Following page
...e and associated gravel
.....
...ple marks..... 974
...rab Creek Valley.....
...rab Valley.....
...ler Channels..... 978
Upper Crab Creek Valley 984
...ple marks.....
Potholes dischargeways.
...ishcock Ridge and Co- 986
.....
.....
.....
.....
...h ...ake River..... 1006
...s ...d-width and mid-
...ey-Palouse tract.....

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Caliche only in loess?

surface caliche was formed after loessial deposition had passed its maximum. It exists also on older rocks where not loess-covered.

The scablands are glacial-river courses where the Palouse and other sediments were swept off the basalt chiefly along preglacial drainage lines, and the basalt itself was notably eroded in places. In these glacial-river courses are extensive stream gravels of the same age and origin. Only the northern edge of the plateau was invaded by the Cordilleran ice sheet.

In the lower reaches of Snake River canyon, in Pasco basin of the Columbia, and in lower Yakima and Walla Walla valleys are widespread lacustrine silts—the Touchet beds—also contemporaneous with glaciation in highlands to the north, east, and west. The Touchet silts record a "Lake Lewis" backwater ponding either from a great blockade in the Columbia gorge across the Cascade Range or from a low stand of this part of the continent and an estuary from the Pacific. "Lake Lewis" is only a general term for possibly several Pleistocene pondings of the Columbia and its tributaries in the southwestern part of the plateau.

The term channeled scabland was first used by Bretz (1923a; 1923b) for the remarkably anastomosing system of glacial-river courses distributed over an area approximately 125 by 125 miles on the plateau.[1] Bretz (1927a) noted that:

> "The channeled scablands . . . cover almost 2000 square miles . . . of the plateau. They are elongate tracts, oriented with the gentle dip slope of the underlying basalt flows, mostly bare rock or with a thin cover of coarse basaltic rubble, commonly with canyons in them, and are bounded by steep slopes of the deep loessial soil of the plateau. They constitute a curious anastomosing pattern, the down-dip convergences inherited from an earlier normal drainage pattern and the divergences, equally numerous, produced by crossing of divides of this older pattern. There are hundreds of tracts of the higher loess-covered areas in the scablands, from a fraction of a square mile to many townships in extent, all discontinuous and bounded by the scabland areas. The steep marginal slopes in loess are in striking contrast to the gentle slopes of the older drainage pattern surviving within each isolated tract. Canyons in the scablands are multiple and anastomosing, amazingly so in some tracts, deep canyons and shallow ones uniting and dividing in a labyrinthine fashion about bare rock knobs and buttes unlike any other land surface on the earth. . . . These canyons are interpreted as channels, not valleys, hence the term 'channeled scabland' ".

This definition dealt only with erosional features. But the glacial rivers that "channeled" the scablands also left deposits whose character, the leading theme in this study, is as extraordinary as that of the erosional forms.

The glacial water that made the scabland crossed the preglacial divide along the high northern margin of the tilted plateau, found gradients of 20–25 feet per mile in the preglacial drainage ways leading southwestward down the dip slope, greatly enlarged them, and crossed minor divides among them to make the anastomosis. At some of these crossings canyons 400–900 feet deep were eroded by cataract recession. Empty rock basins more than 100 feet deep and not of plunge-pool origin occur in many places. The glacial rivers which swept the loessial cover[2] off the underlying basalt and left the sharply expressed marginal scarps, descending from the mature topography of the loess "islands" to the essentially bare basalt of the channel floors, are also recorded by great mounds of basaltic debris, chiefly in the Quincy structural basin and in portions of the canyons of Snake and Columbia rivers which discharged westward. Any satisfactory theory for the genesis of this unique assemblage of land forms must take account of all these features and relations.

Four distinctly different explanations, based on field studies, have been proposed during the past 30 years. At least three theories utilize enough apparently supporting field evidence to have been accepted among geologists acquainted with portions of the region, but each has lacked sufficient evidence to eliminate its rivals.

Field study on which this paper is based is the execution of a long-cherished plan by Bretz to restudy the region with the later

[1] After the appearance of 11 more titles by this author and 5 papers by writers who did not accept his interpretation of the origin of channeled scabland, the details of this definition still satisfactorily encompass all erosional and most depositional features of channeled scabland, except for one writer's explanation which has been vigorously rejected by everyone else acquainted with the region.

[2] Where used without qualification in this paper "loess" includes both the thin, fairly recent loess mantling the mature slopes of the "Palouse topography" and the Pleistocene Palouse soil, itself largely loessial in origin.

rival interpretations in mind. The great Columbia Basin Irrigation Project in the western part of the scabland complex has made new data available from the extensive new excavations and detailed topographic maps by the U. S. Bureau of Reclamation. Several new quadrangle topographic maps by the U. S. Geological Survey have appeared, and the entire region has been photographed by the U. S. Dept. of Agriculture. The field work was carried out with three men working together as a check on a "ruling-theory" tendency.

The finally accepted theory for the origin of this assemblage must consider the entire area. The elephantine character of channeled scabland demands more than cursory inspection, more than detailed study of limited portions. One major phase of the record never before adequately treated is the topography, composition, and structure of the scabland river deposits, the leading theme of the present paper. A. C. Waters, well acquainted with the scabland, wrote the authors that "the best thing you can do to convince your reader is to beg, cajole, even browbeat him into *really looking* at the region's topographic maps". J. H. Mackin, also well conversant with the field, said that "to understand the scabland, one must throw away textbook treatments of river work". A doubting but open-minded

FIGURE 1.—INDEX MAP FOR MOST OF THE QUADRANGLES REFERRED TO IN THIS PAPER
United States Geological Survey.

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FIELD TO IX THIS PAPER

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reader is hereby warned. Maps are repeatedly listed for his critical examination.

Acknowledgments

The field expenses of Bretz and Smith have been largely defrayed by a grant from the Penrose Bequest of The Geological Society of America. Additional funds were provided by the University of Chicago and facilities by the University of Kansas. Thirty-four field days in 1952 were devoted by these two authors to this study. Neff, a resident geologist of the Bureau of Reclamation for 5 years, already possessed much critical information and many original ideas, and both the Bureau of Reclamation and The Geological Society of America cordially acquiesced in making him a coauthor after the project grant had been approved. The District Manager of the Bureau of Reclamation, Mr. H. A. Parker, and District Geologist, Mr. W. E. Walcott, generously provided many facilities and granted the use of any geological data the Bureau possessed. I. S. Allison, R. F. Flint, Leland Horberg, Laurence Nobles, A. C. Trowbridge, A. C. Waters, and A. O. Woodford have critically read an early draft of this paper. For all assistance and co-operation, the writers are very grateful. Smith accepted the role in the field of skeptic for all identifications and interpretations. Bretz admits that he served well. However, for the statements in this paper, unless qualified, there is unanimity of opinion among the three authors.

Previous Investigations

(Bretz)

General Discussion

Leighton (1919, p. 34) first recognized the scablands as glacial-river courses. Pardee (1922, p. 686–687) thought the scablands a product of glacial ice, identifying the bouldery, unsorted deposits as till and glacial drift and rejecting floating ice and running water as agents. Bretz (1923–1932) interpreted both the erosional features and the deposits as the result of a brief but enormous discharge of glacial water, termed the Spokane flood. The streamways were interpreted as channels, not valleys. The mounded gravel deposits were called river bars, although far larger than any other known river-channel deposits. Bretz stressed contemporaneity of discharge through all the channels. Jenkins (1925) approved of the concept that the narrow Wallula Gateway, where the Columbia crosses the Horse Heaven Hills anticline below the plateau scabland, had served as a bottleneck for an excessive quantity of glacial water, the Spokane flood, that caused flooding back up Snake River to Lewiston, Idaho, and even farther.

During the nine years when Bretz's papers were appearing, many voices were raised in expostulation, some recorded in Proceedings of the Geological Society of the Washington Academy of Sciences (V. 17, no. 8, 1927, p. 200–211) and in the Journal of Geology (V. 35, no. 5, 1927, p. 461–468). The general tenor was that this heresy must be gently but firmly stamped out.

In the well-organized "discussion" following a lecture by Bretz before the Geological Society of Washington in 1927, W. C. Alden suggested (not printed in the Proceedings above noted) that the rock basins might be collapsed lava caves, and said "it seems to me impossible that ... the Cordilleran ice ... could, under any probable conditions, have yielded so much water in so short a time". He asked for "repeated floodings of much smaller volume" and suggested that contemporaneous development of all parts was an erroneous interpretation. James Gilluly said "that the actual floods involved at any given time were of the order of magnitude of the present Columbia's or at most a few times as large seems by no means excluded by any evidence as yet presented."[3] G. R. Mansfield said "it does not seem to me to be necessary to assume that all the scabland channels were occupied by water at the same time. ... The scablands seem to me better explained as the effects of persistent ponding and overflow of marginal glacial water which changed their position or their places of outlet from time to time through a somewhat protracted period." To escape the idea of contemporaneity, O. E. Meinzer suggested that "tilting and folding have occurred ... since the cutting of the

[3] The first five of Bretz's papers were then in print.

FIGURE 2.—PHYSIOGRAPHIC DIAGRAM OF CHANNELED SCABLANDS AND ENVIRONS
FROM REHR (1941)

FIGURE 2.—PHYSIOGRAPHIC DIAGRAM OF CHANNELED SCABLANDS AND ENVIRONS
From Rains (1941)

Pleistocene channels" (bringing channel heads to the same level) and said that "before a theory that requires a seemingly impossible quantity of water is accepted, every effort should be made to account for the existing features without employing so violent an assumption." G. O. Smith said (not printed in the discussion) that the loessial scarps margining scabland tracts might be the product of rainwash and erosion by wind rising up over lower basalt cliffs. Not printed in the discussion also was a suggestion from H. G. Ferguson that river ice jams may have caused some of the high-level divide crossings in the anastomosis.

E. T. McKnight, who shared in the discussion, later that year (1927) published elaborated objections to the flood theory, he and his sponsors preferring to believe that certain glacial stream courses entering Columbia River in western Franklin County (the Koontz Coulee group) (Fig. 17; Pl. 1) are hanging because that river has widened its valley in postglacial time, not because the glacial Columbia's surface was at or near the level of the coulee mouths when they were made. Like Meinzer's criticisms, McKnight's had the merit of being based on personal experience; he, as an undergraduate, having "held the rod" during the topographic mapping of three 15-minute quadrangles on the plateau.

Bretz responded to these suggestions and criticisms in the printed "discussion" already noted, also in a reply to McKnight (1927a) and in a paper (1928c) devoted to all alternative hypotheses ever suggested at that time. Although several contributed ideas were acceptable modifications of the original Spokane Flood interpretation, a Pleistocene catastrophic flooding was insisted on. Until 1930, however, no plausible source for the enormous quantity of water demanded in so short a time had been found. Bretz later (1930a, p. 92) ascribed the scabland flooding to an abrupt failure of the ice dam which ponded Glacial Lake Missoula (Pardee, 1910, p. 376–386).

Harding (1929), after spending a day with Bretz during the field season of 1928 and learning that Lake Missoula was to be proposed as the source of the flood water, rushed that statement into print, without consultation or acknowledgment, a few months before Bretz's announcement. Allison (1933) proposed that the flooding was caused by a blockade of floating ice in the Columbia gorge through the Cascade Mountains, and that this blockade gradually grew upstream until the normal meltwater discharge from the Cordilleran ice sheet was "diverted by the ice of accessory blockades into a succession of routes across secondary drainage divides at increasing altitudes, producing scablands and perched gravel deposits along the diversion routes. . . ." Allison favored a landslide as the initiating cause of the Columbia blockade, "with freezing of the river (or the water-ice mixture) and the confinement of the ice in the narrow and somewhat crooked gorge as contributing causes." "The formation within the Columbia River gorge of an ice jam, capable of withstanding the pressure of at least 900, and perhaps 1100, feet of water is a herculean requirement but the field evidence seems inescapably to demand it." Field study for his theory was limited to areas south and west of the main scabland.

E. T. Hodge (1934) published a brief paper on the origin of the Washington scablands, listing a long and complicated series of late Tertiary and Pleistocene events in the region, involving ice jams during three glaciations, but did not support his proposed history with field evidence.

Flint (1938), studying especially the Cheney-Palouse tract, denied that glacial-stream water attained any great volume at any time or place, asserting that "this discharge down the Cheney Palouse tract was less than that of the Snake River today." His thesis was that during normal discharge of Cordilleran meltwater[4]

[4] Flint published (1937) a revision of the drift border as shown in Plate 1 of this paper; he placed it farther south so that it overlapped scabland at the head of the Cheney-Palouse tract. This revision was based on two criteria; (1) smoother slopes and lower relief of the northernmost Palouse hills, and (2) glacially derived erratic boulders and patches of till in the added territory. However, typical steeply sloped, fine-textured Palouse topography in places far from the glaciated area grades into tracts of lower relief and gentler slopes. Moreover U. S. Production and Marketing Administration's mosaics 1, 5, and 6 for Lincoln County, Washington, show no contrast in topography or land use between the two sides of Flint's minutely lobate glacial margin across this tract. Instead, a marked belt of elongated, subparallel loessial hills south of this boundary extends with equal development, spacing,

rising ponded water in Pasco basin (Lake Lewis) at the confluence of the Yakima, Snake, and Columbia rivers (Fig. 17; Pl. 1) caused a gradual aggradation with silt, sand, and gravel over the Cheney-Palouse tract and brought about the divide crossings. Implicit in his view, although not specified, were comparable deposition and interfluve crossing throughout the entire scabland. Lowering of Lake Lewis then allowed the continuing normal discharge to remove the fill in large part, to scarp the bordering loessial hills, and to make the scabland. Various specific aspects of orogeny, epeirogeny, volcanism, and gradation were explored as causes for the ponding, and "valid possibilities" were seen in a dam made by landslides or by a Mt. Hood valley glacier.

Allison (1941) found Flint's fill hypothesis out of harmony with the constructional forms and stratification of the mounded gravel deposits, incorrect in correlating Lake Lewis with deposition of most of the gravel deposits in Snake River canyon, and demanding of the streams eroding the fill "decidedly abnormal, if not impossible, behavior" along the Cheney-Palouse tract. He again urged that only the ice-jam theory could explain the channeled scabland.

Pardee (1942) found high-eddy deposits, bar-like forms, giant current ripples, strongly marked channels, and severely scoured salients in some of the valleys occupied by Glacial Lake Missoula in western Montana. He postulated failure of the lake's ice dam, which caused a sudden, great lowering. Strong currents are indicated by unique giant current-ripple marks that attain amplitudes of 50 feet and have wave lengths of as much as 500 feet. Pardee said nothing in this paper about disposition of the 500 cubic miles of water the lake contained. However, it escaped westward around the north end of the Bitterroot Range into Idaho and thence could have gone only down the Spokane Valley toward the heads of the channeled scabland.

Hobbs (1943; 1947) presented another theory, stating that (1) a lobe of the Cordilleran ice sheet had almost covered the region, (2) scabland was a product of glacial scouring, (3) the rock basins were glacially plucked, (4) the loess, generally considered prescabland in age, was actually deposited by anticyclonic winds off the ice during retreat of his lobe, (5) mutilated moraines recorded at least five stages of retreat, and (6) the channel complex was the product of glacial-border drainage, each retreatal stage developing new channelways across freshly exposed scabland. Hobbs' interpretation of 1943 (unaltered in 1947) was based on inadequate field study and is considered to be invalid. The Palouse loess occurs in hundreds of scarp-bounded, island-like tracts separating or interrupting the scabland channels, and these scarps sharply truncate the older mature topography of such islands, leaving many of their valleys hanging. Reddened zones and caliche layers with root casts and molds are buried deep within the loess. Hobbs was the only investigator who interpreted any land forms of the scablands as moraine relics, and he made only the bland statement that they exist in specified places, citing no evidence to show that they are glacially built deposits and making no comment on how earlier students could have missed them. He actually described a "moraine" in the bottom of one of the channels (Ephrata) for Grand Coulee water across the Quincy gravel fill. Regarding the sequence of border drainages, he required his glacial rivers successively to abandon open *lower* routes for *higher* ones as his lobe retreated, and he used one route (Providence Coulee) that has no scabland, glacial river gravel, or erratics and is far too high for his purpose. Finally he left some of the best-developed scabland (Drumheller, Othello, Moses Coulee, Lower Crab Creek, Palouse-Snake divide, Columbia and

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and orientation northward for 12 miles into his glaciated area. Inspection of the northwestern portion of the Reardan quadrangle map (U. S. Geol. Survey, 1942) will bear out this criticism. Also many glaciated erratic boulders have been found along all scabland river routes, along the Columbia beyond the scabland, and, indeed, back-floated up the Willamette valley of western Oregon. Furthermore, large berg "nests" of these boulders with an accompanying matrix of till are especially numerous in Pasco basin 75 miles or more down the Columbia from the southernmost known glacial drift *in situ*. Because of these facts, Flint's revision does not carry conviction, and the 1928 mapping of the drift border by Bretz is followed in Plate 1. In the absence of any end moraine and of well-marked ground moraine on the plateau east of Grand Coulee, precision in mapping the drift border for this area probably is impossible.

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R. L. Lupher (1944), dealing with the Touchet beds—*i.e.*, fine sediments in contiguous parts of Snake, Walla Walla, Yakima, and Columbia valleys, ascribed by Flint and Allison to deposition in Lake Lewis—briefly discussed the origin of Washington scabland. He found objections to the interpretations of Bretz and Flint and accepted Allison's ice-jam theory.

A reader familiar with Bretz's earlier publications will find several revisions of interpretation in this paper, the most striking one being abandonment of the term "the Spokane Flood" and a demand by all three authors for several scabland floods. Obviously the present paper cannot be simply a series of assertions and denials. Field evidence must be presented in sufficient detail to allow the reader to judge of its appropriateness and adequacy for accompanying interpretations.

Summary of Original Interpretations

(1) The Palouse loess of the basalt plateau is older than the scabland. (Accepted by all critics and writers except Hobbs, who thought it essentially contemporaneous.)

(2) The scabland channel complex has been made by glacial water entering and modifying preglacial drainage lines on the loess-covered plateau. (Only Hobbs has a variant interpretation.)

(3) The scabland rock basins have been made by glaciofluvial erosion, chiefly by plucking in the columnar basalt. (Hobbs has differed, asserting glacial plucking; Alden has suggested that they might be collapsed lava caverns.)

(4) The downstream-facing cliffs interrupting channel floors are abandoned cataracts. (Denied by no critic.)

(5) The loessial scarps bordering scabland channels are marginal steepenings made by glacial rivers. (Only G. O. Smith has expressed doubt.)

(6) The scabland gravel deposits are contemporaneous with the channeling. (Flint demurred, believing the channels were made during removal of former complete fluvioglacial valley fills. The critical items here concern the ability of Flint's low-gradient streams of moderate size to detach great boulders from bedrock, to transport them for miles, then to remove the fill and to make the rugged, channel-bottom scabland topography associated with "residual" hills of gravel. Without a contemporaneous "Lake Lewis", whose rise caused the aggradation and whose immediate subsidence caused the erosion, Flint's theory has no logical foundation. Demonstration that the gravel "remnants" are stream cut terraces is fundamental for his theory, and scabland forms buried under gravel are unallowable.)

Allison postulated a prescabland gravel-terrace system in Lower Snake River canyon, erosional remnants of which were subfluvially shaped by the glacial water from the scablands. (If correct, there must be comparable but unmodified terraces in the canyon upstream from entrance of the scabland rivers. In the terraces modified by the glacial Snake, there should be abundant well-worn Snake River-type pebbles. In unmodified cores of these deposits cementation and/or weathering would be accessory evidence.)

(7) The structure, composition, and topographic expression of these deposits record subfluvial origin as river bars of gigantic size. The undrained fosse depressions among and behind these gravel hills, the midchannel location of many, and the numerous huge current-ripple marks conforming to their shapes are undeniable evidence for bar origin. (Denied by Flint, Gilluly, Hodge, and the sponsors of McKnight. Flint claimed that they are terraced remnants of once-continuous fills, and Gilluly called their long foresets evidence for deltaic origin; Allison accepted them as subfluvial forms, although his concept cannot explain the mid-valley location of many.)

(8) The similar altitude of the upper limit of glacial water in all scabland channel heads and the anastomosing pattern indicate approximately contemporaneous functioning at some time over the entire area. (Strongly questioned by Alden, Gilluly, Hodge, Mansfield and Meinzer, accepted by Flint and Allison. Evidence for contemporaneity at some stage in scabland history must be expected at convergences of channels with separate heads.)

(9) The many minor divide crossings were due to a sufficiently great volume of glacial water to fill pre-existing valleys up to overflow sites. Earlier valley-train deposits may have been a factor in overflow. (Denied by Alden, Flint, Gilluly, Hodge, Mansfield, and Meinzer. Flint specifically shallowed the preglacial valleys with fluvioglacial deposits caused by deep backwater (Lake Lewis) beyond the plateau until spillover into adjacent valleys occurred; this before basalt scabland was made. Allison used local ice jams to make local impoundings and spillovers. There appears to be no third reasonable alternative. Evidence for the flood concept must include demonstration that a general fill never existed and that ice jams left no definite local records of their actual existence.)

(10) Ice-rafted stones and water-transported finer sediments back in valleys, tributary to scabland channels, that did not carry glacial-water discharge were the consequence of back-flooding because of the great volume and depth in the main channels. (Denied or ignored by all but Allison and Flint.)

(11) Bars, high-level channels, tributary valley-mouth deposits, and a "Portland delta" record the flood waters descending the Columbia beyond the plateau, crossing the Cascade Range and entering a Columbia valley estuary. (Allison, 1933, and Hodge, 1934, denied the Portland deposit as a delta; Piper, 1932, denied the flood origin of tributary mouth deposits near The Dalles, Allison and Flint believed a dam (landslide? Mt. Hood glacier? ice jam?) blocked the Columbia Gorge across the Cascades. High-level, berg-rafted, glaciated boulders have been floated to position in lower Columbia and Willamette valleys but perhaps are not all contemporaneous with scabland making. The dam must remain hypothetical until definitive evidence for its location is found on the walls of the gorge.)

(12) Only a great flood could have caused simultaneous discharge of the three great cataracts and one enormous high-gradient spillway out of Quincy basin. (Simultaneity denied or ignored by all opponents of the flood hypothesis, and the four accordant initial discharge levels explained by Meinzer as a fortuitous leveling up by subsequent earth movements. The only other alternatives are that ice jams blocked three of the four dischargeways at a time, in a rotating sequence, or that the basin once had an alluvial fill on which the glacial stream shifted from one dischargeway to another.)

(13) Upper Grand Coulee's dry canyon was made by cataract recession completely through a preglacial divide. (Denied by no critic.)

(14) Water for scabland making came from the bursting of the glacial dam impounding Lake Missoula in western Montana. (Rejected by all except Pardee who discovered evidence for torrential emptying of a large part of the lake. There is little field evidence at or near the dam site to prove a catastrophic bursting, but the lake water certainly discharged westward. Acceptance of evidence for scabland floods entails acceptance of the strong probability of a direct cause-and-effect relationship. (Since this was written, Alden has indicated a "perhaps" acceptance. See footnote 43.)

(15) The scablands east of Grand Coulee were ascribed to a pre-Wisconsin (Spokane) glaciation and Grand Coulee's completion to flood discharge during the Wisconsin glaciation. (Hodge announced three different glaciations during scabland development, while Flint claimed that the Spokane drift is Wisconsin in age.)

Advance Summary of New Evidence and Interpretations

Changes and elaborations in Bretz's earlier interpretations include:

(1) tentative identification of some gravels, both high-level and buried, as remnants of prescabland normal outwash;

(2) recognition of a heavy caliche on the loess and older deposits in part of the region as the marker for immediately prescabland topography;

(3) discovery of giant current-ripple marks on bar deposits in nine different channel-ways, distributed in more than a dozen localities ranging from the northern to the southern, and from the eastern to the western sides of the complex;

(4) establishment of the river-bar origin of the discontinuous mounded gravel deposits in scabland channels from aerial photographs

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taken by the U. S. Agricultural Adjustment Administration, the U. S. Production and Marketing Administration and H. T. U. Smith, from the detailed topographic maps of the U. S. Bureau of Reclamation, and from many extensive new excavations;

(5) recognition of the occurrence of several successive floods, the earliest recorded only in the Columbia valley, the second involving perhaps the entire area, later ones restricted to channels already derpened, and the last one again limited to the Columbia valley;

(6) recognition that Touchet silts were not contemporaneous with scabland making.

Grand Coulee and Quincy Basin

Maps: Grand Coulee (4 sheets), Moses Lake, Othello, Quincy and Winchester quads., U.S.G.S.; K4-5720, sheets 1 and 2, U.S.B.R.

(Bretz, Smith, and Neff)

Grand Coulee

A tandem canyon 50 miles long and more than 900 feet in maximum depth, Grand Coulee is the greatest scabland channel. It is a glacial Columbia River's detour when the river's preglacial course was dammed by a lobe of ice pushing southward from the capacious Okanogan Valley (Pl. 1). Striae and moraine relics near the head of Grand Coulee show that it had present depth before the last invasion by the Okanogan lobe. Grand Coulee has been generally accepted as largely a recessional cataract gorge (Bretz, 1932), its northern half eroded across a previously intact divide, its southern half excavated along the strike of the steep limb of an asymmetrical flexure, the Coulee monocline.

The northern, or Upper, Coulee was initiated where the glacial stream cascaded some 800 feet down the steep southeastern slope of the monocline.[5] When this cascade migrated north of the fractured and steeply tilted zone into high, flat-lying basalt, it became a typical recessional cataract (Steamboat Falls) nearly 900 feet high. Eventually its retreat extended the lengthening gorge across the divide into the preglacial Columbia River valley, and thus the cataract destroyed itself. Scabland records of the glacial river, made before much recession had occurred, exist on the rim of the gorge nearly 1000 feet above the floor. Subsidiary cataracts along both walls, one of them as wide as Niagara and three times as high, tell something of the breadth of the Grand Coulee glacial river before cataract recession narrowed it to a minimum of a mile. (*See* Bretz, 1932.)

These brief items[6] will indicate the magnitude of this scabland river across the Coulee monocline. Along the lower or southern half of Grand Coulee the stream spread widely, enormously enlarged three small, preglacial drainageways, and made a huge new gorge by quarrying out the fractured basalt along about 10 miles of the monocline's steep limb. Minor structures involved in this anastomosing course were four nearly east-west anticlines (High Hill, Trail Lake, Pinto Ridge, and Soap Lake) with separating synclines. Their higher portions stood above the wide-spreading river, but lower parts were crossed by floods and greatly eroded to make five additional canyoned courses (Jasper, Lenore, Unnamed, Dry, and Long Lake) over a width, including the monoclinal course, of about 15 miles. The discharge of all these entered the extensive Quincy structural and topographic basin, largely covered it with basaltic gravel, and made four immense simultaneously operating scabland dischargeways (Crater, Potholes, Frenchman Springs, and Drumheller) leading to the Columbia valley west and southwest of Quincy basin.

Trail Lake Anticline and Bacon Syncline

One of the most significant tracts of this Lower Grand Coulee area is the denuded portion of Trail Lake anticline with Bacon syncline to the south (Pl. 2). Over a width of 5 miles, the glacial floods swept up the gentle northwestern anticlinal slope and descended the steep southeastern slope to enter the pre-

[5] Bureau of Reclamation exploratory drillings found a gravel-filled plunge pool at this place whose bottom is 300 feet lower than the scabland floor immediately downstream, just south of the flexure.

[6] The conclusions regarding Grand Coulee are based on details set forth in another publication (Bretz, 1931). Not having been specifically challenged by critics, the field evidence will not be repeated here.

glacially undrained Bacon syncline.[7] Apparently, this structural basin was still filled with superbasalt sedimentary rock, capped with loess. On a basin floor at about 1650 feet A.T., the first glacial discharge across the anticlinal crest deposited 100 feet of basalt gravel (with some erratics) just south of the crest, burying a loess with a calichified upper zone. The altitude of this high gravel flat proves that there was, as yet, no deep Lower Grand Coulee and no Dry or Long Lake (Spring) Coulee outlet notches in the syncline's rim.

This scabland gravel deposit in Bacon syncline was once called a bar (Bretz, 1932, p. 28). The lower southern and western parts are mounded bars (Fig. 3), but the high flat-topped portion is only a remnant of a larger deposit (Pls. 2, 3), perhaps an outwash plain; its present barlike outline was the result of erosion by later glacial discharge across the Trail Lake anticline when Dry and Long Lake coulees were being notched into the rim of the Bacon syncline. Neff reports small remnants of gravel on the north slope of Pinto Ridge (the southern side of the syncline), at about the same altitude.

Deepening of these notches is considered to have caused eventual removal of most of this gravel and the underlying sedimentary material in the structural basin from the steep southern basaltic limb of the anticline. Three or four cascades began to concentrate the sheet of glacial water, and these, receding north of the axis, became cataracts. One, at the head of the Unnamed Coulee, had retreated about 4000 feet when the last discharge to cross the anticlinal crest subsided. It is a splendid example of an abandoned waterfall with three alcove heads (Pl. 3) whose cliffs are 100–150 feet high, a cataract supplied only by a sheet of water flowing diagonally updip across the unchanneled, gentle northern slope of Trail Lake anticline.[8]

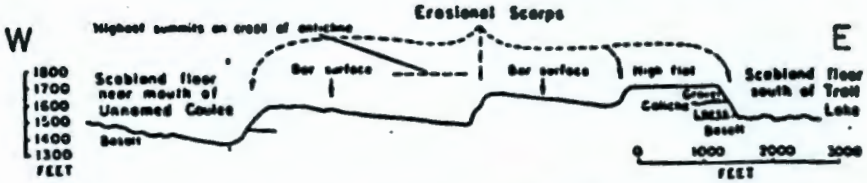

FIGURE 3.—PROFILE OF GRAVEL DEPOSITS ON SOUTH SLOPE OF TRAIL LAKE ANTICLINE

Bacon synclinal basin apparently carries a record of four episodes of glacial-water discharge in distributary fashion out of Upper Grand Coulee across Trail Lake anticline: the first recorded by the high gravel flat, the second and third by the two broad bars just to the southwest which lie 50–200 feet lower, while the fourth completed the Unnamed Coulee cataract's recessional gorge immediately west of the scarp of the lowest bar and 150–200 feet still lower. All three scarps in this gravel-covered tract are erosional, but only the highest can be considered a terrace scarp.

Bacon syncline's bottom scabland at the southwestern outlet hangs between 100 and 150 feet above the floor of Lenore Canyon-Dry Coulee with no suggestion of cataract development at the junction. This seems to record deepening of the canyon-coulee after the last flooding of Bacon syncline. If so, the great Dry Falls cataract group (400 feet high) at the head of Lower Grand Coulee (Bretz, 1932) is younger than the Unnamed Coulee cataract, and a fifth episode of discharge down Grand Coulee is indicated.

It may be that Lenore Canyon never carried

[7] Discovery of two feldspar-bearing flows in the Columbia River basalt of eastern Washington (W. H. Irwin, unpublished manuscript) has made possible a detailed structural mapping by the Bureau of Reclamation for the Columbia Basin Project. The Bureau's map shows that the upper feldspar flow in Bacon syncline is 1375 feet A.T. in the central part and 1700–1775 in the eastern and western low saddles. Their 2-foot interval contour map shows breaching only by glacial-river channels cut into these saddles.

[8] Another, at the head of Long Lake Coulee, is closely paralleled by the Main Canal. Despite a tunnel about 9000 feet long through the anticlinal crest, the canal water, after emerging, drops 165 feet in half a mile to pass the site of the ancient cataract.

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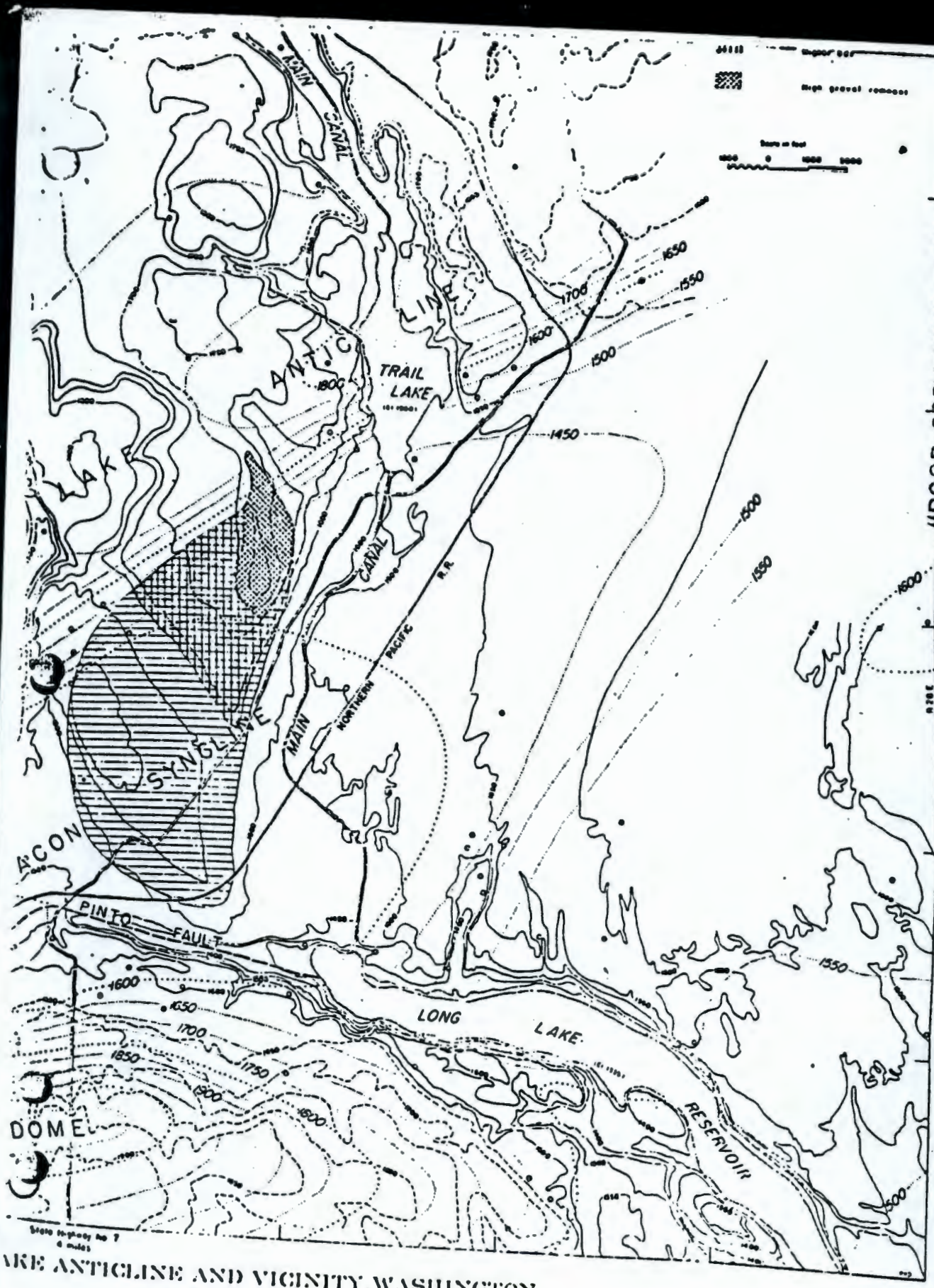
MAP OF TRAIL LAKE ANTICLINE AND VIC



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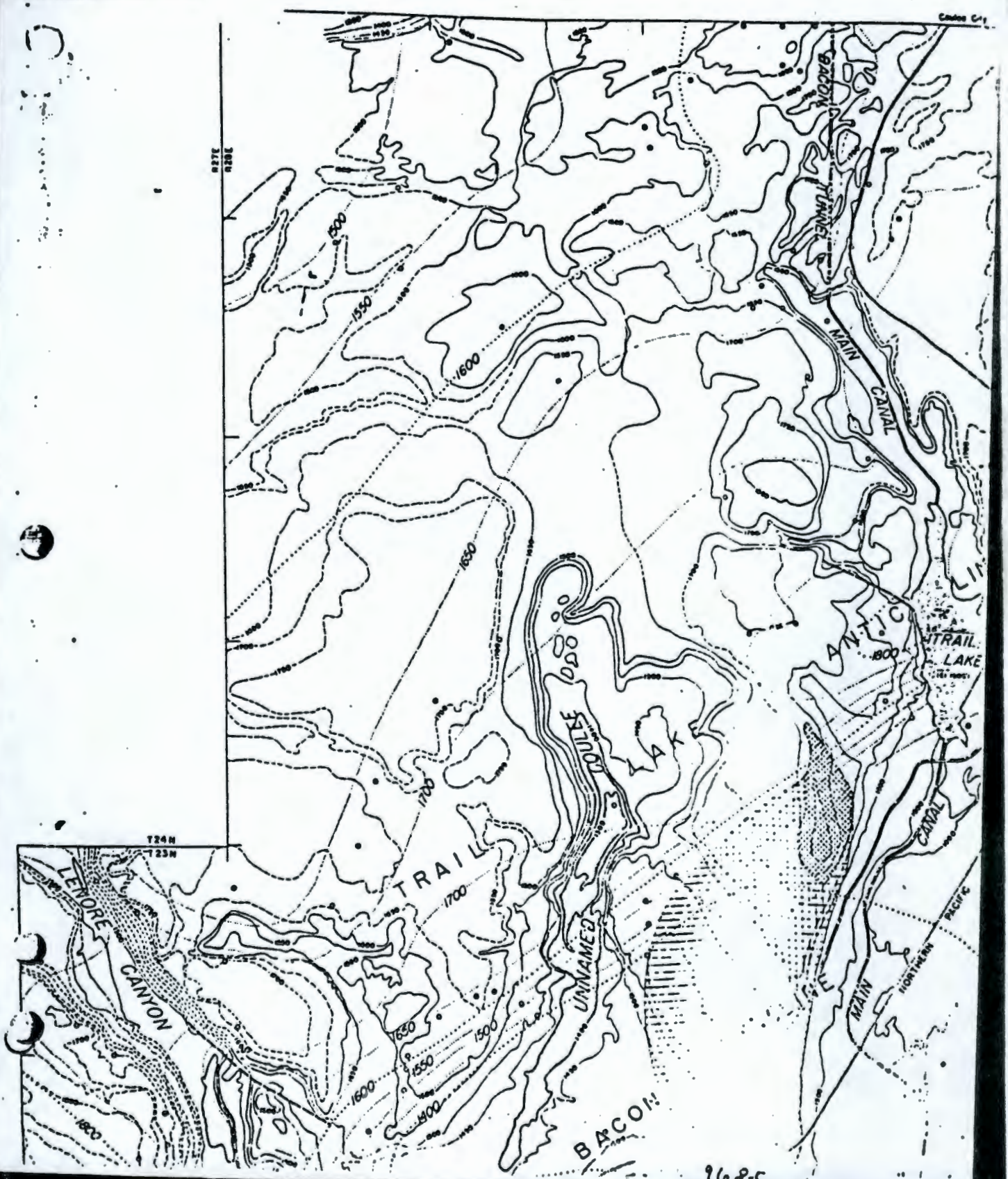
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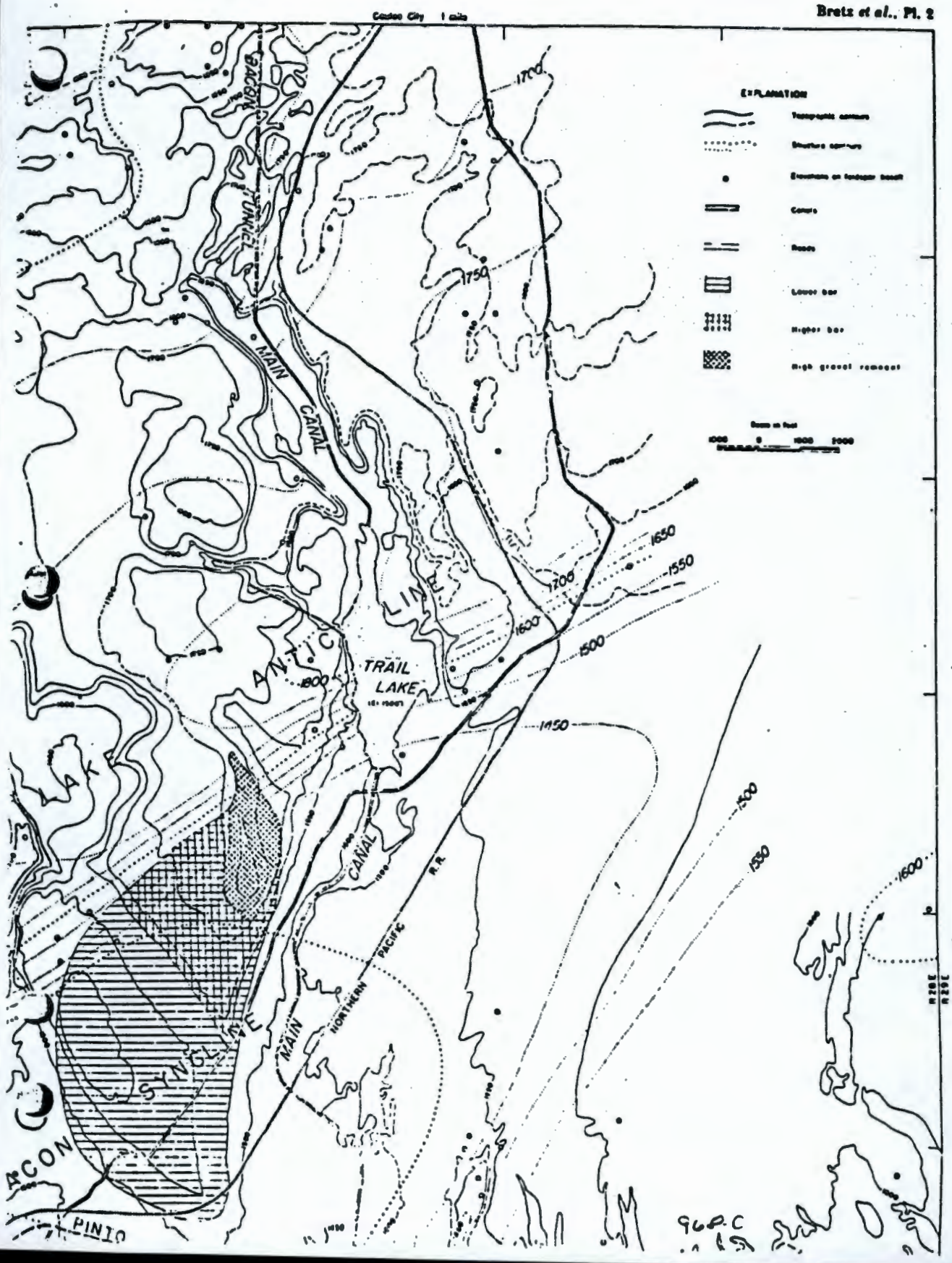
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a through stream from Lower Grand Coulee to Dry Coulee; that floods across the ravaged country north of the canyon were divided by the unsubmerged portion of High Hill, part going west to Lower Grand Coulee, part east to Dry Coulee. Supporting this idea is the narrowness and lack of bars in mid-length of the canyon, and the absence of a continuous gradient.

Soap Lake

The Soap Lake anticline, southernmost subsidiary spur trending eastward from the Coulee monocline, had a small, antecedent drainageway across it which glacial waters obliterated in making the lake basin. However, several miles of this preglacial streamway can be identified farther north, east of the great monoclinal axis (Bretz, 1932). The Bureau of Reclamation found rock bottom 214 feet below the lake surface, with 109 feet of glacial-river gravel above it and 84 feet of postglacial mud above that.

Gravel deposits of the Quincy basin constitute the notched southern rim of the basin 75–250 feet above the present lake surface (Figs. 4, 5). Thus rock bottom in the mouth of Grand Coulee is 290 feet below the lowest gravel surface 7 miles to the south. Were the rim restored, and the fill under the lake removed, there would be a hole in the glacial river channel 340–465 feet deep.[8]

The mouth of Lower Grand Coulee, therefore, has discharged a prodigious stream out on the lower land of Quincy basin (Fig. 4). Because tributary Long Lake and Dry coulees probably once functioned at the same time, and their combined widths near the mouths are about 1½ miles, any estimate of the magnitude of Lower Grand Coulee river at a late functioning must be correspondingly increased.

Grand Coulee water, on emerging from its rock-bound course, spread widely in Quincy basin, and the extensive gravel deposit there records a great decrease in transporting ability. The back slope, northward down to Soap Lake, is a smooth, subfluvial, equilibrium profile lacking in ravines, terraces, scarps, channels, bars, or the hummocky topography left by stranded ice blocks (Waters, 1933). It is a slope adjusted to the volume, velocity, and load of that great river's last flood. Was this slope erosionally developed in previously deposited gravel, or is it a depositional profile of that glacial flood?

Quincy Basin

At least 500 square miles of this large, structural depression are covered with gravel and sand brought in chiefly by Grand Coulee and Upper Crab Creek glacial rivers (Pl. 1). The maximum known thickness is 128 feet. The gravel, like that elsewhere in this Washington complex of glacial streams, is but little weathered and in but few places is incipiently cemented. It is characteristically bluish black, about as "bright" as basalt aggregate from a crusher. This is true for the oldest gravel as well as for the youngest. Except in one place, the amount of weathering since deposition cannot be used to indicate relative age. Freshness of the gravel indicates derivation from below the zone of preglacial weathering, estimated by Neff to average 25 feet in the irrigation-project area. Stained and partially indurated clays and sands containing shells, bones, and wood crop out in places along the basin's margins (Schwennesen and Meinzer, 1918). These are older than the scabland gravel. Above the level reached by glacial streams, near Winchester and Quincy and south to Frenchman Hills, these older sediments carry a caliche as much as 15 feet thick. In many places throughout the scabland a similar caliche overlies loess, Ellensburg, Ringold, Columbia River basalt, and cemented old gravels. Scabland sand and gravel deposits commonly contain fragments of caliche but nowhere possess a caliche cap *in situ*. A heavy caliche is believed to dis-

[8] Silts containing fresh-water shells along Lake Lenore and Soap Lake record a postglacial humid climate when the Soap Lake depression held a much larger lake with overflow down Rocky Ford Channel. Such a lake must have extended northward almost the full length of the Lower Coulee. The closed depression containing Soap Lake thus includes all the other lakes for 25 miles to the north. Present infiltration of irrigation water is raising the level of Soap Lake and, unless checked by increased evaporation from expanded surface and by interception wells, may submerge the city of Soap Lake and reestablish a continuous lake in Lower Grand Coulee.

tinguish the prescabland surface over much of the region.

Although the surface of the Quincy basin's scabland gravel deposit has an east-west cross-sectional relief of nearly 200 feet, owing mostly to later channeling, all parts south of the notched rim of Soap Lake basin have a fairly uniform, gradual, southeasterly slope down toward Drumheller Channels, the largest and deepest of the four glacial spillways out of Quincy basin. The basin fill has no slope toward the three western cataracts.

Three definite channels traverse this southeasterly slope of the gravel plain, the lowest of which, Rocky Ford, contains Moses Lake in its southern part. Its deepest part is sinuous like a river channel, but its broad higher floor is a complex of anastomosing smaller channels.

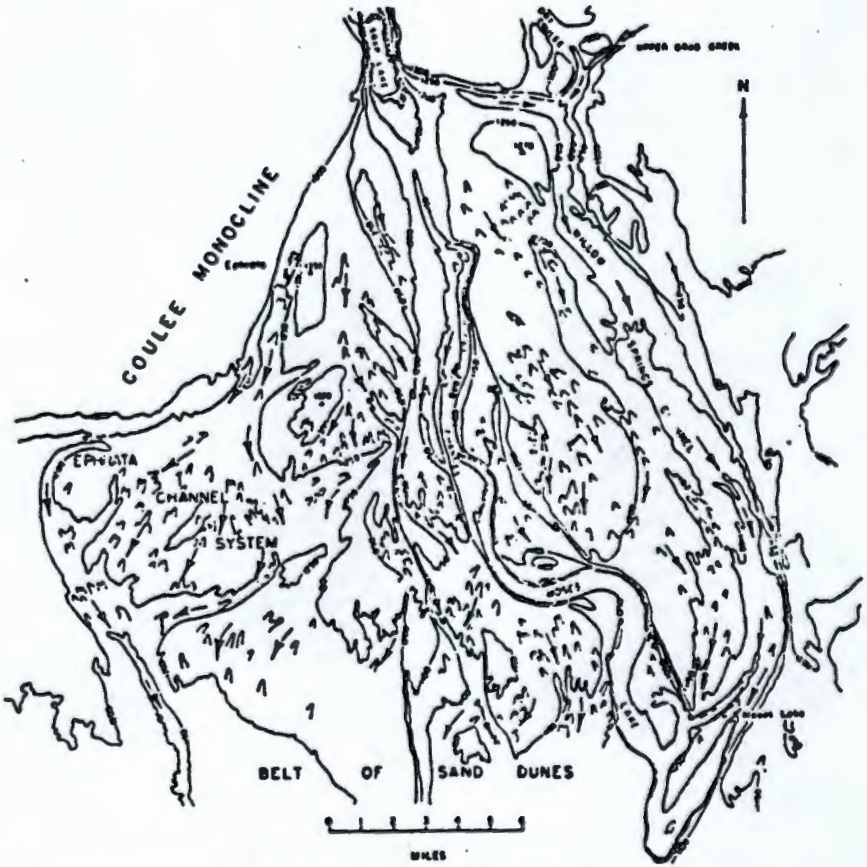

FIGURE 4.—MAIN PORTION OF QUINCY BASIN

Showing the three channels leading from Soap Lake across the gravel fill and the A-shaped heads of minor channels. From U. S. Bureau of Reclamation topographic map R4-5720, sheet 1. Contour interval 50 feet.

A barchan-dune belt has dammed the deeper central part of this channel and made the lake. This ponding has brought out a peculiarity possessed also by Ephrata channel, the highest of the three—the existence of tributary channels (Parker, Lewis, and Pelican horns or bays) which head on the gravel plain south of the rim of Soap Lake basin. If Moses Lake level

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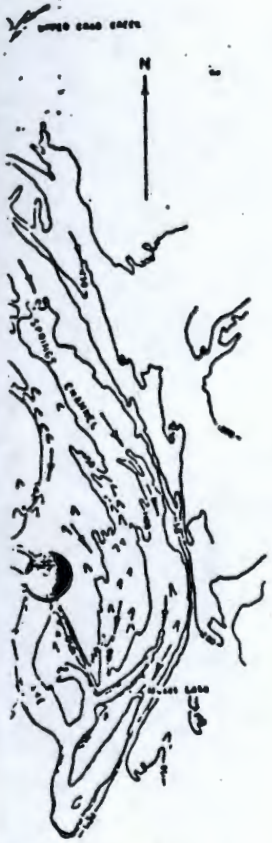

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(1044 feet A.T.) were raised to 1100 or 1150 feet A.T., these horns would lengthen northward, and more horns would appear, as shown in Figure 4. None of them, however, would reach across the Soap Lake rim. At 1150 feet, one would reach up Ephrata channel, and, if flooded to 1200 feet, that channel would also have tributary horns.

If only those hairpin contour loops indicating southward-sloping surfaces are drawn, from the Bureau's topographic map R4-5720 (as As in Fig. 4), the entire gravel fill traversed by the three channels is seen to possess this characteristic. Elongated and subparallel closed basins in them are common. Whether the grooves are separated by constructional forms, or erosion under sheets of water across the entire plain has made them, or both processes have operated, these northward-tapering channels or grooves cannot be explained as post-gravel dissection by local runoff. They must have been made under glacial water flowing southeastward across the basin.

Figure 4 could have been drawn with about half as many similarly oriented As selected to show the very reverse topography, that of prows pointing northwestward. The combination of prows and grooves appears to make a good case for erosional origin under a widespread glacial torrent, thereby requiring a preexisting unaccented gravel plain. But structure cannot be ignored in interpreting the origin of these forms. An unparalleled opportunity to study structure was afforded by the 175 miles of canal excavation completed in 1952 and the many large gravel pits made in development of the Columbia Basin Project.

Boulders, mostly basalt, are embarassingly abundant in some pits, requiring excavators to discard a large portion of the gravel, and are very obvious in spoil heaps along canals. Columnar outlines are common, the greenish patina of a preglacial weathering rind surviving in large part on plane or concave sides, and fresh basalt showing chiefly on bruised and battered projecting edges. Most of them are distributed sporadically in cobble or pebble gravel, its constituents usually not much worn but without weathered surfaces. Many boulders may have been carried by floating ice, but the boulder-laden lee of scabland knobs and buttes in the basin indicate the operation of some agency capable of tearing boulders loose. One large gravel pit (Sec. 17, T. 20 N., R. 29 E.) shows two scabland knobs at the bottom. The large quantity of rejected boulders in the pit came almost entirely from the basal part of the 30-foot section. Everywhere that the bottom of the gravel is known along the two deeper channels, the older sediments are lacking, and the gravel rests directly on unweathered scabland basalt.

The common fore-set bedding of the basaltic gravel, containing erratic material and caliche fragments, is not ordinary current fore setting in horizontal courses of limited thicknesses; it is more like deltaic fore-set structure extending through the entire exposure and deposited at the angle of stability. Only the higher, flatter tracts commonly have nearly horizontal bedding. The long fore-sets are found in excavations on steep slopes where they dip either in conformity with those slopes or at some angle between the slope direction and south. (Examples: the Willow Lake road cut approximately in sec. 6, T. 21 N., R. 28 E., the Larson Air Field pit in sec. 31, T. 20 N., R. 28 E., the Columbia Sand and Gravel Co's pit in sec. 5, T. 19 N., R. 28 E., a pit a mile north of Moses Lake town in sec. 11, T. 19 N., R. 28 E. and the huge pit in the south edge of sections 1 and 2, T. 17 N., R. 28 E.)

The Quincy basin gravel deposits are terraced only along the deeper portions of the Rocky Ford channel, and only the creek and lake indicate a meander pattern in any part of any channel. The notch of Rocky Ford channel in the Soap Lake gravel rim is 110 feet lower than that for Ephrata channel and 50 feet lower than the col at the head of Willow Springs channel. A post-flood glacial Grand Coulee river (a detoured Columbia) and/or discharge of a post-glacial lake in Lower Grand Coulee may well have been responsible for the only normal stream-valley pattern in all of Quincy basin's or, indeed, any other scabland gravel deposits.

The higher bottom portions of Rocky Ford, deepest and widest of the three channels, possess the same aberrant pattern of anastomosing minor channels, A-shaped heads of channel grooves, abundance of elongated closed basins

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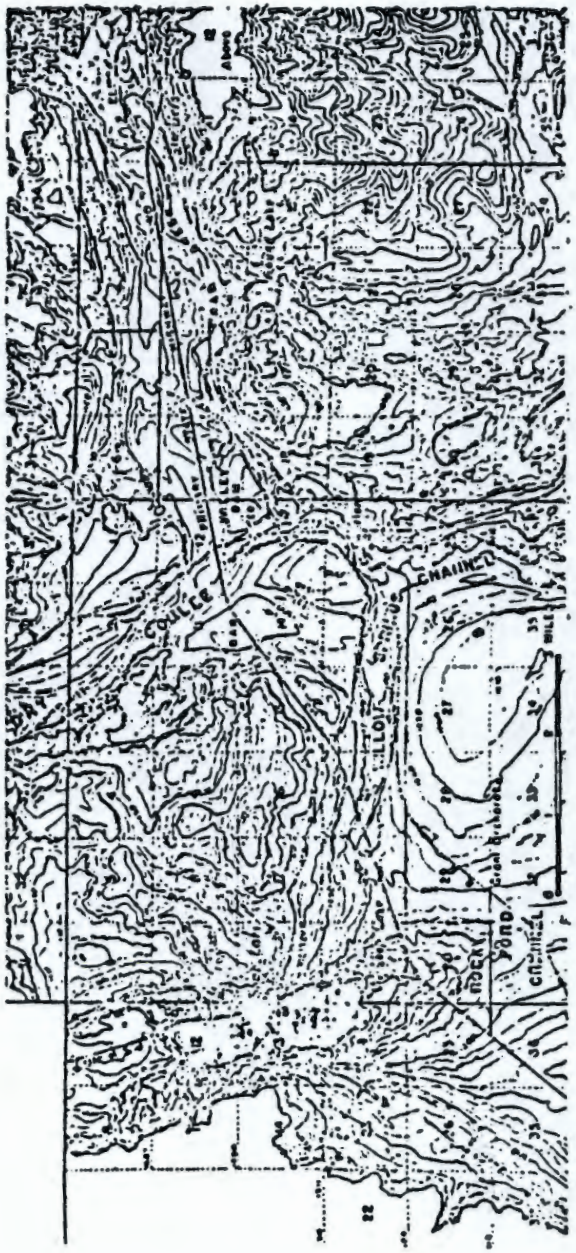

FIGURE 5.—NORTHERN END OF QUINCY BASIN

From U. S. Bureau of Reclamation topographic map R4-5720, sheet 1. Contour interval 10 feet.

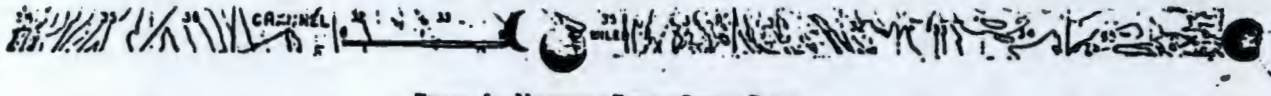

FIGURE 5.—NORTHERN END OF QUINCY BASIN
From U. S. Bureau of Reclamation topographic map R4-5720, sheet 1. Contour interval 10 feet.

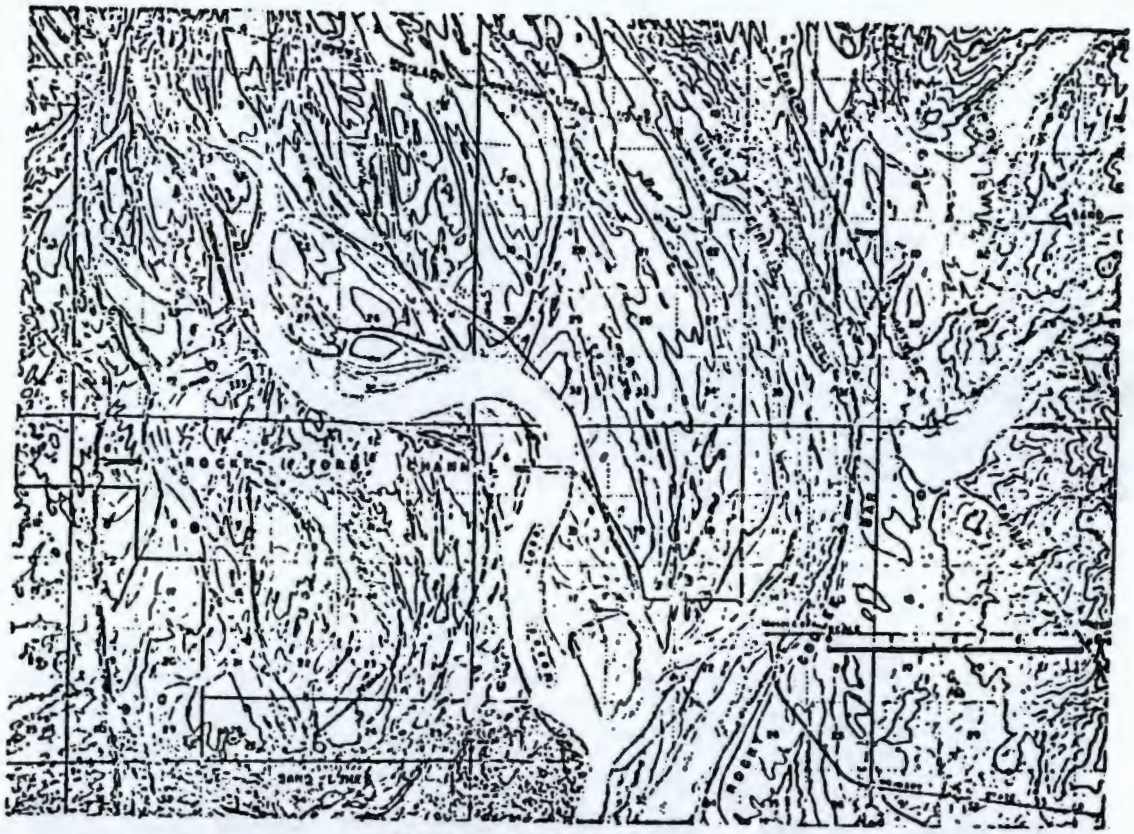

FIGURE 6.—MOSES LAKE AND VICINITY

Closed basins in black with number of hachured contours indicated by circled figures. Map shows: 1—constriction, partial closure, and deflection of Rocky Coulee by bar (with recurved fingers) at entrance to Quincy basin, 2—continuation of the bar southward past Moses Lake town, 3—drowned stream channel containing the lake, 4—dune belt which dams the channel, 5—A-shaped, flood-made anastomosing pattern of channel-like grooves up to 100 feet above the lake, 6—scarp on west side of Rocky Ford-Moses Lake channel rising to the higher gravel plain containing Ephrata channel.

Part of U. S. Bureau of Reclamation topographic map R4-5720, sheet 1. Contour interval 10 feet.

in those grooves, and boulder-strewn areas that Quincy basin has over most of its higher surfaces (Fig. 6).

Even if the three channels across Quincy basin are sequential, as is suggested by their differing altitudes, the channeling must have started with all three, unless we use an implausible, unrecorded rotating sequence of ice dams. They were made under a flood of adequate volume to spread initially over the entire gravel surface, a flood well recorded in the horns of Ephrata channel. But this western channel was too far offside to be deepened as much as the other two, hence was not occupied by later floods that used and deepened Rocky Ford and Willow Springs channels. Because Willow Springs channel enters Rocky Ford at accordant grade, constituting the depressions for the horns of Moses Lake, these two channels must have functioned contemporaneously to the end of the glacial flooding, even though the col of the head of Willow Springs is 50 feet higher than that of Rocky Ford. The need for large volume is again obvious unless we can believe that unrecorded ice jams in proper sequence determined the succession.

Two major points remain to be cleared up: the genetic conditions for the gravel and into which the three channels were trenched, and the reason for this trenching across a tract of earlier glacial-river deposition.

West of Ephrata channel, a 10-mile width of unchanneled plain, underlain by basaltic sand and granule gravel only, lies 25–75 feet higher than the Ephrata channel head. It may be a remnant of preflood outwash once filling almost the entire width of Quincy basin. But east of Ephrata channel, no remnants of such a plain survive from the first episode of trenching. The two upland tracts separating the three channels differ in altitude by 60 feet. Both have the A-shaped groove heads on their southern slopes, undrained depressions on their summits, and long gentle slopes except where later trenching has encroached on them. The western upland has a subsidiary summit 70 feet lower and more strikingly streamlined. The writers can explain these broad hills only as having been subfluvially molded and in no way owing their forms to subaerial erosion. But uncertainty remains as to what extent they were actually built up where they stand.

The reason for the trenching in Quincy basin's glacial river deposits by later rivers of the same character is found in the southeastern outlet to the basin, Drumheller Channels, and is treated in the following section.

PLATE 3.—UNNAMED COULEE AND ASSOCIATED GRAVEL DEPOSITS

FIGURE 1.—Vertical aerial photo showing gravel deposits. Top is north. Shadows fall to the left. Southeastern slope of Trail Lake anticline can be traced diagonally across the photo, from the lower left, by means of the northwest-facing cliffs. The A-shaped small scabland hills in midlength of the coulee are also eroded portions of southeast-dipping basalt flows. The high gravel remnant is scarped on all sides, the eastern and highest scarp having been cut through the gravel and the underlying loess whose caliche cap is shown by the white line along the scarp. Two successively younger gravel deposits, with convex tops, lying southwest of the high gravel remnant, are bars, left by later floods, each becoming scarped as the outlets to Bacon synclinal valley were deepened. The cataract alcoves all head in the same flat-lying flow and presumably date from the last flood. Compare with Plate 2. Photographs AAK. 9A-9 and 11, Agr. Adj. Adm.

FIGURE 2.—Oblique aerial photograph, showing unchanneled scabland leading to the northernmost cataract alcoves. Shadows fall to the right. Looking northeast. Photo by H. T. U. Smith.

PLATE 4.—GIANT CURRENT-RIPPLE MARKS

FIGURE 1.—Two miles east of Odessa. Known to the writers only from the Production and Marketing Administration's aerial photograph AAO-66-247 (herewith reproduced) and from descriptions of the fire north of the road by Lincoln Co. officials. Scaled on the photograph, these giant current ripple marks have wave lengths of about 250 feet. A considerable part of the glacial stream here was a Cheney-Palouse distributary.

FIGURE 2.—Channel floor south of Warden cataracts. When these ripple marks were made, Drumheller carried a glacial river 9 miles wide. Photo by Ag. Adj. Adm. AAH 4A-50.

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FIGURE 1

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UNNAMED COULEE AND ASSOCIATED GRAVEL DEPOSITS

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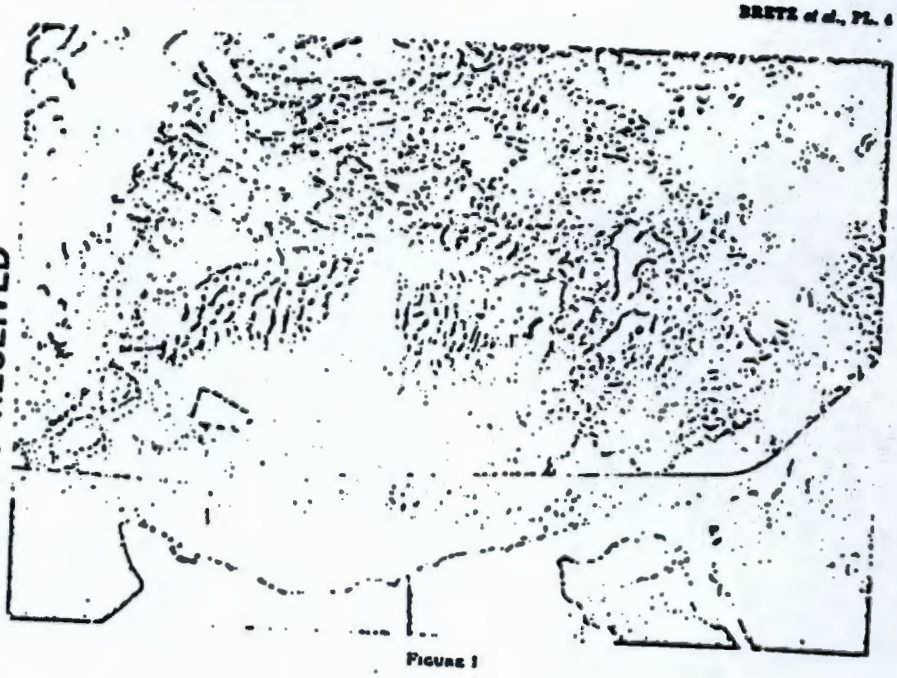

FIGURE 1

FIGURE 2

GIANT CURRENT-RIPPLE MARKS

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FIGURE 1

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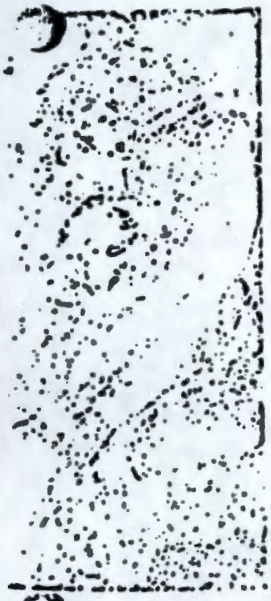

FIGURE 2

BARS IN UPPER CRAB CREEK VALLEY

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FIGURE 1

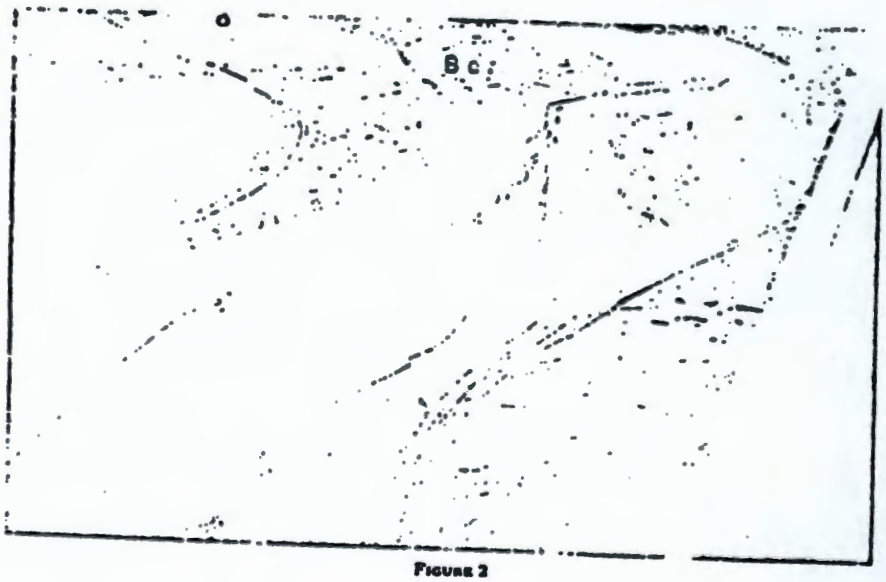

FIGURE 2

BARS IN UPPER CRAB CREEK VALLEY

974-D

Drumheller Channels

Maps: Corfu and Othello quads., U.S.G.S.; R4-5720, sheet 2, U.S.B.R.

(Bretz, Smith, and Neff)

This tract of scabland (Pl. 7; Pl. 10, fig. 1), the deepest dischargeway out of Quincy basin, is an almost unbelievable labyrinth of rock-walled canyons, basins, and buttes about 9 miles wide and 12 miles long, eroded as much as 300 feet deep in the folded basalt of the Lind flexure and the Frenchman Hills anticline. Its magnitude and complexity cannot be explained without the concept of enormous discharge across it fr n Quincy basin, but its history is more complicated than has ever been outlined. It appears to record at least three times of channeling in bedrock unprecedented except in Washington scabland.

What?

Folded with the basalt flows of the Frenchman Hills anticline was an overlying, weak, sedimentary formation. Portions of it have survived all later erosion and crop out low on the anticlinal flanks. Subsequent to deformation and much subaerial erosion came deposition of later Ringold sediments, still flat lying.[10] It now appears certain that the site of Drumheller channels carried such a cover when the first glacial-river discharge out of the closed Quincy basin occurred and that the earlier channels were superimposed from that cover.[11] Both east and west margins of the channeled tract are scarps in sedimentary rock, in place more than 100 feet high. One surviving hill of this rock, 50 feet high and similarly scarped, stands about 2 miles out in the complex. In the 12 miles of Drumheller's length, bases of these scarps descend from 1300 to 950 feet A.T. on the east side and to about 800 feet A.T. on the west side. Although water may have lapped up somewhat on these scarps, the much greater weakness of the sedimentary rock than that of the underlying basalt indicates that scarps were undoubtedly eroded back and channels correspondingly widened until the contact of the two formations was essentially at the edge of the torrent. By this assumption, the surface gradient of water

[10] Neff considers Low Gap (alt. 1510 feet A.T.) in Frenchman Hills anticline (sec. 13, T. 17 N., R. 14 E., Beverly quadrangle) to be a wind gap recording drainage out of an early Quincy basin. This view requires two post-Ellensburg uplifts separated by a long interval of erosion during which the early fold was reduced to a mature topography. The interpretation is based largely on the existence of 138 feet of sand, clay, and caliche in the floor of the gap. Its basalt floor is about 175 feet above the surface of the Quincy basin fill a mile directly north, and approximately 375 feet below the Hills summit a mile to the west. The lack of stream gravel in the gap is taken to record an interval of subsidence and sedimentation following the erosion but preceding the second uplift which made the closed basin the glacial floods found. By this view, the sediments in the gap are early Ringold. Culver (1937) thought that some "Ringold" was older than the folding of Frenchman Hills.

[11] Suggested by J. P. Buwalda but, in error, rejected by Bretz (1928c, p. 218).

Plate 5.—BARS IN UPPER CRAB CREEK VALLEY

Figure 1.—Wilson Creek valley floor a mile above junction with Crab Creek. Looking southwest. Grain field crossed by road may be identified in Figure 1 of Plate 9. Photo by H. T. U. Smith.

Figure 2.—Bar No. 1, looking southward. Vegetation pattern outlines the current-ripple marks. Fosse, with cultivated field, lies between bar top and foreground scabland. Another cultivated tract, in lower left, is in the blocked mouth of a prescabland gulch marked VB in Plate 6. Bar without a number on Plate 6 lies in angle between Wilson Creek and Crab Creek, and its flood-eroded, 150-foot scarp faces observer. Not visible in photograph are giant current-ripple marks on summit of this bar. Photo by H. T. U. Smith.

Plate 6.—BARS IN UPPER CRAB CREEK VALLEY

Bar No. 2 depends from scabland at upstream end, tapers out in midvalley. Undrained fosse on south side is nearly as wide as creek-occupied valley bottom beyond the bar. Unrecognized until seen from the air are the giant current-ripple marks on this bar. Photos by H. T. U. Smith.

Figure 1.—Looking northwest

Figure 2.—Looking west

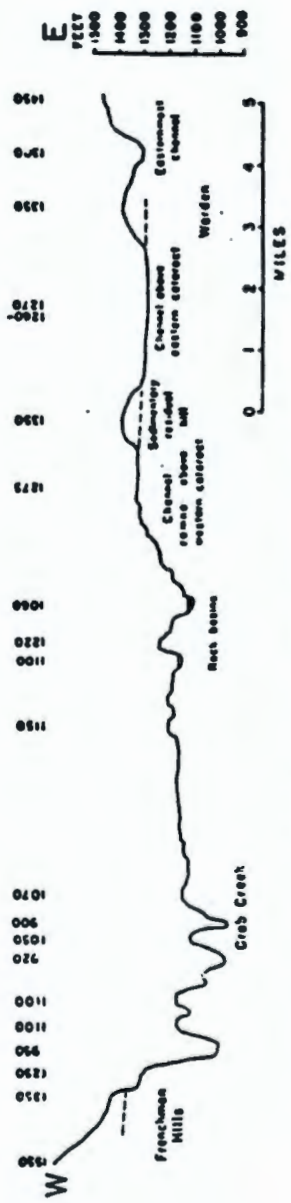

FIGURE 7.—PROFILES ACROSS DRUMHELLER CHANNELS.

Looking north. Profile follows a slightly zigzag course across the head of Drumheller Channels, between Warden and the nose of Frenchman Hills anticline. The easternmost channel has been but slightly deepened or scarped, and the Warden cataract channel floors have been cut but little into basalt. The three deep notches, by one of which Crab Creek escapes from Quincy basin, were made simultaneously. No preglacial drainage course across the anticline could have been deeper in basalt than the 1100-foot flat between Crab Creek and the two rock basins.

escaping down the southern slope of the anticline reached the surprising figure of 30–50 feet per mile. Yet the volume of the first discharge, which removed the overlying sediments, was sufficient to demand a width of 9 miles between bounding scarps. Drumheller at this earliest stage was an extraordinarily wide cascade over the edges of the tilted basalt flows.

Some basalt also was eroded during this first episode. There are two abandoned cataracts and recessional gorges in the eastern part of the group, 3–4 miles southwest of Warden (Othello quadrangle), one on either side of the isolated hill of sedimentary rock. One cataract brink is 1270 feet A.T., the other, 1250. Each is about 50 feet high. The western one has lost its western portion because of subsequent deepening to make rock basins 200 feet lower in the basalt. At comparable altitude and with similar height is part of such a cataract at the scarp base on the west side of the complex, its eastern portion destroyed by later channeling. With a very minor channel just east of Warden, they are the only records of the first glacial stream erosion in basalt at Drumheller Channels. (Fig. 7; Pl. 7.)

A significant item in understanding the mechanics of scabland cataract retreat in the vertically jointed basalt flows is the existence of a dike with irregular but nearly horizontal columns holding up the eastern Warden cataract lip. Plucking was not favored here, retreat stopped at the dike, and no horseshoe outline of the lip developed. Drumheller's great deepening occurred west of this dike.

The 300 feet of deepening since these Warden cataracts operated is assigned to the same later episodes that saw Bacon syncline notched after its high gravel was deposited, and Quincy basin's early gravel deposit channeled. This later deepening at Drumheller caused the reversal of behavior of glacial water traversing Quincy basin. The Warden cataracts are relics of an early scabland floor in Drumheller, probably correlative with the highest gravel in the Soap Lake rim. Sequence in channels is well shown in sections 10 and 13, T. 16 N., R. 29 E., where the channel below the Warden cataract is cut off by, and hangs 100 feet above, a later and deeper channeling. The floor of the hang-

e southern slope of the anti- st ng figure of 30-50 feet va of the first discharge, he overlying sediments, was nd a width of 9 miles between Drumheller at this earlist ordinarily wide cascade over tilted basalt flows.

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ing channel shows giant current-ripple marks (Pl. 4, fig. 2).

A dam (O'Sullivan) 3½ miles long, constructed by the Bureau of Reclamation across the entrance to the lowest of the Drumheller Channels, will impound water up to 1052 feet A.T. and thus raise the level of Moses Lake 8 feet. A huge gravel pit in the south part of sections 1 and 2, T. 17 N., R. 28 E. was studied before it was submerged under this reservoir. The pit is in the flat above the eastern scarp of the united Rocky Ford and Willow Springs channels, a scarp subsequently cut into by local drainage from Lind Coulee.

The gravel is mostly of well-worn pebbles but contains cobbles and boulders up to 2½ feet in diameter, some sporadically distributed, others aggregated in strata. Caliche pebbles and granules are well distributed but not conspicuous constituents. The structure throughout the 40-foot section is that of a delta, with long uninterrupted, south-dipping fore-sets capped by a few feet of top-sets. Altitude of the flat is approximately 1085 feet, 100 feet above the near-by lowest channel floors leading to Drumheller. The scarp is as clearly erosional here as it is in the latitude of Moses Lake. The delta deposit therefore is the southernmost portion of that upper flat and antedates latest use of both the Rocky Ford and Willow Springs channels in gravel and erosion of the deepest of the Drumheller Channels in basalt. The 1070 contact of top-sets on fore-sets records the approximate bottom at the time of deposition. It was about 200 feet lower than the initial discharge over Warden cataracts. This 200 feet of erosion could have occurred during the first discharge southward out of Quincy basin, but more probably the delta is a later overlay (say, at Ephrata channel time) on the southern portion of Quincy basin's earliest and highest gravel, with the contact as yet unrecognized.

Whatever its age, there was a basin here to receive the delta. The basalt of Lind flexure dips below all trenching at this place, but the sedimentary cover must once have been present. Only flood erosion of a channel-bottom hole could have removed this weak rock before Drumheller was notched below about 1060 feet. Known thickness of gravel in this basin is 128 feet. Thus the deeper, later channeling in Drumheller, contemporaneous with Rocky Ford and Willow Springs late channeling, amounted to more than 100 feet.

Attempts to establish a profile northward from the Warden cataracts to the highest gravel in northern Quincy basin have not been satisfactory because terraced surfaces are lacking. A correlation, however, seems logical, and, if correct, it appears that a large proportion of the scablands gravel fill was made during the first flood down Grand Coulee, Crab Creek, and other glacial tributaries to the basin.

If this be correct, then either the spectacular erosion in Grand Coulee was consummated early, or great quantities of basaltic debris went across and out of Quincy basin during later floods. That the second alternative is correct is strongly suggested by the amazing number of enormous granitic boulders along the Rocky Ford and Willow Springs channels, some of them 10, 15, even 20 feet in diameter. The granite, far less conspicuous in the higher, older gravel and in the earlier abandoned Ephrata channel, presumably came down Grand Coulee after its great upper cataract had retreated past Steamboat Rock and uncovered the sub-basalt granite hill tops now so conspicuous in the head of the great coulee (Bretz, 1932, Figs. 33-37).

Upper Crab Creek

Maps: R4-5720, sheet 1 and G-5883, U.S.B.R.

(Bretz, Smith, and Neff)

General Statement

Several glacial rivers entered Quincy basin from the east (Pl. 1). The largest was Upper Crab Creek, leading southwestward across the northern divide from the preglacial Spokane and Columbia valleys. Smaller but highly significant ones were Rocky, Bowers-Weber, and Lind coulees, distributaries from the large Cheney-Palouse tract.

Crab Creek carried the discharge of seven glacial rivers from the northeast and five spill-over distributaries from the Cheney-Palouse tract. Although it already had a valley deep in basalt, at some time Crab Creek had

two broad, uncanyoned, spillover distributaries across the upland south of it and leading to the east side of Quincy basin. One theory (Flint, 1938) calls for so much aggradation by glacial streams in preglacial valleys that water spilled across interfluve tracts. Later removal of most of such fill has largely restored capacity of the original valleys. Upper Crab Creek valley contains great gravel deposits which, by that theory, are but terraced remnants of such a fill. An excellent place to test this idea is the vicinity of Wilson Creek's junction with Crab Creek, located where the supposed filling produced the distributary overflow.

Plate 8 is a 2-foot interval contour map of 12 sections in T. 22 N., R. 29 E., made by the Bureau of Reclamation. The scabland geology on it was mapped by Bretz and Smith. Bretz (1928a; 1928b) has published descriptions and figures of these deposits, identifying them as river bars so greatly exceeding the magnitude of known river bars that some alternative seemed called for. But this extraordinarily revealing map and the accompanying aerial photographs should make clear the impossibility of defending any alternative.

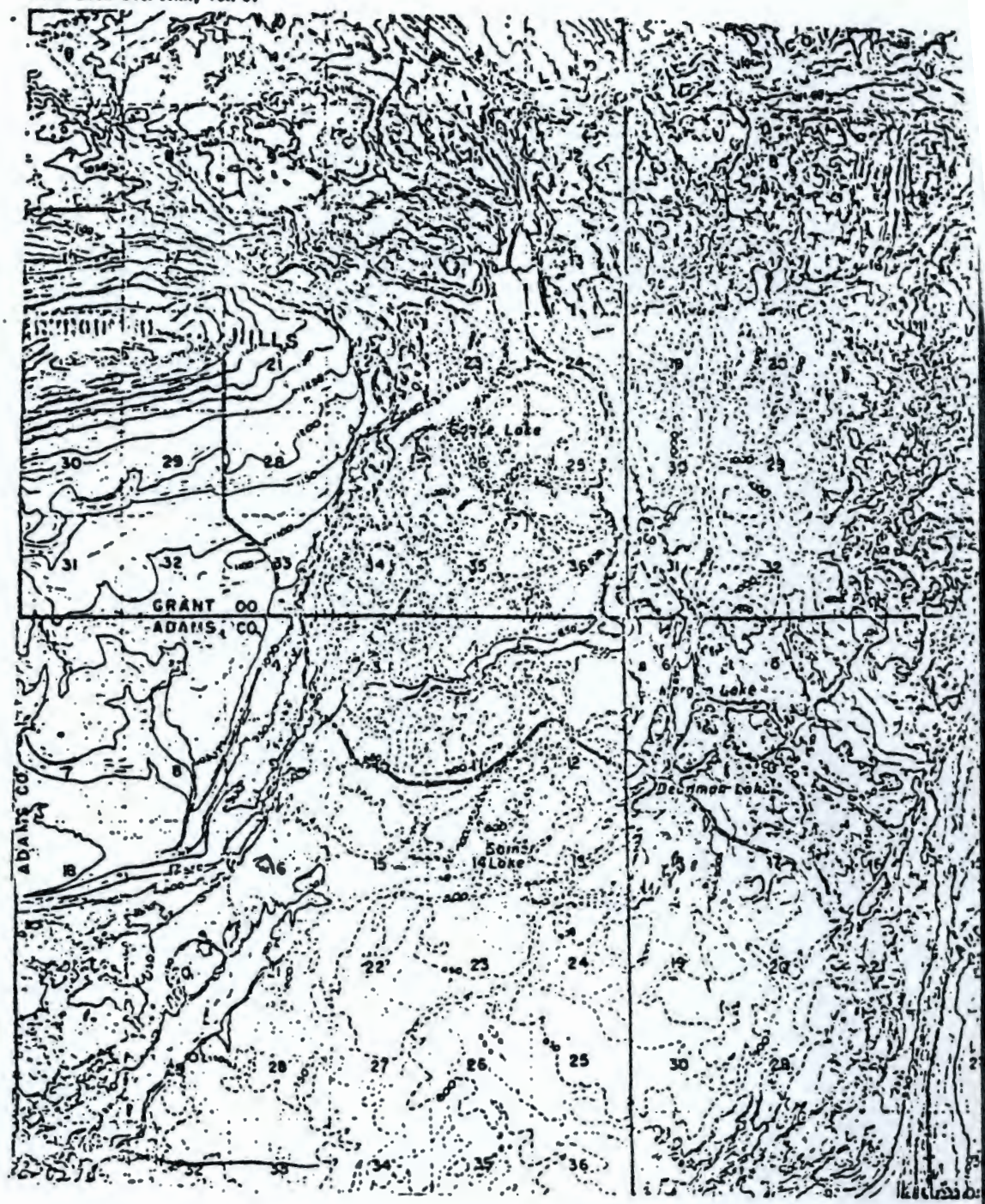
Bar No. 1, directly north of the town of Wilson Creek, has a broad summit 120 feet above valley bottom with linear undulations transverse to valley length and averaging 10 feet high and 250 feet apart (Pl. 5, fig. 2). The upstream (eastward) slopes of the low ridges are between 7° and 9°, the downstream slopes are 19°–22°. No excavations exist. Only medium-sized pebbles lie on the surface. Aerial photographs show the pattern of these asymmetrical undulations to be that of current ripples, weakest at the ends farthest from the center of the valley, strongest on the brink of the descent toward that valley. Two shallow undrained sags lie between the ripple-marked top of the bar and the scabland wall north of it. This bar tapers and lowers toward the west, continuing to hug the north wall of Crab Creek valley but having another shallow undrained sag on its north side. Two capacious ravines in basalt were blocked by the bar's growth, and subsequent drainage has cut much narrower ravines across the gravel blockade.

Bar No. 2 (Pls. 6, 8) lies along the south side of the creek valley opposite the western end of Ba. No. 1. It can be well seen from State Highway 7. It extends westward from the scabland ledge carrying the highway, lying almost wholly out on the valley floor. The fosse between it and the ledge covers about 40 acres and was a closed depression 10–14 feet deep before the railroad grading.

A gravel pit low on the north slope of the bar shows uninterrupted deltalike fore-sets dipping diagonally down the slope and down valley. Another pit, at the extreme east end, close to the base of the basalt cliff from which the deposit depends, shows an anticline-like structure of steep, long fore-sets for the full height of this end of the bar. Highly angular basalt boulders up to 8 feet in diameter lie almost where they fell from the downstream-facing cliff into the growing gravel deposit. This bar summit is more than 60 feet above the fosse on the south and nearly 80 feet above the flat valley bottom on the north. The downstream tapering end is a quarter of a mile out in the valley from the nearest scabland wall.

Bar No. 3 (Pl. 8), also on the south side of the valley, shares with No. 2 in enclosing the fosse back of and between them, and rises 94 feet above that depression in a quarter of a mile. It is made irregular by a scabland shoulder which projects northward into it and rises above it as a knob of bare rock. Just beyond that is a small fosse in the bar summit. Thence the bar tapers down to valley bottom with another fosse, an eighth of a mile wide, between it and the scabland of the valley's south side.

A large shallow pit on the bar summit shows no structure but reveals many large, angular basalt boulders, 5–6 feet in diameter, and one 6-foot granite boulder. The remainder of the deposit is composed of pebble and small-cobble gravel, fairly well worn, with almost no sand or granule gravel. The nearest upstream source for basalt boulders is a knobby scabland bench 3000–4000 feet distant, its summit no higher than that of the bar. If this gravel hill is a constructional form, these boulders had to cross the fosse and then be rolled up the stoss end of the bar to the summit, nearly 100 feet higher. If it be an erosional remnant, and a stream bed such as Flint has postulated once existed for them to travel on from the scabland knobs, boulders 5 and 6 feet in diameter



MAP OF DRUMHELLER CHAN

Interval for continuous contours 10 feet; for dashed contours 25 feet. U. S

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:UMHELLER CHANNELS, WASHINGTON

d contours 25 feet. U. S. Bureau of Reclamation topographic map R4—5720, sheet 1.

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moved more than half a mile on no gradient at all. Transportation by floating ice must be invoked unless the glacial river had a velocity competent to move them either on a level or even upgrade.

The valley bottom between Bars No. 3 and No. 4 (Pl. 8) is reduced to only a third or a fourth of its average width in this township. This narrows, confined only by gravel, is inexplicable by the fill-and-dissection theory. Even the empty fosse south of the west end of Bar No. 3 is nearly twice as wide as the narrows occupied by the creek. The outline of the prescabland valley is readily recognized from Plate 8, and the narrows immediately becomes understandable if Bar No. 3's distal taper grew downstream from an anchorage on the scabland shoulder in its mid-length. Cross-sectional room for the central bottom current of the glacial river was provided on the proximal end of Bar No. 4 where, over about 40 acres, the deposit grew only 20 feet above the valley bottom. A third of a mile farther down valley, the summit of Bar No. 4 is nearly 100 feet above valley bottom on either side. Length of the gravel hill and accompanying fosse is 2 miles. The streamless fosse to the north is nearly twice as wide as the creek-occupied part of the valley floor. Bar No. 4 lies in mid-valley, does not make contact with either side except at the very head.

This bar is defended by a splendid example of "trenched spur buttes" (Bretz, 1928b, p. 472, Fig. 23) where the tip of a preglacial divide between the main valley and a tributary from the north could not be tolerated by the glacial river and was plucked and notched by bottom currents into a linear group of ragged scabland buttes. The Great Northern Railroad traverses the length of the fosse and crosses this divide tip by one of the notches (Pl. 8) Only simultaneous functioning of all the notches could have produced or maintained the width of the fosse at its eastern end.

These streamlined bars assuredly are not terraces with outlines softened by subsequent slope wash. Their shapes and their fosse depressions cannot be due to leisurely erosion by late-glacial or postglacial streams. But may they not be remnants of a former valley fill which became gouged into the present topography beneath a flood or floods of the character read from Grand Coulee, Quincy basin, and Drumheller Channels? May not the bar forms be erosional instead of depositional? The composition and structure and the existence of fossae seem to debar that interpretation also.

These features do not fit Allison's ice-jam theory whereby properly located blockades in the glacial river laterally detoured the escaping water around the edges of the dams to make the scabland walls and to erode and rebuild remnants of an older, high level gravel into bar forms. Allison's idea would better explain these features of Upper Crab Creek if his ice jam were placed somewhere upstream, and the alterations for which it was responsible were ascribed to a flooding downstream when the dam finally gave way. Judged by his interpretation of trenched spur buttes in Snake River canyon, he would make those of this tract either abandoned preglacial courses of Crab Creek or ice-jam "run-arounds."

But these Crab Creek bars are not high enough on the valley slopes for Allison's theory. They are not perched, their bases are essentially on the valley bottom, 100–200 feet lower than the bottoms of most of the notches. They do not contain any old gravel materials and are embarrassingly in the way wherever one may wish to place an ice jam. The features near Wilson Creek cannot be thus explained.

Comparison with Yakima Valley Gravel Deposits

A comparison of the topography, composition, and structure of these scabland gravel deposits with remnants of an extensive, deep gravel fill in Yakima Valley near Ellensburg are illuminating. Drainage areas of Yakima River above Ellensburg and of Upper Crab Creek are approximately the same. The Yakima Valley deposit is definitely older than Crab Creek gravels, but both, considered as once-continuous valley fills, have been subjected to erosion by glacial and postglacial water.

The Yakima gravel is terraced in two very definite levels. The lower terrace has as flat a surface as the modern flood plain. Erosion by local runoff is essentially nil, and the terrace is wasting away only from lateral attack by the river. This is the identical procedure of the

fill-and-cut theory. The upper terrace has a dissected margin of mature slopes but, back from the valleyward edge, is almost as flat as the younger terrace. There are no residual hills isolated on the upper terrace, and only one was seen on the lower. It stands so near the break between the two terraces and has such gentle slopes that it clearly is but an outlier of the upper flat.

Many highway cuts show the gravel of both terraces to be well sorted and well worn, far more so than most scabland gravel. There are some included sand lenses and strata of small boulders. Sorting and wear resemble that typical of scabland gravel only near basalt cliffs along the narrower part of Yakima Valley above Ellensburg. Here the gravel may be rather rubbly and contain large, angular boulders, obviously fallen from these cliffs during the aggradation. Stratification is horizontal almost everywhere, with only shallow fore-sets if any. Nothing resembling the long fore-sets of scabland gravel was seen.

The dendritic pattern of the slope separating the two terraces resembles nothing in scabland gravel topography. Dissection of the Yakima Valley fill here is a textbook example. Comparison of topography, composition, and structure with scabland gravel deposits is all contrast! Yakima Valley never had a Lake Missoula type of flood, and no barlike forms were made during deposition or dissection of its gravel.

Bars in Wilson Creek Valley

Bars up Wilson Creek Valley a short distance east of the mapped area carry even better-developed giant current ripples than those on Bar No. 1; maximum relief is nearly 20 feet. They occur at three levels, ranging from the broad valley bottom itself to the highest bar summit where they are close to the upper scabland, 150 feet above the valley floor. Ripples of the lowest group have wave lengths averaging 300 feet (Pl. 5, fig. 1; Pl. 9, fig. 1) and are most conspicuous where partially submerged in a flood-irrigated tract. Because two definite erosional scarps in gravel separate the three ripple-bearing surfaces, three floods are read from this topography. Except for cutting a narrow trench, postglacial Wilson Creek has done nothing to modify the valley floor, and existence of the ripples across the entire bottom proves that the last glacial river to use this route was not one of the leisurely meandering streams of Flint's concept.[18]

Giant current ripple marks are difficult to see at ground level, even aerial photographs fail to record them if the surface carries a good cover of sage brush (Pl. 4, fig. 1). The ripples shown cover a bar about 2 miles east of Odessa, some 25 miles up Crab Creek from Wilson Creek junction. There are 13 of them in a distance of 3300 feet. The clear depiction north of the straight east-west line, a road, is due to a brush fire shortly before the photograph was taken. Brush on the south side of the road was not burned, and the ripples show so faintly that they could well be overlooked.

The writers do not rest their case for enormous glacial rivers on current ripples alone but are convinced that only Pardee's interpretation (1942) for the Lake Missoula features will account for the ripple marks near Wilson Creek town.[19]

Black Rock Coulee

Reference has been made to two wide tracts of not markedly canyoned scabland in the downstream angle between Upper Crab Creek valley and Quincy basin, high above both lowland tracts (Fig. 8; Pl. 1). The southeastern of these divergences, Black Rock Coulee, takes off from the creek valley about midway between Marlin

[18] Flint came close to recognizing giant current ripples and thus to destroying any validity his hypothesis then appeared to possess. On page 477 (1938) he said "Here and there the fill surfaces [of his 'erosional remnants'] are marked by faint ridges up to several hundred feet long, 20 to 50 feet broad and a few feet high. It is quite possible that some of these are at least in part constructional . . . ." But "none of these forms, even if constructional, constitutes, in itself evidence of deep streams".

[19] Subaqueous "sand waves" of this size have been known in the Mississippi River for more than 50 years (Lane and Eiden, 1940), in flood waters 60-90 feet deep. But both regressive and progressive sand waves fail to survive as flood velocity and depth decrease (Bucher, 1919). The features here described did survive, therefore are true current ripples. Unrippled original surfaces of scabland gravel deposits apparently did not experience a sufficiently high bottom velocity at close of deposition. An interesting sidelight on the hydraulics of these glacial rivers will appear when the giant current ripples are given careful detailed study.

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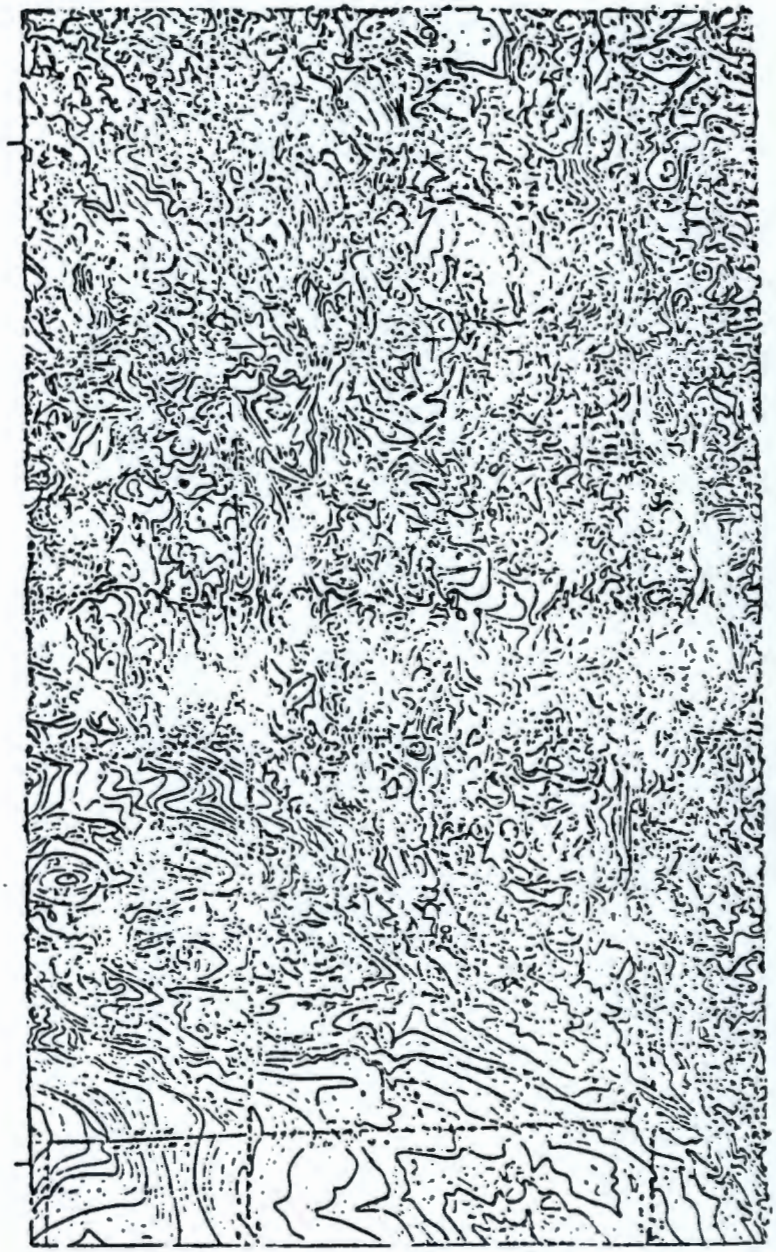

FIGURE 8.—SUMMIT OF UPPER CRAB CREEK QUINCY BASIN DIVIDE

Scabland, scarp, and surviving bare topography on summit of interfluve between Upper Crab Creek and east edge of Quincy Basin. Record of the early flood that entered Black Rock coulee. Altitude of highest and oldest current-rippled bar east of the town (see Pl. 9, fig. 1) falls within the altitude range of this scabland. Total width on summit is 5 miles, total vertical range about 200 feet. Heavy contours at 10 foot intervals. From U. S. Bureau of Reclamation topographic map R4-5720, sheet 1.

(Krupp) and Irby and enters Quincy basin about 12 miles south of the latitude of Soap Lake. Its altitude at the divergence is more than 250 feet above Crab Creek valley bottom, and at its junction with Willow Springs trench it hangs 200 feet. But Black Rock Coulee drainage does not enter the trench. About 3 miles short of the brink of the eastern Willow Springs scarp it turns southward and flows parallel to, but *on top of*, the scarp to enter the mouth of Rocky Coulee. In like manner, drainage from some 15 square miles of adjacent scabland north of Black Rock coulee is detoured southward without crossing the scarp (Fig. 5).

Black Rock Coulee debouches on a high basalt flat thinly covered with scabland gravel whose altitude strongly suggests contemporaneity with the high gravel separating the three channels in Quincy basin. Furthermore, this scabland between Crab Creek and the basin is not vigorously expressed, and some is weathered down into a coarse residual soil, unlike any basalt in the lower scabland of the region. Black Rock Coulee and its associated high scabland (Fig. 8) is probably an early flood record. The broad summits of the Crab Creek bars, streamlined in conformity with the valley shape, are higher than some of the rock basins and intricate channels of the scabland farthest west on the interfluve between the creek valley and Quincy basin, and are about as high as butte tops over most of that tract. Both the giant ripples and the scabland basins required adequately deep water for their production and must be contemporaneous. The bars are oriented for a deeper part of the glacial-river current, whose direction was determined by preglacial Crab Creek valley in basalt. In these relationships is convincing evidence that the interfluve overflow was not due to a Crab Creek valley fill or an ice jam at the time but resulted from a volume that demanded more capacity for its channel than preglacial drainage had ever made for its valley. Upper limit of scabland at the foot of loessial scarps on this interfluve is 1500 feet A.T. Floors of near-by valley-bottom fossae are at about 1250 feet. The glacial river was more than 200 feet deep at this place.

Crab Creek valley was dammed at its entrance into Quincy basin late in scabland history by a gravel deposit with eastward-(up-valley-) dipping fore-sets recording backfill from Dry Coulee (Fig. 5). Silts overlying the lower scabland gravel for 10 miles or more upstream show that the creek valley was ponded as a consequence of the bar building. The gravel dam, cut in section by State Highway 7, is at least 50–70 feet thick. Crab Creek has subsequently cut a narrow gulch through it. The backfilling episode must post-date all glacial-river discharge down Crab Creek. It is to be correlated with the last functioning of Dry Coulee, later than the deep notching in the west saddle of Bacon syncline. It must postdate completion of Upper Grand Coulee's recessional gorge and the final capture by Grand Coulee of all Cordilleran glacial drainage to cross the plateau.

Although constituting a flat-topped and still nearly complete valley fill, the eastward-dipping fore-sets of this Crab Creek deposit and the silts east of it debar its interpretation as a record of Flint's hypothetical aggradation. It is also impossible to explain as the consequence of any ice jam. The gravel was carried *upvalley* in a large glacial-river course.

With this valley-mouth dam is correlated a well-marked bar crossed by State Highway 7 a mile west of the scarp of the dam. It lies almost in the middle of Dry Coulee, its summit at about the same altitude as that of the dam. The bar top is 30 feet above the channel on the west, 50 feet above that on the east, and 80 feet above the bottom of a closed depression immediately upstream. A pit on its western slope shows long deltaic fore-sets dipping west toward the smaller of the two bounding channels.

Rocky, Bowers-Weber, and Lind Coulees

Maps: Moses Lake, Othello, Schrag, Wheeler quad. maps U.S.G.S.; R4-5720, 1 & 2, U.S.B.R.

(Bretz, Smith, and Neff)

The lower ends of these coulees are crossed by siphons of the East Low Canal (Pl. 1) where excavation and topographic mapping by the Bureau of Reclamation have revealed some instructive details of the scabland picture. All

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three coulees are distributaries from the extensive Cheney-Palouse tract and in prescabland time all headed on the west side of a divide which was crossed during the scabland making. Flint (1938) made this divide crossing possible by aggrading the Cheney-Palouse tract with glacial outwash deposited under ordinary conditions, disputing Bretz who had earlier repeatedly called for enormous volume to explain the divide crossings.

The entrance of Rocky Coulee to Quincy basin is narrowed to an eighth of its width a mile farther upstream and about a fourth of its average width for the first 10 miles above the constriction. A closed depression occupies the coulee floor for the first 2 miles upstream. Its bottom is 100 feet *higher* than that of Willow Springs channel half a mile to the west, and its drainage (when it overflows), after passing the constriction, turns south and flows parallel to the Willow Springs channel, *but on top of the scarp*, nowhere more than 3 miles back from the brink, until the scarp dies out about 6 miles to the south. Even there, Rocky Coulee's drainage continues its lateral course, refusing to join the main drainage south out of Moses Lake for 5 more miles and finally entering Drumheller Channels as a part of Lind Coulee discharge. Thus, with Black Rock Coulee's detoured drainage there is a total of 18 miles of this anomalous southward flow closely parallel to the Willow Springs channel but well above it and nowhere descending its scarp.

The topographic map suggests, and field examination proves, that Rocky Coulee drainage, beyond the constricted entrance to Quincy basin, is kept from spilling over the Willow Springs channel scarp by a long, low barrier of scabland gravel which tops the scarp and slopes gently eastward away from it. This barrier is most pronounced 2 miles southeast of Moses Lake town where crossed by U. S. Highway 10. Figure 6 shows a form resembling a wide spit pointed south with fingers recurved eastward. The highway cut on its eastern (lee) edge shows only loose basaltic sand and granule gravel. No structure is revealed. On the flat immediately to the east, roadside and irrigation ditches show caliche *in situ* for several miles eastward, and only the lack of a loessial cover here suggests alteration by glacial water.

Directly east of Moses Lake town, a large pit in this barrier shows coarser material at 1190 feet A.T. with some boulders of basalt and caliche but no interbedded sand or silt. The conclusion that the barrier is a natural levee type of bar and that it grew laterally eastward on to a higher marginal surface seems inescapable. This feature which constricted and detoured Rocky and Black Rock coulees is a part of the high gravel plain, older than the deep channeling across the basin. Where crossed by Highway 10, it is 80–100 feet lower than the Warden cataract lips. Either it was built after Drumheller had been considerably deepened or it was deposited in water 75–100 feet deep. The bar form is readily identifiable for 6 or 7 miles.

The lower few miles of Bowers-Weber Coulee (Pl. 1) carries a silt deposit, well exposed in road cuts along U. S. Highway 10 east of the caliche-covered plain above-noted and conspicuous as far east as Schrag (1244 feet A.T., Pl. 1). The deposit consists of alternating silt units, one finer than the other, each perfectly sorted, each with crinkly laminae that look like weak current records. The finer-textured member is prevailingly thicker, reaches a maximum of 18 inches, and is lighter-colored. The coarser silt grades up into the finer. Berg-deposited lenses of coarse sand containing non-basalt pebbles and a granite boulder 15 inches long indicate deposition in glacial water.

These silts lie only a little lower than the Warden cataract lips and should be correlated with their functioning. Ponding north of and below the 1250 Warden sill seems to be recorded while nonflood glacial drainage was arriving in Quincy basin, perhaps during the closing stages of the first flood episode or the early stages of the second.

Lind Coulee is crossed by the East Low Canal 4 miles east of Warden. Two siphons are to be used, a scabland butte (the summit of Lind flexure) in mid-coulee carrying a short stretch of open canal between them. The south end of the southern siphon terminates in a gravel deposit (altitude 1247 feet A.T.) on the coulee slopes where excavations expose a 20-foot section soon to be obliterated by back filling.[14] The material is all fine gravel and coarse sand, per-

[14] Exploration for foundations here penetrated 88 feet of gravel.

haps 20 per cent caliche bits, the remainder bluish-black basalt, stratified in repeated courses of short fore-sets which without exception dip away from the open Lind Coulee and toward the adjacent, small, tributary valley. The topography here looks like a rounded-off terrace, and, at first glance, the structure and composition seem to support that interpretation.

But the key to understanding the deposit is in the consistently 5- to 10 degree coulee-ward dip of the different nearly horizontal courses. They dip parallel to the surface slope, each course inclined in the *opposite* direction to that of its component fore-sets. All strikes parallel that of the slope. The deposit is a typical river bar marginal to the central current, its accretions swept back up and out of the main current and added to the accumulation in a protected re-entrant. The bar originally dammed the minor tributary here and extended at least 3000 feet farther down-coulee, grading into finer material with less-marked stratification. It must date back to the functioning of Warden cataracts.

Twenty-five miles farther up the coulee and a mile east of the town of Lind, at the junction of two glacial rivers (Pl. 1), the floors of three pits in scabland gravel are so covered with rejected boulders that one may cross without stepping off boulders. They average 3 feet in diameter, a few are 6 feet. Almost all are clearly from large-columned basalt knobs in sight up the coulee. Among the bruised but unrounded, unsmoothed basalts was one angular granite, 3 feet in diameter.

At Ritzville (Pl. 1), near the divergence of one of these coulees from Cow Creek valley in the Cheney-Palouse tract, a poorly sorted, bouldery gravel lies on the floor half a mile downstream from a low, channel-bottom, basalt knob. The very little-worn boulders are fortuitously distributed in the deposit. Some are 5 feet or more in diameter. One 3-foot quartzite boulder was found. Poorly developed fore-sets dip down along the coulee.

At Ralston (Pl. 1), near the divergence of the other coulee from Cow Creek valley, is a similar showing of bouldery gravel on the channel floor, with fragments up to 3 feet in diameter. There are no basalt outcrops near by. Neither here nor at Lind or Ritzville is there any body of finer, well-sorted material. It is all coarse, comparable, except for the boulders, to that shown in Flint's Figure 2 of Plate 2.

Both Ralston and Ritzville tell the same story that was read at Lind. Glacial torrents capable of tearing large blocks of basalt loose and transporting them along the low gradients of the preglacial coulees left these records. Such bouldery stream debris derived and transported on such gradients (about 25 feet per mile) cannot be harmonized with Flint's theory of moderate streams.

Floors of the coulee heads near Ritzville and Ralston hang 50–75 feet above the bottom of Cow Creek valley, which is but a modified preglacial drainage way. By the hypothesis here advocated, the larger scabland tract was under water deep enough to reach the top of the former divides in loess. These boulders were dislodged from parent ledges by the distributary streams. In the absence of steep gradient, only great volume will suffice for the velocity indicated. A basalt bench at least 50 feet above the coulee floor at Lind carries scabland gravel. This high-lying, divide-crossing distributary should have been abandoned at the very beginning of Flint's dissection episode, and its 50-foot fill should still be intact.

If several floods traversed the Cheney-Palouse tract, some deepening of Cow Creek's preglacial valley probably occurred. The evidence at the mouth of Bowers-Weber Coulee is that no flood came down it from the Cheney-Palouse tract after the silting episode, which is correlated with the first flood in Quincy basin. Therefore, these high-lying, distributary coulees between Crab Creek on the north and Washtucna Coulee on the south are believed to have been occupied only during an early scabland making. If so, removal of any hypothetical gravel fills must be dated from that same early episode, before the Bowers-Weber silts were deposited.

Western Part of Quincy Basin and Adjacent Columbia River Valley

Colockum Pass, Malaga, Quincy quad. maps, U.S.G.S. and U.S.B.R. map R4-5720, sheet 1

(Bretz, Smith, and Neff)

Babcock and Evergreen ridges constitute one long, low, north-south, structural elevation

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MAP OF BARS IN UPPER CRAB CREEK VALLEY, WASHINGTON

Below junction of Wilson Creek glacial river. Part of U. S. Bureau of Reclamation topographic map G 5883. Contour interval 2 feet.

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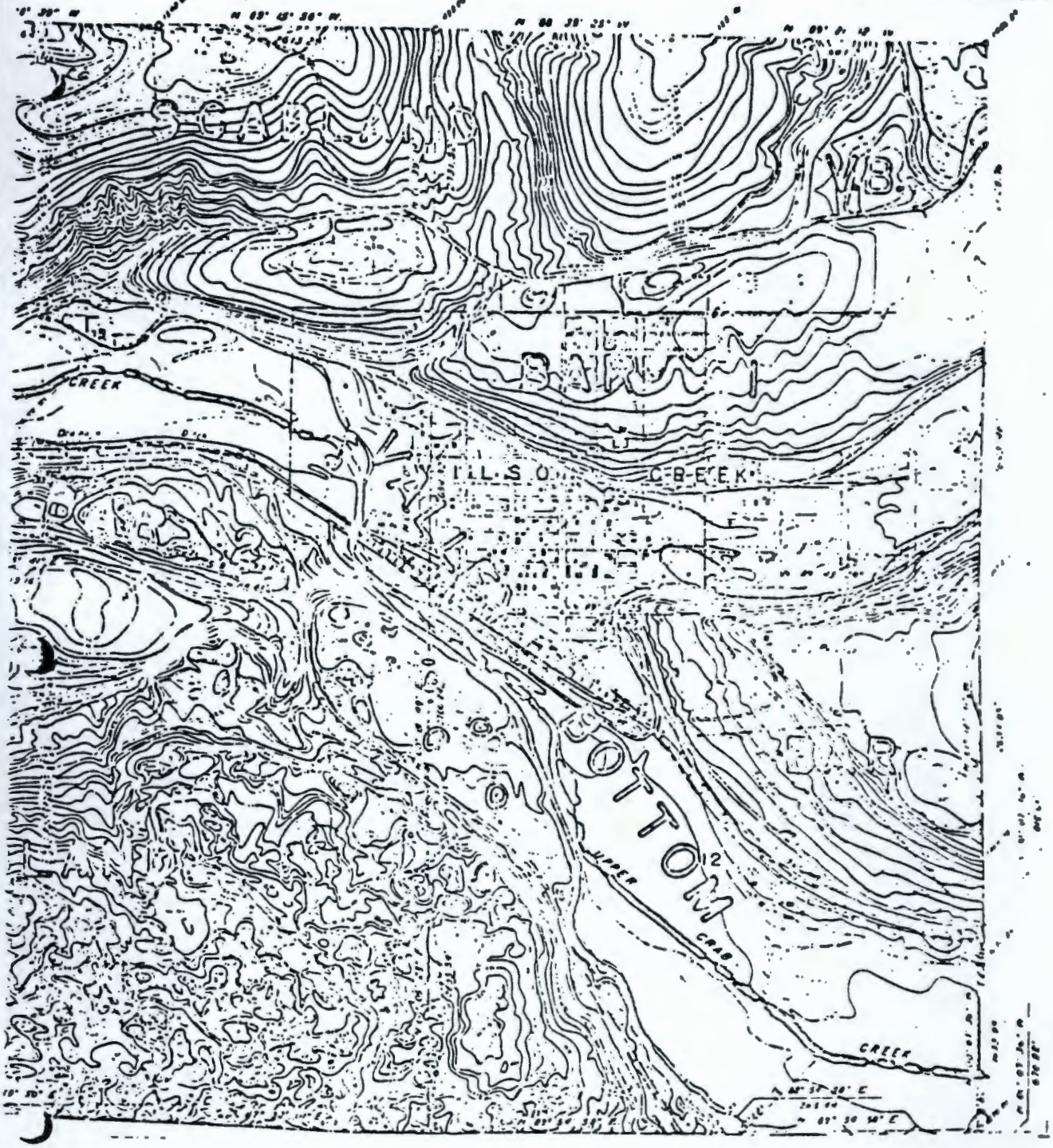

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Western Part of Quincy Basin and Adjacent Columbia River Valley

Colockum Pass, Malaga, Quincy quad. maps, U.S.G.S. and U.S.B.R. map R4-5720, sheet 1

(Bretz, Smith, and Neff)

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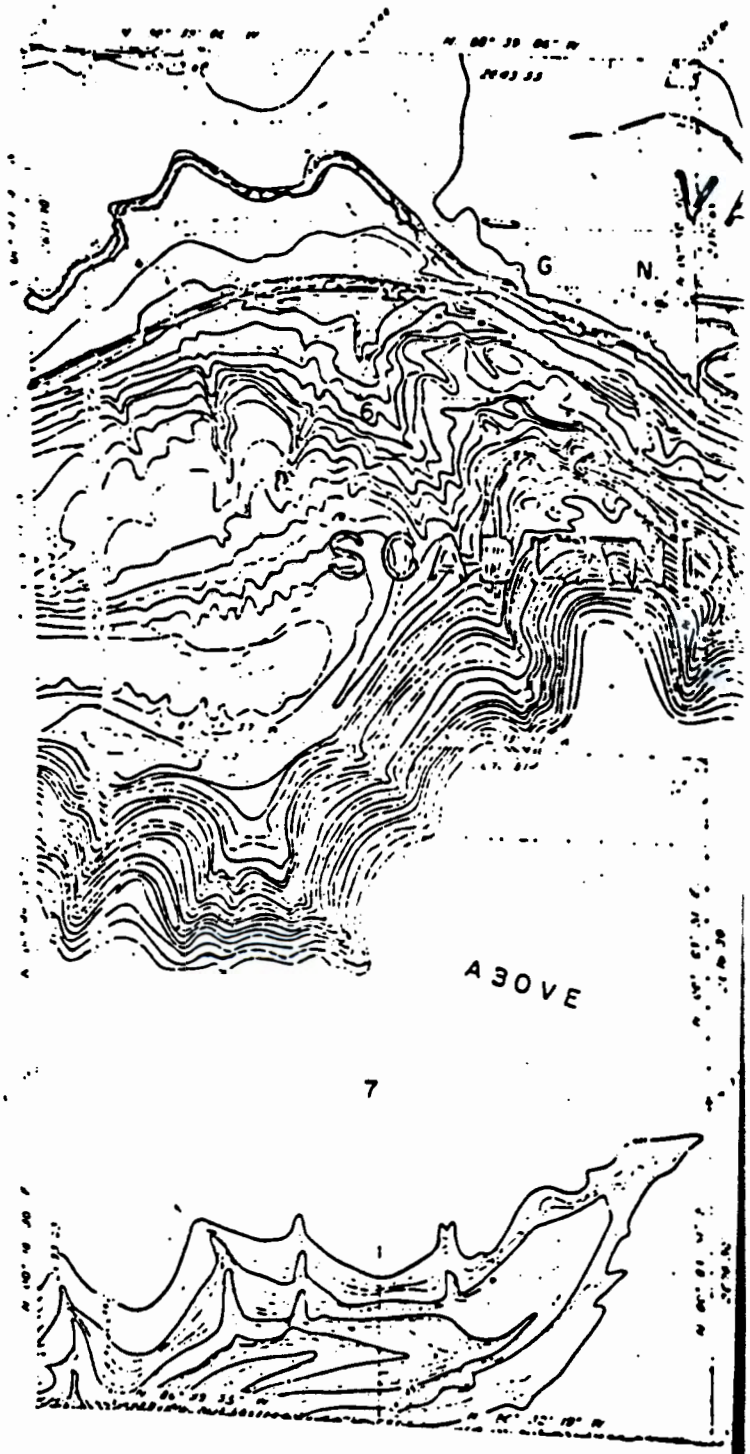

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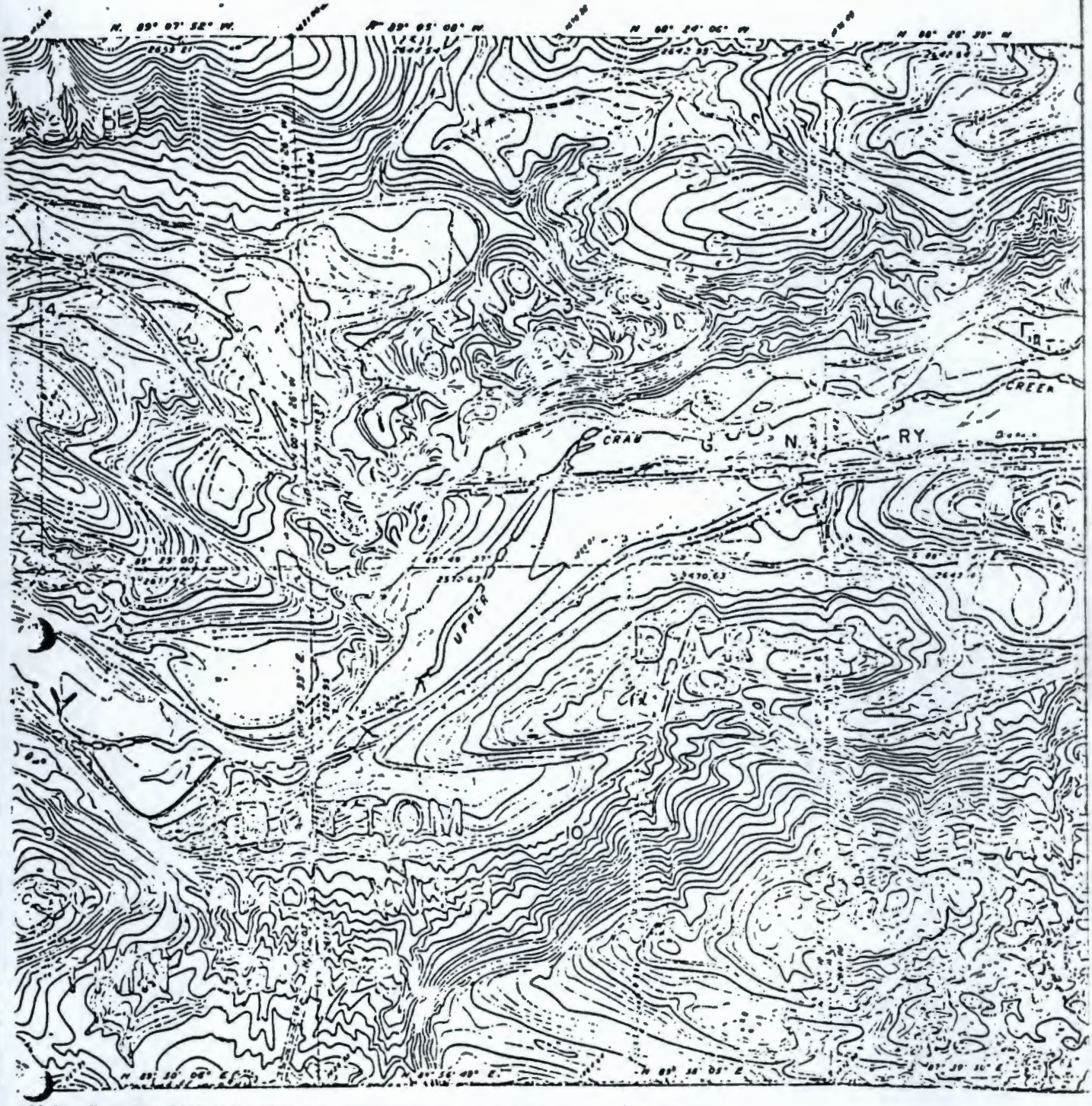

OF BARS IN UPPER CRAB CREEK VALLEY, WASHINGTON

Creek glacial river. Part of U. S. Bureau of Reclamation topographic map G 5883. Contour interval 2 feet.

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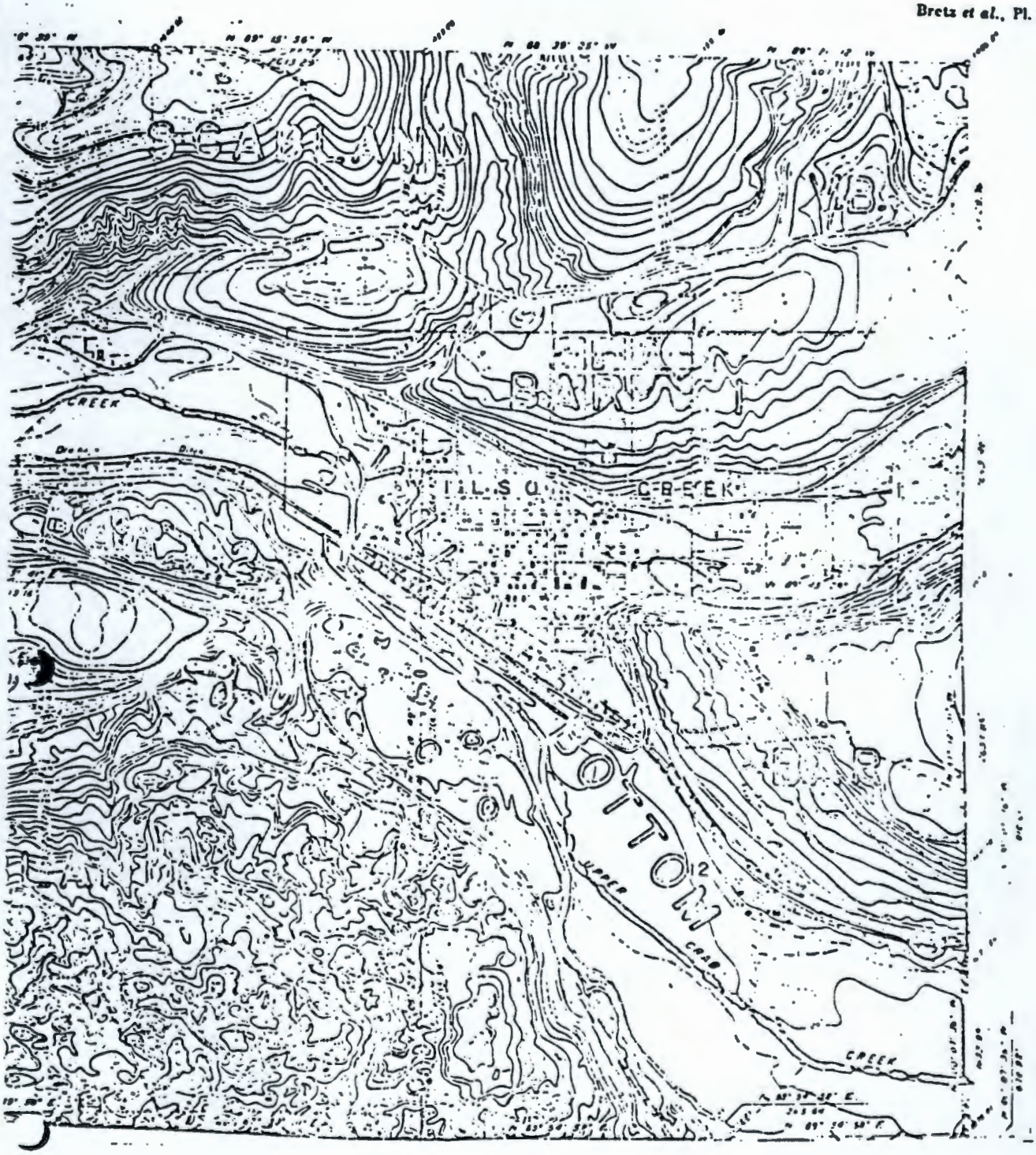

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separating Quincy basin from Columbia River valley, cut into two by recession across it of the huge double Potholes cataract, nearly 1½ miles in total width. (*See* Pl. 1) The two ridges are actually the toe of the much greater uplift west of the Columbia (Table Mountain), amputated by the river in maintaining its antecedent course. Of several sags in the elongated summit of this ridge, two more (Crater and Frenchman Springs) also became dischargeways to the Columbia. Just west of each sag, the water plunged several hundred feet over the valley's eastern wall. Two of the cataracts thus engendered (Potholes and Frenchman Springs) receded essentially the full length of the notch across the ridge, but the third and smallest (Crater) retreated so little that its channel in the floor of its notch is still largely intact.

At the head of all three spillways, the Quincy basin surface slopes eastward away from Babcock and Evergreen, so that channel-bottom altitudes are readily obtained. Crater's channel head is 1280, the other two are 1210. But the original notches were so modified that estimates of initial altitudes found by the discharging water may vary with the observer. Bretz has long maintained that the cataracts were contemporaneous, with the upper limit of stream functioning in each notch at about 1300 (the same as at Warden cataracts), and that the 70-foot higher altitude of the channel to the smallest falls is the result of less volume and briefer use.

One of three conceivable alternatives to this idea of contemporaneous functioning is Meinzer's assumption of a remarkable coincidence in subsequent warping which brought the cataract upper limits into approximately the same horizontal plane. Another is an equally remarkable rotating succession of unrecorded ice jams. A third alternative is that, at the time of cataract discharge, the basin possessed an evenly graded alluvial fill leading from the mouth of Grand Coulee down to the three outlet places, and that shiftings of the detoured glacial (but nonflood) Columbia on this aggrading plain made possible a succession in use. Such an occurrence would be recorded in considerable remnants of the plain between adjacent spillways lying at the altitude of the highest channel scars and sloping up back into the basin.

But the slope of the plain, 10–20 feet to the mile, is down toward the southeast all the way to Ephrata channel and Frenchman Hills. It certainly is not the original slope of an outwash plain leading to the cataracts. Furthermore, it is largely unchanneled and in 25 50-foot U.S. B.R. test holes boulders have been found only close to the cataracts' channel heads. Its eastern part is heavily covered with basaltic sand and granule gravel, and the western part is composed mostly of sands and clays with a heavy caliche. Two caliches separated by sand or cemented gravel in some holes indicate prescabland origin. The cataract channel heads are cut into a caliche cap.

The eastern portion may be part of a normal outwash plain, but its slopes indicate drainage out through Drumheller before Ephrata channel time, not by way of the cataracts. Thus the falls may date from an early flood, after which ordinary meltwater discharge from Cordilleran ice may have built a plain in Quincy basin adjusted to Drumheller's depth at that time. Later floods then destroyed all but the extreme western part of this plain. Only the freshness of the cataract features (Pl. 10, fig. 2) seems out of harmony with this sequence.

A gravel deposit with most surprising structure lies on this plain a few miles southeast of the head of the Potholes, well exposed in a large pit (SW ¼ Sec. 32, T. 19 N., R. 24 E.) a mile east of the former post office of Burke. The material is coarse, with many basalt cobbles and some boulders whose diameters reach 5½ feet. Caliche boulders 3 feet in diameter are present, also several large granites. The stratification is dominantly highly inclined with dips toward the east, southeast, and south, *away from* the cataract head. Either these are backset beds as suggested by J. H. Mackin[16], or they record a reverse flow through the Potholes notch, out of the Columbia Valley and into the Quincy basin; Neff holds this latter view. Imbrication is so poorly developed that no decision as to which way the water flowed could be made from the deposit. If flow was eastward, the debris could have been obtained over the 3-mile stretch between The Potholes and the pit, at an altitude of about 1240 feet. A continuous gradient exists thence southeast and east to Drumheller's deepest channels. If the flow was westward, all debris must have been imported in floating ice.

[16] Personal communication.

It is conceivable that a flood down Columbia River, but not across the scablands, produced an ice jam in the narrows where the river crosses the Saddle Mountains anticline, 20 miles farther south (Pl. 1). However, such a jam would detour the Columbia flood not alone back through The Potholes notch but also back through Crater, Frenchman Springs, and Lower Crab Creek. Furthermore, the Saddle Mountains gap is 1¼ miles wide and only a mile long, and at present depth of the narrows the dam there would have to be 500 feet high. Detoured discharge would have to bypass a complete ice blockade by way of Othello Channels at the east end of Saddle Mountains. The lowest and largest of these channels has a floor at about 900 feet A.T. But it is difficult to believe that such a dam ever could exist. This problematical Burke gravel needs further study.

The steep, gullied, but largely soil-cove and caliche-bearing slopes descending into Columbia Valley at the northern end of B cock Ridge (Quincy and Colockum Pass qu rangles) have one great cliffed alcove of more recent origin, recording the 200-foot of glacial water over Crater cataract. Su position of this cliff and alcove on the o topography was accompanied by remaking the gulch into a scabland canyon; Wil Springs Draw, whose floor strangely enoug an aggraded flat 950 feet A.T., hangs al 450 feet above the Columbia, 2¾ miles f the cataract.

The flat is continued out in the Colum valley as a terrace for 1–2 miles on both s of the mouth of the Draw. Composition structure are well exposed in the mouth w the terrace is a puzzling combination of bu

PLATE 9.—GIANT CURRENT-RIPPLE MARKS

FIGURE 1.—Giant current-ripple marks at three levels in Wilson Creek valley a mile above junction Crab Creek. Note how cultivation pattern along contact of grain field with valley bottom bar shows ma tude of ripples. The dark area is a flood-irrigated alfalfa field. Photo AAR-3A-80 of Agr. Adj. Adm.

FIGURE 2.—Staircase Rapids bar. Valley east of the ripple-marked surface was partially blocked by growth, and the tortuous stream meanders are on a silt flat. Drainage pattern east of creek is that of Pa Hills topography. Production and Marketing Adm photo AAP-26-188.

FIGURE 3.—Giant current ripple marks in Snake River valley at mouth of Devils Canyon. Produc and Marketing Adm. photo AAR-9A-11.

PLATE 10.—DRUMHELLER AND POTHOLES DISCHARGEWAYS

FIGURE 1.—Drumheller Channels topography. Looking southward from O'Sullivan Dam. U. S. Bu of Reclamation photo. Px222-117-142.

FIGURE 2.—Northern alcove of The Potholes cataract in 1954. Water is waste and leakage from W Canal about 2 miles distant and 75 feet higher than cataract brink.

Magnitudes involved: Lake in plunge basin is 125 feet deep. Top of bar on north side of alcove is 50 feet above lake surface, 175–200 feet above bottom of plunge pool. Bar fosse largely filled with talus. C back of bar are, including talus, 300 feet high. Scarp of gravel terrace along the Columbia is 150 feet h and its summit is approximately 250 feet above river. Nearer cliff, across which lake discharges, is 150 high above gravel terrace.

Sequences involved: Cataract originated approximately at the near end of the plunge basin. Its t retreat was nearly 2 miles. Tip of the ridge separating the two alcoves is about an eighth of a mile l from the prescabland line of cliffs. Basalt bench below this cliff (part of bench south from Crater catar is gashed by glacial-river chutes, recording cascades rather than cataracts and presumed to be of subflu origin. Gravel of the terrace overlaps a little on scabland of this bench.

Correlations proposed: Gravel terrace has right altitude above the Columbia to be correlative with W Bar and Beverly Bar. The inconspicuous but recognizable, very bouldery, flattish mound buried under gravel is a dump from early cataract retreat, comparable to that at Vantage Bridge. Scabland beneath ter gravel is older than the terrace. Cascade chutes are later than the initial Potholes cataract. They and bar north of the plunge basin may date from a late flood out of Quincy basin. U. S. Bureau of Reclama photo P-222-177-35237

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T[illegible]eep, gullied, but largely soil-covered [illegible] [illegible]he-bearing slopes descending into the [illegible]lumbia Valley at the northern end of Bab[illegible]k Ridge (Quincy and Colockum Pass quad[illegible]ngles) have one great cliffed alcove of far [illegible]re recent origin, recording the 200 foot spill [illegible] glacial water over Crater cataract. Super[illegible]sition of this cliff and alcove on the older [illegible]pography was accompanied by remaking of [illegible]e gulch into a scabland canyon; Willow [illegible]rings Draw, whose floor strangely enough is [illegible] aggraded flat 950 feet A.T., hangs about [illegible]0 feet above the Columbia, 2½ miles from [illegible]e cataract.

The flat is continued out in the Columbia [illegible]lley as a terrace for 1–2 miles on both sides [illegible] the mouth of the Draw. Composition and [illegible]ructure are well exposed in the mouth where [illegible]e terrace is a puzzling combination of buried

[illegible]T-RIPPLE MARKS

[illegible] in Wilson Creek valley a mile above junction with [illegible]f grain field with valley bottom bar shows magni[illegible]cld. Photo AAR-3A-80 of Agr. Adj. Adm.

[illegible]pie-marked surface was partially blocked by bar [illegible]t. Drainage pattern east of creek is that of Palouse [illegible]to. [illegible] P-26-188.

[illegible] at mouth of Devils Canyon. Production

[illegible]OTHOLES DISCHARGEWAYS

[illegible]g southward from O'Sullivan Dam. U. S. Bureau

[illegible]t in 1954. Water is waste and leakage from West [illegible]aract brink.

[illegible] deep. Top of bar on north side of alcove is 50–75 [illegible]unge pool. Bar fosse largely filled with talus. Cliffs [illegible]avel terrace along the Columbia is 150 feet high, [illegible]rater cliff, across which lake discharges, is 150 feet

[illegible]y at the near end of the plunge basin. Its total [illegible]he two alcoves is about an eighth of a mile back [illegible]is cliff (part of bench south from Crater cataract) [illegible]er than cataracts and presumed to be of subfluvial [illegible] of this bench.

[illegible]e above the Columbia to be correlative with West [illegible]e, very bouldery, flattish mound buried under this [illegible] that at Vantage Bridge. Scabland beneath terrace [illegible] than the initial Potholes cataract. They and the [illegible]out of Quincy basin. U. S. Bureau of Reclamation

FIGURE 1

FIGURE 2

FIGURE 3

GIANT CURRENT-RIPPLE MARKS

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986-A

FIGURE 1

FIGURE 2

DRUMHELLER AND POTHOLES DISCHARGEWAYS

986-B

BEST AVAILABLE COPY

FIGURE 1

FIGURE 2

BENCH BETWEEN BABCOCK RIDGE AND COLUMBIA RIVER

986-C BEST AVAILABLE COPY

FIGURE 1

FIGURE 2

FIGURE 3

SCABLAND BARS

986-D

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and semiburied scabland knobs, granitic sand, and scabland basaltic debris, into which postglacial drainage from the Draw has cut a narrow gulch and become superimposed on a buried shoulder of basalt.

The granitic sand, beneath the basaltic debris, is part of a Columbia valley fill not definitely identified farther down stream but conspicuous for miles upstream. There is but little basalt in its well-sorted, uniform material, and it has very few and only thin gravel members. It is a record of a leisurely Columbia's slow aggradation from river level, 550 feet A.T., up to rude terrace tops at 1300 feet A.T. Remnants back in tributary gulches testify to the existence of a valley system of present proportions when it was laid down, clearly in prescabland time. Apparently its dissection was also well advanced when the first flood discharged over Crater cataract.

In contrast is the coarse, very poorly sorted, almost 100 per cent basaltic debris in the same 950-foot terrace, strongly fore-set out of Willow Springs Draw, cobbly and bouldery and unworn to an unusual degree even for scabland torrent deposits. The terrace top does not appear to record a Columbia valley bottom at that time; it seems better interpreted as a later, lateral beveling. The fact that Crater has no empty plunge-pool basin, in contrast with Potholes and Frenchman Springs, strongly suggests that deepening of the two larger notches so decreased Crater's volume that its earlier plunge basin could not be kept flushed out.

The cliffed western side of Babcock and Evergreen ridges is the eastern wall of the Columbia River valley. It carries a great rock bench, locally a mile wide, extending from The Crater southward past both The Potholes and Frenchman Springs cataracts for the full length of the Quincy quadrangle (Pl. 13, fig. 2). The surface of this bench descends from about 1350 feet A.T. at the north to 875 at the south—a structural slope. Its topography is very instructive. Above 1300-1350 feet, the bench has gently rolling surfaces without outcrops, and the cliff overlooking it is only a smoothly sloped, steep hillside, also lacking in outcrops. There is no scabland in the view.

South of this, as far approximately as the crossing of the 1200-foot contour (Quincy quadrangle map), the bench is definitely scabland with buttes and rock basins but very few actual rock outcrops; almost all surfaces are thinly covered with weathered rubble. The cliff above it is talus-covered almost or quite to the summit, and the talus has a soil and vegetation cover (Pl. 11, fig. 1).

South of the 1200-foot contour, the bench is typical, vigorously expressed butte-and-basin scabland, and the cliff is bare, actively growing talus climbing only half to three fourths of its height (Pl. 11, fig. 2).

The bench is held up by the same basalt flow throughout the range of these contrasts, and the only material obscuring any part of its surface is a gravel bar overlapping the southern part of the more subdued scabland and possessing a fosse 20–30 feet deep between it and the cliff talus. It is a lateral accompaniment of the fresher topography. Here is scabland of two different ages.

A small deposit of gravel belonging to the older scabland lies in the west end of a notch across Babcock Ridge (sec. 20, T. 20 N., R. 23 E.) which was not reached by glacial water

PLATE 11.—BENCH BETWEEN BABCOCK RIDGE AND COLUMBIA RIVER

FIGURE 1.—Cliff above older scabland. Looking northeast. Photo by H. T. U. Smith
FIGURE 2.—Cliff above younger scabland. Looking southeast. Photo by H. T. U. Smith

PLATE 12.—SCABLAND BARS

FIGURE 1. C.M. and St. P.R.R. section through Beverly bar, showing foreset bedding composed of boulders. Looking south. Man in photo for scale.

FIGURE 2.—Near Sperry. Foresets dipping into coulee from higher marginal scabland.

FIGURE 3.—North of Harder. Terminal part of "terrace." Skyline and railroad mark horizontality in the view.

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from Quincy basin. It is a bar with convex surface (Pl. 13, fig. 2) about 50 feet above the scabland bench and it blocks the mouth of the notch and detours drainage past it on both sides. A granite cobble was found near the top. Another such deposit has a gravel-pit exposure (near the line between sections 17 and 18) between 1250 and 1375 feet A.T. on the nonscabland northern part of the bench. This deposit is composed largely of mixed basaltic granule gravel and granitic sand but contains considerable rubbly cobble basalt; the fragments are completely angular and much weathered. One fresh granite boulder was found. The pit is on the slope of a small sag (a little below 1350 feet) which became a minor, high-level channel across the nonscabland tract at the height of the earlier flooding of the bench. The locally derived coarse material was already loose, weathered debris, and the granitic sand and bluish-black granule gravel were carried here by the current that bore the berg-floated granite.

The southward slope of the structural bench is about 30 feet to the mile, and its entire surface below 1350 feet was unquestionably swept by the first flood. Did the cataracts out of Quincy basin function at that time?

If the surface gradient of the flooded Columbia was 10 feet to the mile, the cliff now notched by Potholes cataract must have been nearly submerged, and Frenchman Springs cataract could have had no more than 50–60 feet of plunge. A lesser gradient would bring the flood surface even closer to the brink of this southern cataract. Under such conditions, Crater could not have existed. Indeed, if there was no comparable flooding of Quincy basin at that time, the Crater notch must have carried water east into the basin.[16] The cataracts apparently belong to the second episode of flooding when, after a long interval of weathering, older scabland below 1200 feet on the bench was refreshed.

That there was a debris-empty Columbia valley of present depth when the western cataracts operated is clear from exposures made in relocating U. S. Highway 10 from Vantage Bridge to the summit of Frenchman Springs cataract. One now can see most of this splendid, abandoned waterfall from the window of his car. The floor of the cataract alcove is about 875 feet A.T., the Columbia below it is a little above 500. Debris from the cataract making, dumped over into Columbia valley, extends down at least to 600 feet A.T. and is well exposed in the highway's long, diagonal grade across it. Perhaps the most outstanding collection of rejected boulders in any scabland gravel pit occurs at the head of this grade. Their average diameter is 3 feet, a few reach 6 feet. They have been rolled at least a mile from some large-columned flows in the cataract ledges, but many still retain columnar outlines with only bruised, battered, and chipped edges. There is almost no sorting in the pit or highway exposures and no aggregation of boulders into strata. What rude stratification does exist is that of long fore sets dipping toward and down into Columbia Valley. A confirmed skeptic is likely to try to make this deposit a talus!

It may well be that no one short-lived flood could have made all these cataract scars. Certainly no flood of the magnitude recorded could be more than short-lived. However, it is almost certain that the cataracts were contemporaneous, and surely no river of moderate size is recorded by the double Potholes cataract, 1½ miles wide. The debris spilled into the Columbia at Frenchman Springs is not a record of many centuries of slow cataract retreat. The way the lip of Potholes breaks into a series of smaller chutes (AAR-8F-194 and 195, also U.S.B.R. 10-foot contour map) is evidence that the last discharge over this cataract was of lessened volume. This may record the shrinking last stages of a flood or a later, smaller flood. But it was the last discharge over Frenchman Springs' southern cataract that dumped the great rubble into a debris-empty Columbia Valley.

Moses Coulee

Maps: Malaga quad., U.S.G.S.

(Bretz and Neff)

Moses Coulee, second only to Grand Coulee in magnitude, enters Columbia valley only a

[16] Since the field study by the three authors, Neff has found a mounded bouldery deposit exposed in West Canal sections at the head of the Crater cataract channel (SE¼ Sec. 14, T. 20 N., R. 23 E.) which contains slightly bruised columnar fragments 7 feet long in a largely unsorted gravel of caliche, basalt, interflow siltstone, and intact masses of loess. He feels that this deposit records an eastward flow through the Crater notch at some time previous to the last discharge westward.

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Springs quad., U.S.G.S.

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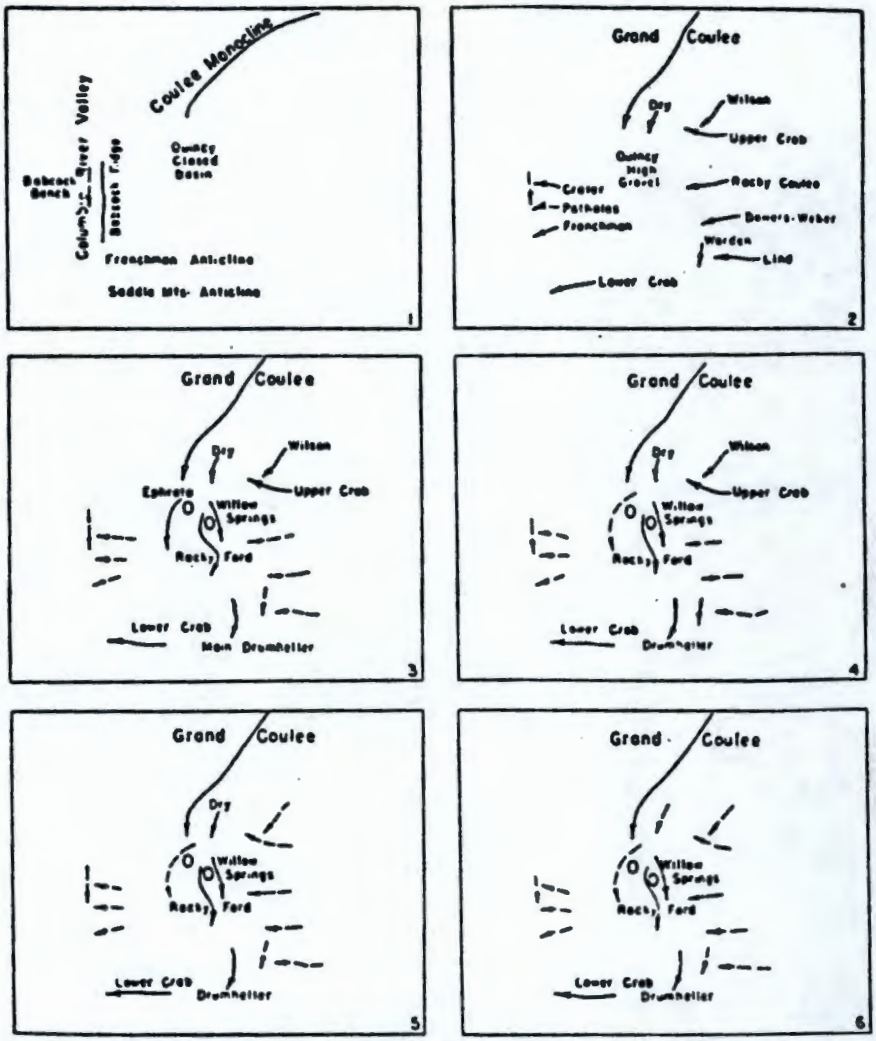

FIGURE 9.—SEQUENCE IN CHANNEL OPERATION, QUINCY BASIN AND ENVIRONS

few miles upstream from Crater cataract (Pl. 1). Although its headward connections with the rest of the plateau scabland complex are largely concealed by deposits of the latest Okanogan lobe to cross the Columbia, there is fair evidence of a scabland surface at about 2400 feet A.T. beneath the drift as far south as the coulee head, but no farther. The well-developed terminal moraine of this lobe blocks Moses Coulee at the crossing (10 miles from the head) with hills half as high as the coulee is deep, and associated outwash gravel extends down-coulee for a few miles in valley-train fashion. The great coulee, therefore, already existed in essentially full development before this latest glacial transgression on the plateau and must predate the later events in Grand Coulee history.

At the debouchure of Moses Coulee into the Columbia valley are remains of an enormous deposit of very little-worn boulders, sand, and gravel, nearly all basalt; its fore-set structure indicates a once-complete blockade of the

greater valley. Presumed moraine topography just upstream from this blockade and on the same side of the river appears to record contemporaneous glacial ice in Columbia valley. Bretz (1930b, p. 381) has suggested that this was made by a Wenatchee Valley glacier pushing out into Columbia valley. But Page (1939) has since shown that any such glacier must date further back than the late Wisconsin advance of the Okanogan lobe, and its drift should show pronounced weathering, a feature it does not possess. Its debris, furthermore, is essentially all basalt. Perhaps it is a record of ice blocks floated down from a breakup of the Okanogan lobe. The early Columbia valley flood recorded on the bench west of Babcock Ridge probably entered the master valley via Moses Coulee.

Correlation of Events and Sequences thus far Presented

(Bretz, Smith, and Neff)

Inspection of Plate 1 and Figure 4 shows that, during and after the episode which saw Ephrata channel eroded, water had ceased to reach the three western cataracts. A provisional chronology from data thus far submitted therefore would include (Fig. 9):

(1) The earliest flooding on the Babcock bench, apparently before Grand Coulee had been initiated

(2) The earliest recorded plateau flooding (because of an early Okanogan lobe dam) with
  (a) Operation of Grand Coulee and Crab Creek glacial rivers,
  (b) Cataract making at the three western spillways,
  (c) Deposition of the high gravel of Quincy basin,
  (d) Operation of Black Rock, Rocky, Bowers-Weber, and Lind coulees,
  (e) Beginnings at Warden cataracts of the Drumheller spill across the nose of Frenchman Hills anticline.

(3) The flood which initiated the three channels across Quincy basin and today is recorded only by the Ephrata channel (the three western cataracts and the four eastern coulees then abandoned; Drumheller deepened)

(4) The flood which used only Rocky Ford and Willow Springs channels, and continued the deepening of Drumheller Channels (Upper Crab Creek still functioning)

(5) The last flood down Grand and Dry coulees, making the Upper Crab Creek dam and adjacent Dry coulee bar (Steamboat Falls destroyed, Bacon syncline's western notch left hanging, all scabland channels, east of Grand Coulee abandoned)

(6) The final flood down Grand Coulee alone which completed the great Dry Falls cataract and Soap Lake basin and used both the Willow Springs and Rocky Ford channels.

The vertical succession of bars in Wilson Creek valley should date from the second, third, and fourth floods, because deepening of the channels across the Quincy basin fill permitted trenching back up Crab Creek and because at stage 5 Crab Creek valley was blockaded by Dry Coulee gravel. A seventh flood is recorded by the Beverly bar at the junction of Lower Crab Creek and Columbia River.

Lower Crab Creek

Maps: Beverly, Boylston, Corfu, Othello, and Smyrna; U.S.G.S.; R4-5720, sheet 2; U.S.B.R.

(Bretz, Smith, and Neff)

Discharge across the nose of Frenchman Hills (site of Drumheller Channels) entered an east-west synclinal valley between this anticline on the north and Saddle Mountains anticline on the south (Pl. 1). The syncline deepens and broadens eastward from the Columbia to the Channels; descent of the surface of the basalt along its axis is about 250 feet in 27 miles. The Bureau of Reclamation terms this eastern low broadening the Othello basin. The scarps in superbasalt sediments bounding Drumheller Channels continue westward along the syncline for some miles and make it clear that Othello basin was still largely filled when the earliest scabland flood arrived. The top of the basalt lay so low in the center of the basin that it escaped the terrible treatment meted out to that upraised in the Channels area. There is a plane tract of several square miles in the bottom

greater valley. Presumed moraine topography just upstream from this blockade and on the same side of the river appears to record contemporaneous glacial ice in Columbia valley. Bretz (1930b, p. 381) has suggested that this was made by a Wenatchee Valley glacier pushing out into Columbia valley. But Page (1939) has since shown that any such glacier must date further back than the late Wisconsin advance of the Okanogan lobe, and its drift should show pronounced weathering, a feature it does not possess. Its debris, furthermore, is essentially all basalt. Perhaps it is a record of ice blocks floated down from a breakup of the Okanogan lobe. The early Columbia valley flood recorded on the bench west of Babcock Ridge probably entered the master valley via Moses Coulee.

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(3) The flood which initiated the three channels across Quincy basin and today is recorded only by the Ephrata channel (the three western cataracts and the four eastern coulees then abandoned; Drumheller deepened)

(4) The flood which used only Rocky Ford and Willow Springs channels, and continued the deepening of Drumheller Channels (Upper Crab Creek still functioning)

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Lower Crab Creek

Maps: Beverly, Boylston, Corfu, Othello, and Smyrna; U.S.G.S.; R4-5720, sheet 2; U.S.B.R.

(Bretz, Smith, and Neff)

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of the syncline near Corfu where the original basalt surface, although denuded, was not eroded.

Lower Crab Creek, after passing southward through Drumheller Channels' lowest gash, turns westward and follows this syncline, against the pitch, to the Columbia, descending about 100 feet in 25 miles. West of the Corfu flat, the syncline has well-developed scabland all the way. Some features of this glacial river channel deserve examination with reference to Allison's theory of ice jams.

One of these features is Natural Corral (Smyrna, formerly Red Rock, quadrangle). Another (shared by the Smyrna and Beverly quadrangles) may be called the Jericho coulee (Fig. 10). Both are accessory lateral canyons semiparallel to Crab Creek with looped courses back in higher scabland slopes along the north side of the synclinal valley. On the maps they look like detours for bypassing short, wide ice jams. But neither one has an eastern (upstream) connection with the main channel comparable to the remainder of the "run-around" canyon, and at neither place is there any narrowness, shallowness, or crookedness in the main valley favorable for initiating and maintaining an ice jam. Furthermore, the Natural Corral lateral canyon is only 3 miles long, allowing for only a short jam in Crab Creek, apparently too short, like Saddle Mountains gap, to provide the frictional locking of ice on ice and on shore to maintain a dam for the many years required if a moderately proportioned glacial river eroded the Corral canyon.

The Jericho lateral canyon (Fig. 10) is tandem, its total length of 9 miles almost completely broken in two in midlength by the disappearance there of the south retaining wall. Its floor at this breakdown is 60 feet above Crab Creek a mile to the south, yet its ephemeral drainage fails to find the gap and goes on west, parallel to Crab Creek, to end in a closed depression only 13 feet above the creek. This closure is due to Columbia River's Beverly bar, a late feature once entirely blocking the Crab Creek valley mouth, and dealt with in a later paragraph.

Two sequential ice jams therefore would be required for making the Jericho tandem canyon a "run-around". What should be the field evidence, other than mappable forms, to support the ice-jam theory? Allison (1941, p. 673) cited "The dozens of piles of iceberg-rafted till on the northeast flank of Rattlesnake Hills and in Cold Creek valley" as proof that great quantities of bergs reached the wide Pasco basin. They, with isolated berg "nests" and lone erratic boulders in so many places in the scablands, are irrefutable evidence for abundant floating glacial ice (*see* Bretz, 1930b, p. 410, Fig. 7) and, where closely spaced, are equally good evidence for the grounding of large numbers of these bergs. In Pasco basin, they obviously drifted ashore in a wide semiponded tract. If densely packed in a narrow valley, there should be at least as good a record.

With this criterion in mind, the two broadest and flattest butte tops enclosed by these looped lateral canyons were traversed. Not one erratic was found, nothing but bare or nearly bare basalt. Berg ice never made an ice jam along this scabland route. River ice, also used by Allison and favored by Lupher (1944, p. 1493) for damming and detouring glacial streams, would inevitably trap many of the abundant bergs, and a marginal record of this should survive.[11]

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Lower Crab Creek, after passing southward through Drumheller Channels' lowest gash, turns westward and follows this syncline, against the pitch, to the Columbia, descending about 100 feet in 25 miles. West of the Corfu flat, the syncline has well-developed scabland all the way. Some features of this glacial river channel deserve examination with reference to Allison's theory of ice jams.

One of these features is Natural Corral (Smyrna, formerly Red Rock, quadrangle). Another (shared by the Smyrna and Beverly quadrangles) may be called the Jericho coulee (Fig. 10). Both are accessory lateral canyons semiparallel to Crab Creek with looped courses back in higher scabland slopes along the north side of the synclinal valley. On the maps they look like detours for bypassing short, wide ice jams. But neither one has an eastern (upstream) connection with the main channel comparable to the remainder of the "run-around" canyon, and at neither place is there any narrowness, shallowness, or crookedness in the main valley favorable for initiating and maintaining an ice jam. Furthermore, the Natural Corral lateral canyon is only 3 miles long, allowing for only a short jam in Crab Creek, apparently too short, like Saddle Mountains gap, to provide the frictional locking of ice on ice and on shore to maintain a dam for the many years required if a moderately proportioned glacial river eroded the Corral canyon.

The Jericho lateral canyon (Fig. 10) is tandem, its total length of 9 miles almost completely broken in two in midlength by the disappearance there of the south retaining wall. Its floor at this breakdown is 60 feet above Crab Creek a mile to the south, yet its ephemeral drainage fails to find the gap and goes on west, parallel to Crab Creek, to end in a closed depression only 13 feet above the creek. This closure is due to Columbia River's Beverly bar, a late feature once entirely blocking the Crab Creek valley mouth, and dealt with in a later paragraph.

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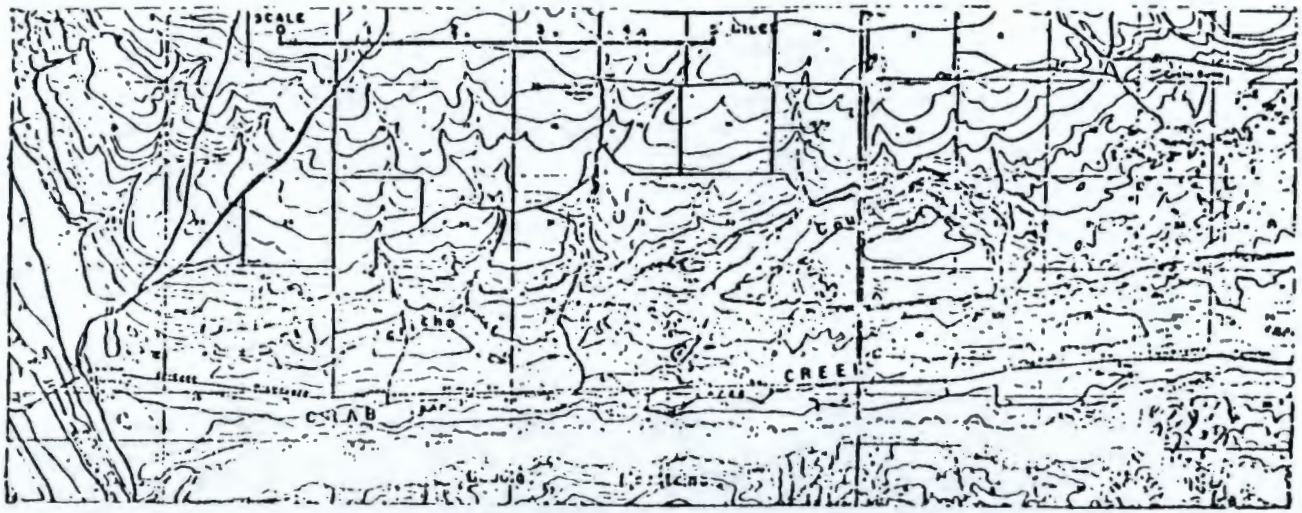

FIGURE 10.—LOWER CRAB CREEK AND JERICHO COULEE
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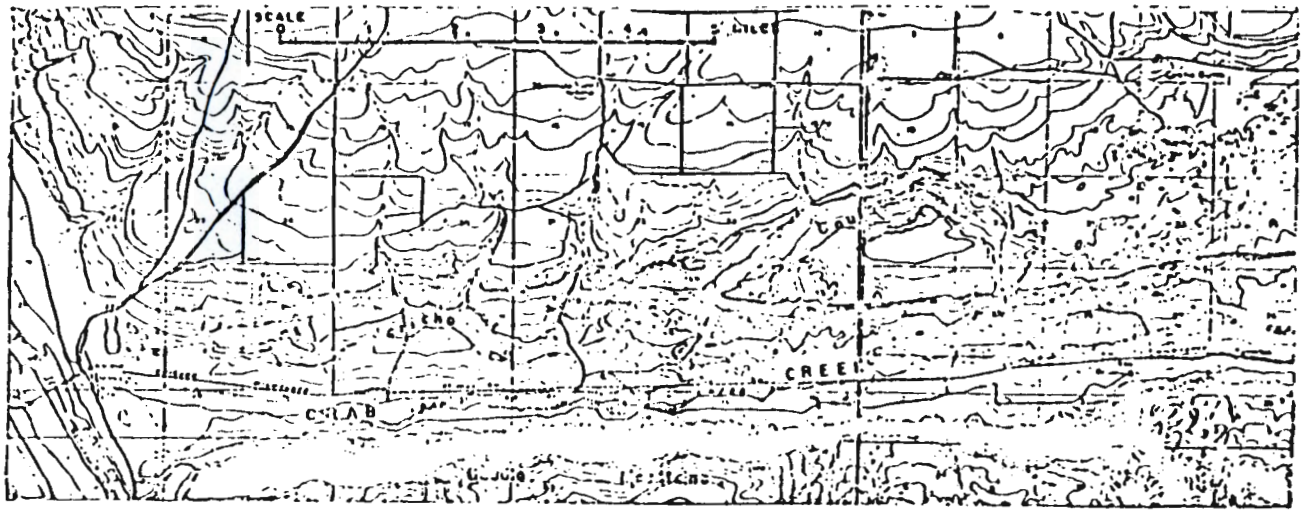

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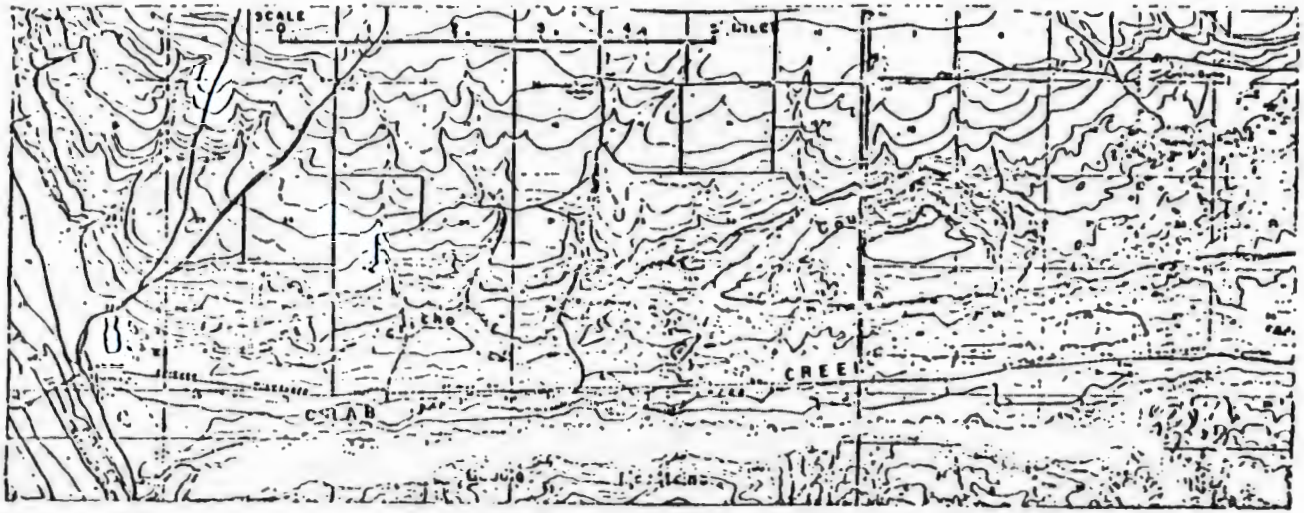

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The Beverly bar (Fig. 11) is defended by scabland at the upstream angle between the Columbia River and Crab Creek and originally made a dam across the mouth of the creek valley. Its proximal end is 125 feet above the Columbia and almost 100 feet above the sump in which the Jericho lateral canyon terminates. Its linear form narrows and lowers southward for 1½ miles. It is actually made of two parallel bar ridges with a linear closed depression almost a mile long between them. Silts on the floor of Crab Creek valley prove that the creek was ponded by the bar. The creek has since cut a narrow ravine 40 feet deep across the low southern end of the deposit.

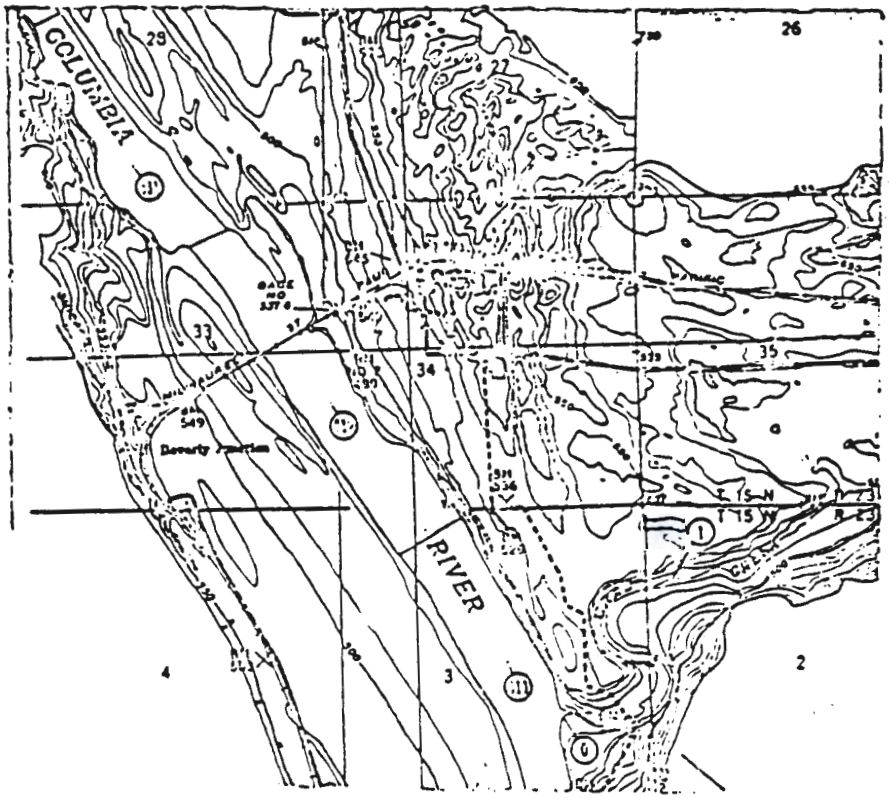

FIGURE 11.—BEVERLY BAR

Mouth of Crab Creek glacial river channel. Part of "Columbia River Priest Rapids to Rock Island Dam, Washington" map. U. S. Geol. Survey, U. S. Bureau of Reclamation and State of Washington. Contour interval on land 10 feet.

Composition and structure of the bar are well shown in a railroad cut nearly 30 feet deep across the higher, northern part. The western ridge is made of much coarser material than the eastern one. The riverward slope is almost wholly of boulders 3–6 feet in diameter. The body of this ridge shows long, lee (eastward) foresets, some of them almost entirely of be

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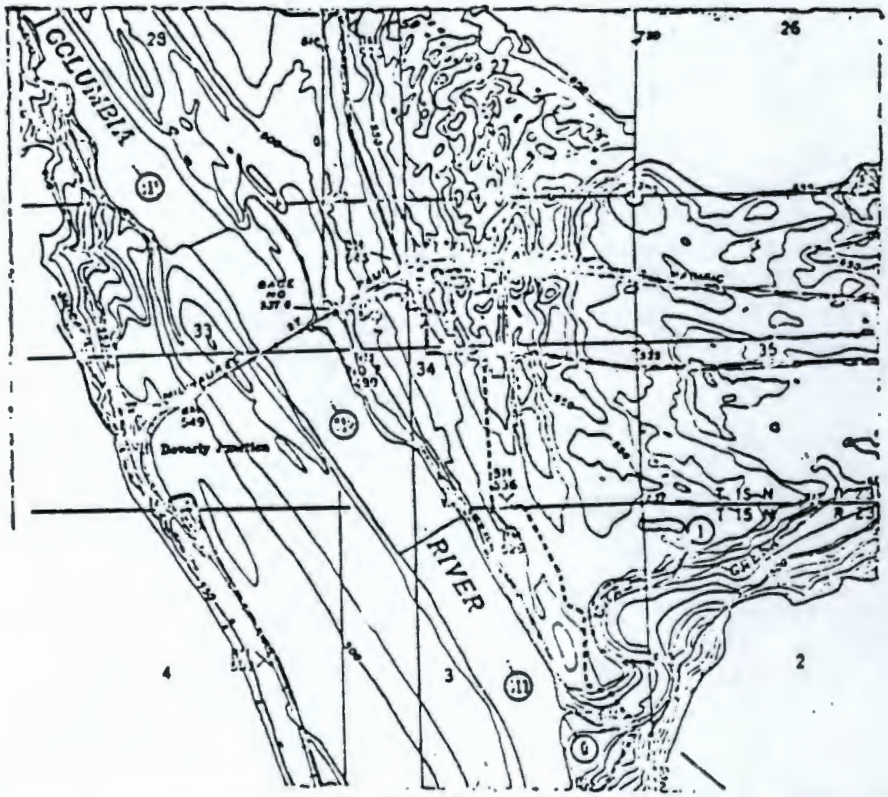

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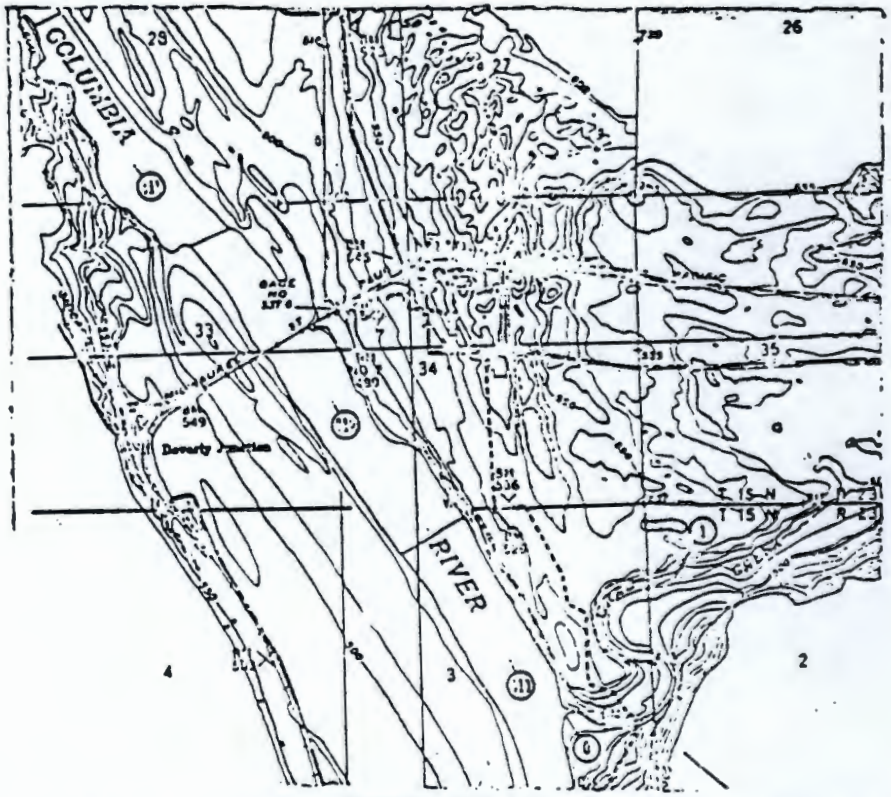

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The Beverly bar is nearly 30 miles downstream from the giant current ripples on West Bar (nearly opposite Crater cataract, Pl. 1; Bretz, 1930b, p. 400) whose altitudes range from 150 to 250 feet above the Columbia and up to 750 feet A.T. The giant ripples and the bar are probably contemporaneous.

The Beverly bar is 20 miles south of Potholes cataract, and its top is about 600 feet lower than the aberrant, east-dipping gravel near Burke. If the two gravel deposits, each recording a greatly flooded Columbia after the plateau glacial rivers had ceased to flow, were contemporaneous, and if the Columbia then had a surface gradient of 10 feet to the mile, water was 400 feet deep over the top of this bar. The two deposits are not necessarily of the same age, but there is no reasonable alternative explanation for the origin of the Beverly deposit. Saddle Mountains gap could not have been blocked when it was made. Because the bar was built after the last functioning of Lower Crab Creek glacial river, this Columbia flood must postdate the last of Grand Coulee's discharge. It is to be added to the floods previously listed, and perhaps to be correlated with the break-up of the Okanogan lobe dam described by Waters (1933, p. 763–820).

The morainelike topography in Columbia valley just upstream from remains of the Moses Coulee blockade is between 275 and 300 feet above the river, not too high to be correlated with the Beverly bar deposit and the West Bar current ripple marks.

One may best visualize the excessive erosion along Lower Crab Creek by comparing the character of Saddle Mountains and its adjacent syncline east of the Columbia (Beverly and Smyrna quadrangle maps) with that west of the Columbia (Boylston quadrangle map). The altitudes of the anticlinal summit and of the top of the basalt in the syncline on both sides of the river are about the same; the relief approximates 1300–1500 feet. Along Lower Crab Creek, glacial-stream erosion has bitten a channel into the basalt a mile wide on the bottom (far in excess of the creek's needs), whereas west of the river local drainage along the syncline has made only a narrow, V-shaped gulch (Johnson Creek) a third of a mile wide at the top.[18] The Chicago, Milwaukee and St. Paul railroad, crossing the Columbia 550 feet A.T. (bridge altitude), follows the floor of Lower Crab Creek channel eastward to climb only 200 feet in 20 miles. On the west side of the river, this railroad climbs nearly 500 feet (in a long diagonal) to get to the synclinal floor on basalt only 2 miles in a direct line from the river.

The steeply tilted and possibly faulted north face of the Saddle Mountains anticline west of the river is as well aligned as the east side. Rock outcrops and growing talus are almost completely lacking on this scarp. A cover of soil and vegetation mounts to the summit. Short gulches furrow the slope, but they show few if any outcrops. The debris-covered front descends with gradually decreasing slope, making a conspicuous concave profile. At the summit, this slope passes in most places without a break into a smooth, convex profile over the top.

East of the Columbia, the northern face of Saddle Mountains is cliffed above an actively growing talus which in places has mounted only half way to the summit, 1500–2000 feet above Crab Creek Channel floor. The talus extends to the bottom of this channel and has no concave profile. Locally, landslide is a marked feature of the front. A slide 4 miles wide between Corfu and Taunton (Corfu quadrangle) extends from the bottom of the scarp to the very top, 1¼ miles in the horizontal and 1200 feet vertically. There is no suggestion of slides west of the river; no undercutting by a great glacial river occurred there.

Although no field evidence is known to support the idea, the Taunton-Corfu slide may have been a factor in initiating the Othello Channels divergence (Pl. 1). If so, an under-

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The Beverly bar is nearly 30 miles downstream from the giant current ripples on West Bar (nearly opposite Crater cataract, Pl. 1; Bretz, 1930b, p. 400) whose altitudes range from 150 to 250 feet above the Columbia and up to 750 feet A.T. The giant ripples and the bar are probably contemporaneous.

The Beverly bar is 20 miles south of Potholes cataract, and its top is about 600 feet lower than the aberrant, east-dipping gravel near Burke. If the two gravel deposits, each recording a greatly flooded Columbia after the plateau glacial rivers had ceased to flow, were contemporaneous, and if the Columbia then had a surface gradient of 10 feet to the mile, water was 400 feet deep over the top of this bar. The two deposits are not necessarily of the same age, but there is no reasonable alternative explanation for the origin of the Beverly deposit. Saddle Mountains gap could not have been blocked when it was made. Because the bar was built after the last functioning of Lower Crab Creek glacial river, this Columbia flood must postdate the last of Grand Coulee's discharge. It is to be added to the floods previously listed, and perhaps to be correlated with the break-up of the Okanogan lobe dam described by Waters (1933, p. 763–820).

The morainelike topography in Columbia valley just upstream from remains of the Moses Coulee blockade is between 275 and 300 feet above the river, not too high to be correlated with the Beverly bar deposit and the West Bar current ripple marks.

One may best visualize the excessive erosion along Lower Crab Creek by comparing the character of Saddle Mountains and its adjacent syncline east of the Columbia (Beverly and Smyrna quadrangle maps) with that west of the Columbia (Boylston quadrangle map). The altitudes of the anticlinal summit and of the top of the basalt in the syncline on both sides of the river are about the same; the relief approximates 1300–1500 feet. Along Lower Crab Creek, glacial-stream erosion has bitten a channel into the basalt a mile wide on the bottom (far in excess of the creek's needs), whereas west of the river local drainage along the syncline has made only a narrow, V-shaped gulch (Johnson Creek) a third of a mile wide at the top.[10] The Chicago, Milwaukee and St. Paul railroad, crossing the Columbia 550 feet A.T. (bridge altitude), follows the floor of Lower Crab Creek channel eastward to climb only 200 feet in 20 miles. On the west side of the river, this railroad climbs nearly 500 feet (in a long diagonal) to get to the synclinal floor on basalt only 2 miles in a direct line from the river.

The steeply tilted and possibly faulted north face of the Saddle Mountains anticline west of the river is as well aligned as the east side. Rock outcrops and growing talus are almost completely lacking on this scarp. A cover of soil and vegetation mounts to the summit. Short gulches furrow the slope, but they show few if any outcrops. The debris-covered front descends with gradually decreasing slope, making a conspicuous concave profile. At the summit, this slope passes in most places without a break into a smooth, convex profile over the top.

East of the Columbia, the northern face of Saddle Mountains is cliffed above an actively growing talus which in places has mounted only half way to the summit, 1500–2000 feet above Crab Creek Channel floor. The talus extends to the bottom of this channel and has no concave profile. Locally, landslide is a marked feature of the front. A slide 4 miles wide between Corfu and Taunton (Corfu quadrangle) extends from the bottom of the scarp to the very top, 1¼ miles in the horizontal and 1200 feet vertically. There is no suggestion of slides west of the river; no undercutting by a great glacial river occurred there.

Although no field evidence is known to support the idea, the Taunton-Corfu slide may have been a factor in initiating the Othello Channels divergence (Pl. 1). If so, an under-

[10] Johnson Creek has been working through all post-deformation time. Lower Crab Creek, up to the time of diversion of glacial water down Grand Coulee, appears to have been scarcely larger than Johnson.

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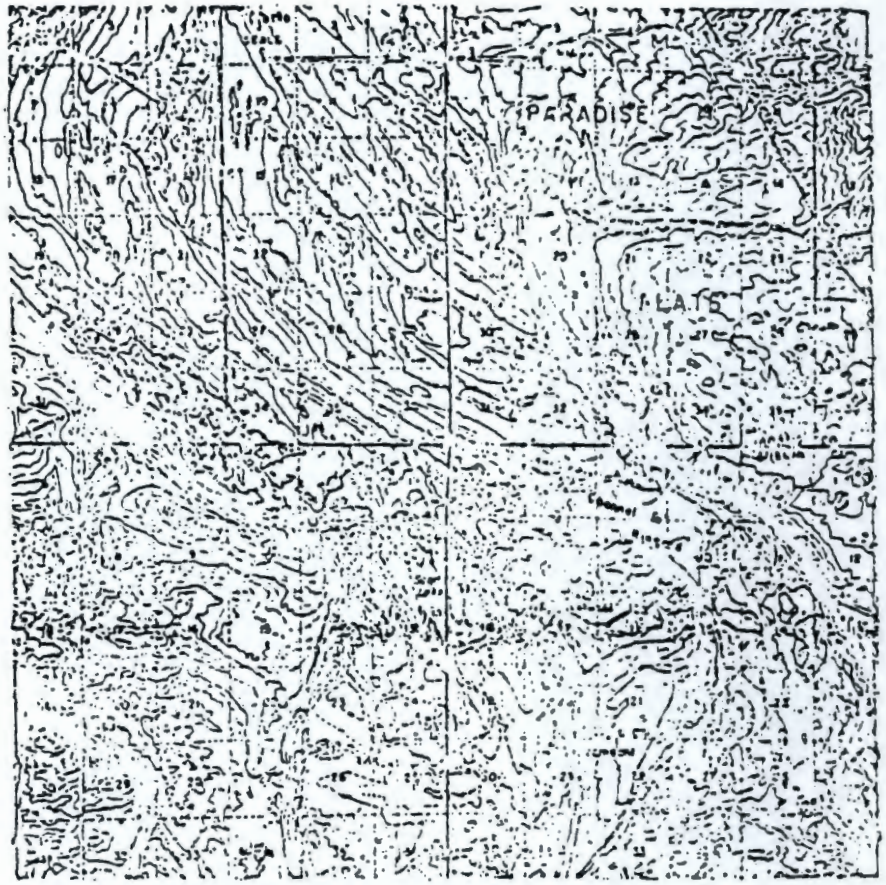

FIGURE 12.—MAP OF OTHELLO CHANNELS
Interval for continuous contours 10 feet, for dashed contours 25 feet. From U. S. Bureau of Reclamation topographic map R4-5720, sheet 2.

cutting of the mountain front by an earlier flood down Crab Creek alone seems required.

OTHELLO AND KOONTZ COULEE CHANNELS

Maps: Connell, Eltopia, Hanford, Othello and Scooteney Lake, U.S.G.S.; R4-5720, sheets 2 and 3; U.S.B.R.

(Bretz, Smith, and Neff)

Two groups of glacial-river channels lead south and southwest from Othello basin (Pl. 1); the Othello group (Fig. 12), crosses the axis of the Saddle Mountain anticline (much as Drumheller Channels cross the Frenchman Hills fold), and the distributary Koontz group (Fig. 17) crosses farther southwest, traversing a plain of sedimentary rock (Ringold formation) to reach the Columbia valley in the Pasco basin. They carried water from Quincy basin that failed to follow the Lower Crab Creek channel. The crossing was made at the eastern low terminal portion of the anticline and was initiated on a cover of sedimentary rock, in part folded but more largely of unfolded Ringold. Deep trenching into the deformed basalt flows beneath has made part of Othello Channels almost as wild

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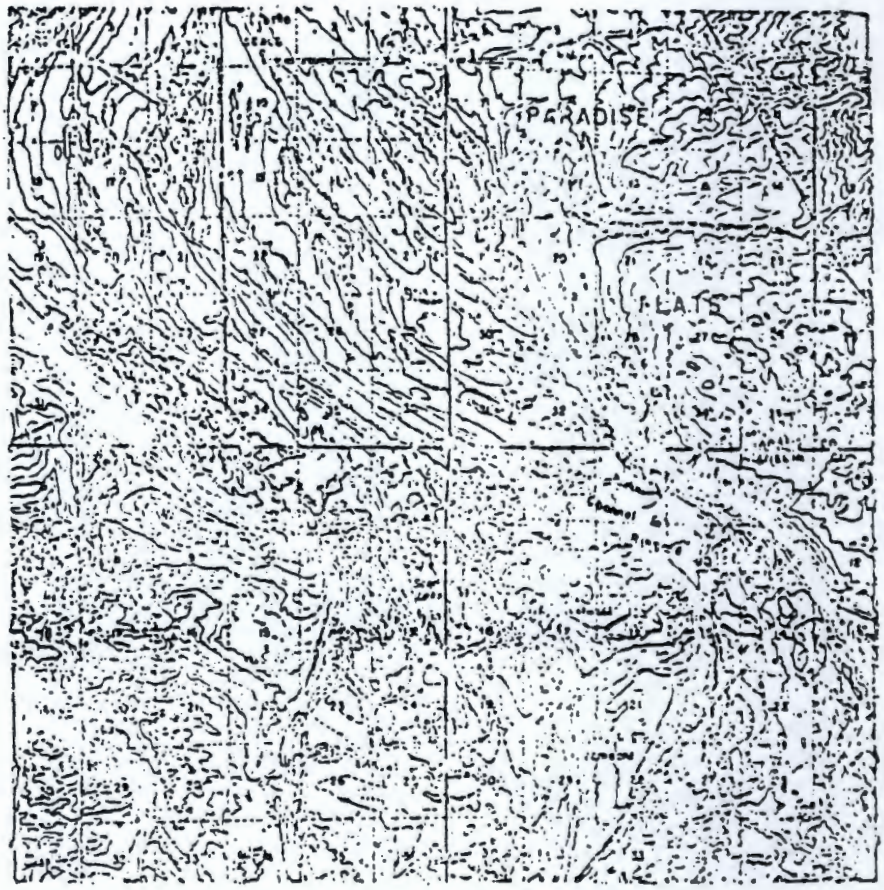

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a scabland topography as Drumheller, although only a third as wide and a fourth as long.

The outstanding rock basin of Othello Channels, containing Scooteney Lake in the bottom (Scooteney Lake map), has a closure of 135 feet.[10] Like Drumheller, Othello Channels has a scarped residual hill of the once-overlying sedimentary rock, more than a mile across and its summit nearly 200 feet above the highest adjacent basalt scabland. East of this hill, Othello's largest channel is a mile wide and 100 feet deep in the sediments but is floored by basalt (Fig. 12).

East of Othello Channels is a plain a few miles wide determined by the flat-lying Ringold formation and constituting a prominent topographic feature from Warden 20 miles south to Connell (Pl. 1). The plain (Paradise Flats) overlooks glacial drainage channels from the Warden cataracts to Washtucna Coulee. The west-facing scarp is almost continuous from Lind Coulee to Esquatzel Coulee, and its base descends 200 feet in 20 miles.

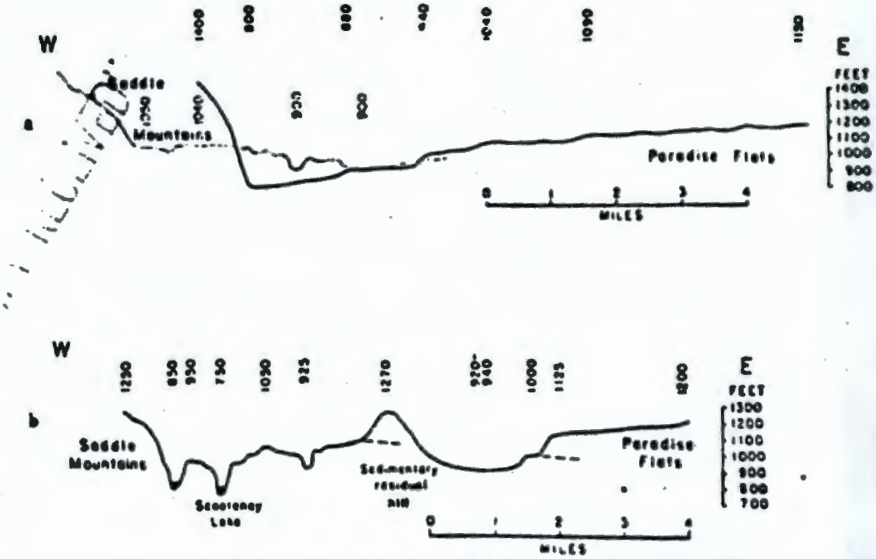

FIGURE 13.—PROFILES ACROSS OTHELLO CHANNELS

Looking north. a—Northeast-southwest profile across head of Channels, showing four successive channel floors. Taunton-Anson terrace profile, dotted, drawn for a parallel cross section 2¾ miles farther northwest. b—Nearly east-west profile where Channels transect Saddle Mountains anticline. About 7 miles southeast of section in Figure a.

The northernmost 8 miles of Othello Channels divergence (Othello quadrangle map) lies in the Othello basin where the record is largely in broad trenches without basalt scabland but with abundant evidence of the magnitude and transporting ability of the glacial discharge. Here four distinct, successive, terracelike channel-floor levels, separated by scarps, are recognizable in the field and on the Bureau of Reclamation contour map R4-5720, sheet 2 (Figs. 12, 13), each younger one trenched into the bottom of the immediately earlier one. All these channels shifted southwestward, in the plane of the cross section. The youngest, still intact and full of undrained depressions, has *no continuous gradient* of its bottom for its 8 miles of length. A little farther north, a remnant of the highest channel floor, the Taunton-Anson terrace, lies against the face of the mountain (secs.

[10] When the irrigation project is completed, this rock basin will be filled to its northern sill, 820 feet A.T. with a minor reservoir, and a channel in the southern and higher rim will be excavated 70 feet in maximum depth for 1200 feet through basalt to lead that water southward. Bottom water in the Othello glacial river here flowed 200 feet *uphill* for that distance, yet continued to pluck basalt from the channel bottom and carry it away.

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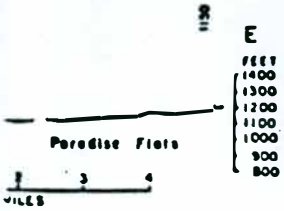

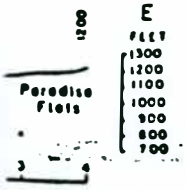

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10, 11, 14, 15, T. 15 N., R. 28 E.) and drops off 100-150 feet directly to the bottom of the lowest channel. This terrace is surfaced with at least 28 feet of gravel and boulders.

These channel floors are strewn with boulders. Excavators found basalt blocks so large that, even with modern equipment, the boulders could not be moved without blasting. They must have come from Drumheller, travelling across the sedimentary rock then flooring Othello basin for 10 miles on a gradient of about 15 feet to the mile. Not one of the channel terraces records a leisurely river of moderate size.

Another significant feature of this broad, headward part of the Othello divergence is a low, linear gravel mound a little above 1110 feet A.T. margining a part of Paradise Flats on the brink of its western scarp. A mile east of Othello town two active pits in it showed almost no boulders of basalt but many of caliche. The gravel is fore-set-bedded and dips dominantly southeastward diagonally away from the highest channel, at the top of whose bluff it lies. Immediately east of this deposit, the Flats have caliche in place to the grass roots. This gravel constitutes a channel-margin bar, a kind of natural levee, like the one southeast of Moses Lake town and is, insofar as known, the highest record of glacial water using Othello's scabland channels. The descent from the brink of Warden cataract to this place is 14 feet per mile. However, the surface gradient of the river probably was greater because the first altitude is on a channel floor, the second is a channel-margin record. Absence of basalt boulders suggests that the levee bar antedates excavation in basalt at Warden cataracts.

This complex of channels across the eastern tip of the Saddle Mountains anticline (Fig. 12), composed of three western, canyonlike, parallel slots cut in basalt and one mile-wide, equally deep eastern channel eroded largely in weak sedimentary rock (Scooteney Lake quadrangle map), poses a problem of origin and succession in development. Only if the preglacial surface of the sedimentary cover at the site of the Channels were lowest where the narrow notches developed would any such gashes in basalt be made. Only if glacial water demanded greater width than the 3 miles across the basalt portion or if these gashes were choked with ice would discovery of the soft-rock route occur. But by the time this happened the deep, slotlike canyons and rock basins were essentially complete. Downstream sills of two of them are but 10 and 30 feet higher than the basalt floor of the soft-rock channel and one is 50 feet lower.[19] No detailed succession of repeated floods through Othello is determinable at present, but probably the basin had no preglacial outlet and Lower Crab Creek glacial channel must date from the inception of Othello Channels.

In the lee of the isolated hill in the middle of the Othello group is a barlike mound, tapering to a point about 4 miles farther south (Fig. 12). It has a core of Ringold but is heavily veneered with scabland gravel. Its mapped surface has the same suggestive A's as are shown in the co[illegible]s of the Bureau of Reclamation topogr[illegible] map for the hills separating the three Quincy basin channels. They indicate subfluvial molding by a current crossing diagonally southwestward from overflow out of the eastern channel. After molding came the scarping and possibly 100 feet of channel deepening on each side to make the taper form. The deposit may be comparable in origin to the high gravel remnant in Bacon syncline.

Beyond the end of this barlike form, all Othello channels become one, the Ringold having been swept off the basalt for a width of 10 miles and a cover of gravel left, interrupted by a few minor scabland tracts. About 10 miles south of the isolated hill, this wide, stream-swept tract breaks up into separate channelways with flat-topped, steeply scarped, prow-pointed, isolated hills of Ringold separating them. Jackass Mountain (Eltopia quadrangle) is the southernmost of these residual elevations which divided the Othello Channels discharge, part going southwestward into the Koontz Coulee group and part southeastward into Esquatzel Coulee, but both eventually reaching Pasco basin (Pl. 1).

The Koontz Channels (Fig. 17; Pl. 1) consist of two groups, one with channel heads as much as 200 feet higher than, and truncated by the scarps of, those of the lower group. This truncation records at least two episodes of glacial-

[19] One must be on his guard in dealing with bottom gradient of these unconventional giant rivers. This 50-foot lower, downstream sill must be balanced against an upstream sill 50 feet higher than the soft-rock channel head.

river discharge out of Othello Channels and across the Ringold plain.

Yet these higher Koontz channels do not record the earliest glacial discharge across this plain. Streams that made no channels left a widespread mantle of boulderless caliche and basalt sand and gravel, containing granite, quartzite, and Ringold pebbles, and overlying caliche *in situ*, 50 feet or more above the floors of the highest Koontz channels. On the summit of White Bluffs, overlooking the Columbia 500 feet below (in T. 10 and 11 N., R. 28 and 29 E.), this glacial stream debris is fore-set-bedded, dipping up to 15° S. and SE. Its altitude, 900 feet A.T., is only 200 feet lower than the natural levee east of Othello town, nearly 25 miles upstream. The bedding and mantle character prove that berg transportation was not involved. Was this earliest record on the Ringold plain made by ordinary meltwater streams? Is it to be grouped with the high gravel of Bacon syncline, the unchanneled, boulderless sand and granule gravel in western Quincy basin, and the fine gravel apparently underlying the marked bars in Washtucna Coulee? Is it possibly preflood outwash?[21] Did it come from a completely filled Washtucna instead of Othello?

The featureless flat traversed by the Potholes East Canal (Fig. 17; Pl. 1) 2 miles west of Mesa (Scooteney Lake quadrangle) has a southward slope and, on the Bureau of Reclamation contour map, carries numerous A's of contour loops like those in Quincy basin. The flat is covered with about 10 feet of very coarse gravel containing many 1- to 2-foot boulders and locally overlying remnants of Ringold. This gravel came from Othello Channels and was carried at least 5 miles on a gradient of about 20 feet to the mile without the development of channels or bars. It seems that the near-by channels in basalt and Ringold did not then exist and that the flood water was too heavily laden to do any deepening on this gradient. Correlation of this flat with some of the higher, hanging Koontz channels seems feasible and would place it in the record of the second discharge out of Othello. If correct, there was no open Washtucna-Esquatzel Coulee at that time. Probable Ringold sediments beneath scabland gravel in lower Washtucna indicate that the plateau drainage system was well developed in basalt before Ringold deposition. This part of the pre-Ringold Washtucna-Esquatzel Coulee may have been still unexhumed when this second glacial discharge took place. Or it may have held a normal outwash of preflood age. Re-excavation came after deposition of the gravel cap on the flat west of Mesa and was effected by glacial flood water. Scabland channels were also initiated in later stages of this second flooding although most of them were deepened during later floods. Younger bars superposed on older bars in Esquatzel, described in later paragraphs, require at least a fourth flood.

The northernmost Koontz channel does not reach the Columbia. It opens westward on a Ringold plain at about 800 feet A.T. (Hanford quadrangle map) which descends to 700 feet 4 or 5 miles farther west and there terminates in the White Bluffs summit (Fig. 17) 300 feet above the river. This channel has a small distributary hanging about 75 feet higher at both ends; therefore it is not to be explained as a shallower contemporaneous spillway.

These channels differ from all others of the group in failing to reach the Columbia bluffs. Lack of channeling across the intervening plain indicates that a Columbia flood covered the flat when they functioned.

All other Koontz channels reach the bluff summits a few miles farther south and have hanging mouths. In Rs. 28 E. and 29 E. (Hanford and Scooteney Lake quadrangles) deeper channels truncate shallower ones to provide notches in the cliff summit ranging from 525 to 775 feet A.T., all within a 4-mile length of the bluff. Not all differences in altitude can be imputed to differing depths of water in contemporaneously operating channels and do not seem adequately explained by a lowering of the Columbia during one episode of Koontz channel activity. From the channel-mouth relations of the entire group, there appear to have been at least three episodes, each succeeding one finding a lower level of water (or debris) in the master valley.

[21] A Bureau of Reclamation test pit in SW ¼ Sec. 5, T. 11 N., R. 29 E., found, in descending order, 5 feet of sandy silt, 11.7 feet of coarse sand with caliche gravel, 2 feet of fine, sandy silt, 5.3 feet of basalt sand and caliche fragments, beneath which was at least 8 feet of very compact caliche.

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Earlier Flooding in Quincy and Othello Basins

(Bretz and Neff)

For simplicity and clarity, discharge of Warden cataracts has been presented as part of the earliest glacial overflow from Quincy basin, coincident with that over the three western cataracts and with the discovery of basalt in any outlet channel bottoms. This was the writers' interpretation in 1952. Neff's subsequent studies, however, have uncovered evidence of earlier and higher floodings, the record apparently convincing but not detailed, and with some correlations uncertain.

Neff's evidence consists of hundreds of erratic blocks on the north slope of Frenchman Hills and the east slope of Babcock-Evergreen Ridge, some in clusters, some with associated gravel, up to 1360 feet A.T. In addition is a significant little stream-cut notch across the Evergreen summit a mile north of Frenchman Spring cataract, its floor at 1350 having a deposit of west-dipping fore-set gravel 5 feet thick and terminating at the western end in a cirquelike waterfall alcove, well shown on Sheet 2 of the U.S.B.R. map R4-5720.

A few boulders have been found at a comparable altitude along the east side of Quincy basin, and a tract several miles wide (east-west), denuded of its Palouse loess down to a caliche zone, margins the Willow Creek-Moses Lake trench from Rocky Coulee to Warden and lies below an altitude of about 1350. This flat has almost no southward gradient for the 15 miles of its length, and it disappears in the latitude of the cataract. It reappears at a lower altitude east of Othello town, south of the Frenchman Hills and Lind structures, with a caliche pavement under a thin loess, and there has stream gravel up to 1160 feet A.T.

These boulders and this flat in Quincy basin, 100 feet higher than the Warden cataract brink, indicate that the sedimentary cover at the site of Drumheller was sufficiently thick and extensive to have briefly held back the body of water responsible for flotation of the boulder-carrying bergs and the scour of loess from the flat. There must have been adequate volume to supply this discharge and the four spills acr Babcock-Evergreen, three of which became great cararacts in later floods.

Othello basin has some erratic boulders on the south slope of Frenchman Hills up to 1180 feet and apparently must have been sufficiently enclosed for their flotation. The residual hill in the middle of Othello Channel is good evidence that this basin's south rim originally stood high enough for such closure. A low summit notch on Frenchman Hills (Sec. 21, T. 17 N., R. 26 E. Smyrna map), altitude about 1370 feet A.T., separates boulders at 1360 on the north from boulders scarcely 2 miles distant on the south at 1150. A 10 foot greater depth of flood water in Quincy basin would have spilled across this preglacial divide. Since the caliche cap in the notch is intact and there is no scour on the slope down to 1180, water in the basin apparently never has stood higher than 1360.

Othello Channels has an accessory stream channel across Saddle Mountains ridge with a floor at 1150-1160 in a notch originally bottomed at 1190 or less (Fig. 12). A neighboring notch floored at 1210 was not used. The two lie about 3 miles west of the main Othello scabland (Scott Lake quadrangle map). Discharge through the channeled notch appears to have gone down a near-by, high-level Koontz channel in pre-Warden time.

At the time of this earliest-recorded Othello basin flooding with discharge across Saddle Mountains axis, either no well-opened Lower Crab Creek valley existed or the water gap of the Columbia farther west was closed. Ponding in Pasco basin, and therefore in the gap, cannot explain the discharge southward across the anticline. Possibly the great Taunton-Corfu slide was a factor, but it is much more probable that the course of Lower Crab was still largely unexcavated below the level of the Royal Slope, a broad structural terrace above 1150 and some 25 miles farther west. Initiation of both Lower Crab and Othello channels apparently came at this time.

Washtucna Coulee

Maps: Benge, Connell, Eltopia Hacs, Washtucna quadrangle maps, U.S.G.S., R4-5720, sheet 3, U.S.B.R.

(Bretz and Smith)

Drainage

Glacial drainage from the north entered the preglacial Palouse River valley in mid-length

and followed it for about 25 miles, denuding more than 750 square miles of the Cheney-Palouse scabland tract. In the vicinity of Hooper and Washtucna, where the Palouse and Snake rivers were flowing parallel and about 10 miles apart, the distribution of scabland shows that a large portion of this glacial water escaped southward from the Palouse Valley across the divide and entered the canyon of Snake River, making scabland of the divide top (Pl. 1). Palouse River today is detoured from its former course along now streamless Washtucna Coulee into a striking, joint-determined scabland canyon which cuts through the preglacial divide. For some reason, perhaps incomplete removal of Ringold fill or of prescabland glacial outwash in the old course, Washtucna Coulee could not carry very much of the glacial water. Bretz insisted that the divide crossing was because of a volume far too great for Washtucna's capacity. Allison would doubtless explain the short-cut by an ice jam somewhere down the abandoned valley. Flint specifically referred the spillover to an aggradation of the lower Palouse Valley (Washtucna Coulee) until overflow was inevitable. He supposed "a very low route" available across the breached divide. Washtucna Coulee has another scabland short-cut to the Snake across the divide, 15 miles farther west—the streamless Devils Canyon.

Near Connell, about 35 miles down Washtucna Coulee, the character of the old valley changes considerably with entrance near that town of glacial drainage from Othello Channels. Thence downstream, it is known as Esquatzel Coulee. Some hitherto undescribed and some disputed features of Washtucna-Esquatzel are significant for a successful theory for the origin of scabland.

Staircase Rapids and its Bar

Staircase Rapids bar, 1–3 miles north of the town of Washtucna (Fig. 14; Pl. 1; Washtucna quadrangle map), lies in the mouth of a tributary entering from the north at the head of the abandoned portion of the prescabland Palouse river valley. The bar was made by a small, divergent strand of water escaping westward from the Cheney-Palouse tract and entering Washtucna along the short tributary to the old Palouse. The deposit, 150 feet thick, lies in the last 2 miles of this tributary but does not make contact with the east side. Flint (1938, p. 478–479) noted (1) south-dipping fore-sets in this bar as constituting "more or less flat-lying lenticular courses" instead of delta fore-sets, (2) terraces on the south face of the deposit which Bretz had described as a deltalike front, (3) cut-and-fill bedding, and (4) failure of fore-sets to parallel the eastern slope, also interpreted by Bretz as a constructional front. He concluded that the deposit is but a remnant of a more extensive valley fill, and held that the unfilled eastern part of the tributary valley mouth was the result of subsequent dissection because he found "a thin but distinct covering of identical material" on the eastern slope.

Allison (1941, p. 69) accepted Flint's interpretation although he upheld Bretz's view that the eastern front had "constructional lobings . . . ." because of "a reshaping . . . . [by] a later discharge".

Flint's interpretation of Staircase Rapids bar contains faulty reasoning and is in serious conflict with several lines of field evidence.

(1) If his general picture is to be internally consistent, his episode of aggradation must have begun, in this region, with deposition at the very bottom of the preglacial Palouse Valley and its equally deep major tributary, Cow Creek, which enters from the north. For the Staircase divergent spillover to occur from his "shallow" Cheney-Palouse river, the floor of Cow Creek valley had to be aggraded until it was close to the altitude of the divide at the head of the Staircase tributary (Fig. 14). At present that would require nearly 400 feet of filling in Cow Creek valley. This figure should be reduced by whatever deepening that valley had during scabland making. The three rival interpretations, however, consider present depths of the main preglacial valleys largely to date from prescabland time.

Only gradually could main valley bottoms have been raised by the procedure on which Flint insisted. Thus the mouth of the Staircase tributary gulch would inevitably have become back-filled from Washtucna's rising fill long before the Rapids could take origin. Four hundred feet of filling in Washtucna would have back-filled the tributary mouth 100 feet higher than the present top of the deposit and would

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e east side. Flint (1938,
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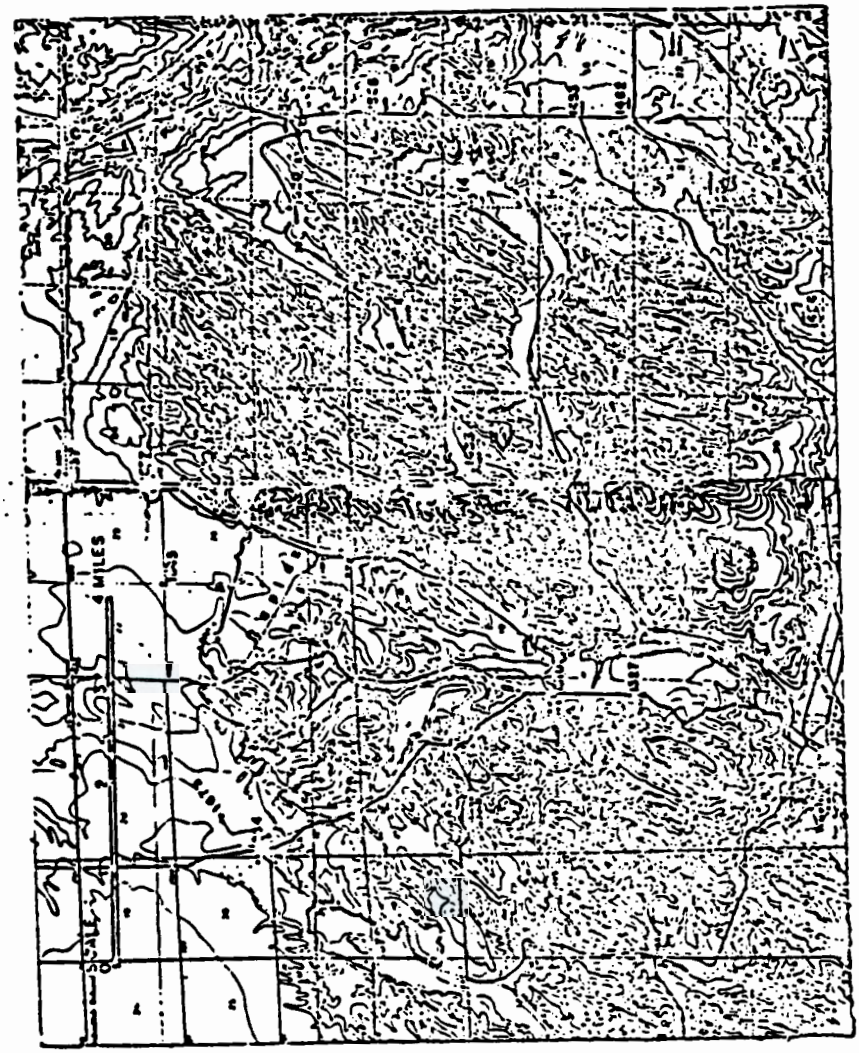

FIGURE 14.—STAIRCASE RAPIDS AND ENVIRONS

Part of Washtucna and Benge topographic maps, U. S. Geol. Survey. Contour intervals: Washtucna, 25 feet, Benge, 40 feet.

have produced only back-dipping fore-sets, if any. Only at the very last of Flint's episode of aggradation could any glacial water have been detoured from Cow Creek down Staircase. It would have found the little valley mouth already filled!

(2) The head of Staircase Rapids, interrupted by a small loessial island, is 3½ miles wide, and the brink of the uppermost falls is 1625–1650 feet A.T. The "bar" surface, 4 miles downstream, is 1300-1325 feet A.T. Flint took that surface and associated thin gravel to the east to be "remnants of a continuous fill graded to the fill in Washtucna Coulee". The gradient of any fill along the Staircase tributary valley therefore was 75 feet or more to the mile. It can be reduced to about 50 feet by considering the "bar" surface originally to have been 100 feet higher. Even this is an impossibly steep gradient. A proponent might conceive therefore that this channel never had a fill upstream from the "bar", that its scabland was made *during* the general aggradation, not afterward as Flint believed.

(3) It is impossible however to adjust this alternative to the fill-and cut theory because a mile west of the head of the Rapids the western part of this divergent Cheney-Palouse strand entered its own separate spillway at close to 1675 feet A.T. (Fig. 14). For Flint's shallow glacial river ever to reach the head of this westernmost strand, a fill nearly 50 feet thick must have existed where the uppermost cataract brink now stands. Thus a once-continuous fill along the Staircase tributary to the "bar" is demanded, and its gradient must have been nearly 90 feet to the mile, instead of, his estimated 13 feet for the aggradation in the Cheney-Palouse-Washtucna tract.

(4) There is, however, *no* gradient shown on the topographic map for the entire 2-mile length of the "bar". Instead, an undrained sag a mile long occupies the valley bottom at the *head* of the bar and, upstream from it, descent over the Rapids is 350 feet in a trifle more than 2 miles.

(5) Furthermore, the bar top is 100 feet lower than bases of loessial scarps 3 miles distant, almost directly across Washtucna Coulee. By Flint's view the flat-topped gravel remnant in this protected place should be as high as near-by scarp bases, 1400 feet A.T. From Flint's gradients the original surface of this deposit would have been 130 feet still higher.

(6) The only two scabland channels which could have carried glacial water to erode the inner valley along the east side of the bar have heads but 25 feet lower than the low brink of the uppermost Staircase falls. Yet the deposit was trenched (?) 150 feet deep and not by Staircase discharge. Nor can the supposed trenching be ascribed to postglacial streams for, above the junction of the small channels with Staircase, the latter carries runoff from more than 16 square miles, the former from only 13. Eleven square miles of Staircase postglacial drainage enters the closed depression at the head of the bar and has not yet obliterated it.

(7) The two minor channels become one on the Benge-Washtucna quadrangle boundary, 1½ miles northeast of the bar. In each, a little above the junction, there is a flat-topped, undissected gravel flat (at 1400 and 1440 feet A.T.) with steep, downvalley-facing terminal slopes and fore-set beds descending about 100 feet to an empty channel floor. Gradient thence downstream is 75 feet in the 1½ miles, terminating in the silt-filled flat with intricate meanders locally dammed by one of the Staircase bar's lobations (Pl. 9, fig. 2). Gullying in this flat shows 18 feet of postglacial silt and sand with root casts. A large vertebral bone was also found. Upstream from the gravel flats are low but definite scabby basalt outcrops, one ledge constituting a waterfall more than 40 feet high with a plunge basin recognizable on the topographic map.

These features record the same kind and time of experience that is written in Staircase Rapids and completely disprove Flint's theory for the origin of the 150-foot trench alongside the Staircase bar.

(8) Finally, the volume and velocity of this minor divergence could never, by Flint's interpretation, have made the giant current ripples on the bar top (Pl. 9, fig. 2). The deeper part of the deposit could be a remnant of preflood, normal outwash (largely removed from Washtucna itself) and modified by later flood water, as Allison thought, but, if so, it must have been a backfill. The southward dip of it fore-sets does not agree with this view.

1400 feet A.T. From Flint's surface of this deposit n 150 feet still higher.

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Allison's theory cannot explain the Staircase divergence unless the Cheney-Palouse tract was blocked with a huge ice jam in place of Flint's fill. For the westernmost distributary strand (item 3) to have operated, another ice jam must have formed along the steplike cascade, 3½ miles wide and nearly 50 feet thick at the upper end. The wonder is, here and elsewhere, that only the larger streamways became clogged; that minor ones carried off all the floating ice which entered them or were saved by timely failure of the major channels' blockades.

Other Deposits

The U. S. Geological Survey map (1954) of Haas quadrangle shows large patches of gravel (Qsu) associated with essentially bare basalt (Tcb) along both sides of Washtucna Coulee for 12 miles southwest of the coulee head. Near the head, gravel-covered areas extend a mile back on top of the preglacial coulee bluffs and touch the base of loessial scarps at 1400 feet A.T. The material is dominantly sand, granule gravel; and coarser basaltic debris, subangular to subrounded and stratified in thin lenticular foresets. It obviously is the marginal deposit of the highest flood, more than 100 feet above bluff summits and 400 feet above the coulee floor. Recognized in the map description as scabland gravel, it is as high as loessial scarp bases margining the Palouse-Snake divide scabland and therefore cannot record an early valley train in the coulee. A comparable gravel-covered area on this divide summit, 5–6 miles distant, south of Hooper (shown on Starbuck geologic map), reaches 1320 feet A.T.

Directly south of Washtucna town, a local hill of gravel rises from the coulee floor (about 1020 feet A.T.) to a summit more than 1200 feet A.T. (NE ¼ Sec. 33, T. 15 N., R. 36 E.) (Haas and Washtucna quadrangles). It lies in the lee (west) of scabland knobs on the south side of the coulee, but its summit stands free from the coulee wall except at the head. It is half a mile long, as is the fosse between it and the wall. The deposit terminates to the west in a rather abruptly tapering nose between the fosse and the coulee floor.

The Spokane, Portland, and Seattle Railroad has made a long cut 30 feet deep through the hill's lower, northern edge, and, although structure is no longer decipherable, composition is well shown. There is none of the size sorting on which Flint based his theory of aggradation by moderate streams. Boulders up to 8, 10, even 12 feet in diameter clearly are broken columns from the scabland knobs at the proximal end. No strata of boulders are indicated; the big pieces lying at random in the cobble and pebble gravel. At the distal end of the hill the material is all well-rounded pebble gravel, the finest material of the entire exposure.

This gravel hill, standing almost free from contact with the coulee wall and partially enclosing an unfilled tract back of it, was made by a scabland river flowing down Washtucna Coulee. It is not perched on the valley wall. Its summit is 75 feet lower than the lowest spillover across the Palouse-Snake divide. The fosse is in no sense a gully of postscabland origin. The hill is a bar of coarse detritus in the protected lee of knobs which contributed boulders to it only under the urge of a stream adequate to detach and transport them. That stream was at least 200 feet deep.

At Sperry (or McAdam) siding (Pl. 1; Pl. 12, fig. 2; Haas quadrangle) a deposit of fine-textured, well-sorted gravel, with a few strata of nut- to egg-sized pebbles, masks the north wall of Washtucna Coulee. Texturally and topographically it would fit the fill-and-cut theory, but its structure is that of long foresets dipping 20° throughout the entire 40 foot pit wall directly *into* the coulee *from* the higher scabland ledges. The dip parallels the slope but is a little steeper (*see* Flint, Pl. 4, figs. 1, 2). The fore-sets, reaching to the bottom of the coulee, prove that Washtucna had no fill (above present bottom level) when these foresets were made. The valleyward slope is essentially constructional. It may have a core of older gravel.

There are two gravel deposits near the east end of Washtucna Lake (Pl. 1; Haas quadrangle). One, at Harder siding, is about a mile long. It lies against and largely covers the north wall of the coulee. No section was afforded, but the form is significant. The deposit has a flattish top which breaks smoothly over into a steep valleyward slope. But that top is

not level! Along its length, it slopes down to the west, and the departure from horizontality is 3° (Pl. 12, fig. 3). In other words, its east end lies approximately at the top of the coulee wall, and its west end, a mile distant, not far above the bottom. Should such a form be called a terrace?

The other deposit near the lake lies south of Wacota Siding in the lee of scabland eminences. Its surface slopes even more steeply westward; the steepness increasing at the terminus which reaches lake level at high-water stages. A profusion of big boulders lies on the floor of the pit in this deposit, but no structure was seen. The form and size are perfect for subfluvial shaping of flood debris lodged in this place. The location down in the basin of this lake without outlet is an awkward fact to fit into Flint's theory.

About midway between Kahlotus and Estes (Connell quadrangle map) a large gravel deposit conceals the northern scabland wall for about a mile. Three pits in the base of its slope yield a well-sorted, pea-size gravel. The bedding at the west end of the deposit dips 20° toward the valley through 40 feet of exposure. In a few places interrupting short fore-sets dip away from the valley. Two other pits show long fore-sets with a 5-degree dip toward the valley and a 5-degree dip along the valley, respectively. The top of this deposit, above which is scabland, is flattish and descends westward with a 3-degree slope throughout its length and tapers out for no apparent local reason. Should this form and structure be interpreted as simply a terraced remnant of a once-continuous fill?

Just west of Sulfur Lake[a] in Washtucna Coulee (Pl. 1; Connell quadrangle map), a smoothly rounded, east-west elongated, gravel hill about half a mile long stands out on the coulee floor. Its top is more than 50 feet above the adjacent coulee bottom, more than 100 feet above near-by Sulfur Lake, and more than 30 feet above an undrained depression (a fosse) on the north side of it. There are no exposures. Most of this nearly mid-channel hill is lower than the site of Connell; in other words, it stands *down* in the long, closed depression of Washtucna Coulee. It is not "perched" on the valley slopes. Bars are equilibrium forms in stream beds. Some may be of erosional origin, shaped from older alluvial deposits. But only a stream capable of making the 12-mile long, 100-foot deep depression could have sculptured this hill from a former continuous valley fill.

A fill in the mouth of Hardesty Coulee (Pl. 1), which enters Washtucna from the north just east of this mid-channel hill, has a flat, level top close to 1100 feet A.T. and rests on basalt in the gulch at about 950 feet. Much of it is granule gravel of bluish-black basalt, but it has strata of nut- and egg-size pebbles. There are cobbles and small boulders of quartzite and granite on the coulee floor. Sections are poor and show only indistinct horizontal bedding. Buried beneath portions of this gravel are silts and sands, the basal part containing a thin conglomerate of basalt and the whole taken to be a remnant of the Ringold formation. If so, Hardesty Coulee was a valley eroded in basalt essentially to present depths when the Ringold was deposited.

Although there is no definite knickpoint along lower Hardesty, there is a pronounced narrowing where the stream enters and crosses this gravel fill, a narrowness that has persisted while and since, according to the fill-and-cut theory, Washtucna Coulee was essentially cleaned out by the subsequent erosion of a distributary from the Cheney-Palouse tract. Trenching of the gravel deposit has contributed to filling of the Sulfur Lake depression which nevertheless is still 100 feet deep. Debris from Hardesty cannot get out of that hole.

The fill at the mouth of Hardesty has a good terrace form 150 feet above the level of the Connell "blockade" although more than 100 feet below the base of loessial scarps. Its composition indicates consanguinity with those other "terraces" whose flat tops slope down-coulee. Its constriction of the tributary valley seems quite out of harmony with the picture of essentially complete valley re-excavation of Washtucna by a river of moderate size.

Rattlesnake Coulee (Pl. 1; Connell quad-

[a] A serious flaw in Flint's explanation, noted by Allison, is its failure to account for the Sulfur Lake depression. The basin is 12 or 13 miles long and more than 100 feet deep in the bottom of one of the valleys whose fill he believed was removed by later normal glacial river work. It has bare scabland buttes in mid-channel at the lake.

rangle map) enters Washtucna about 2¼ miles east of Connell, and its discharge thence flows east (upvalley) for 4 miles to enter Sulfur Lake. Its mouth contains a gravel deposit made back in it from the larger valley. A pit here shows bedding fore-set up the tributary out of the main valley for the full height of the section, 20 feet. No horizontal members were seen. Some of the fore-sets are at the angle of stability, others a little less steep. A seam of light-colored sand conforms perfectly with fore-set gravel above and below. Under the bluish-black, fore-set, fine gravel is a foot or so of older, stained and softened gravel and sand with horizontal bedding, taken to be a basal part of the Ringold. On both sides of the coulee mouth, the top of this deposit is a rounded form with a depression, now drained, up to 30 feet deep between it and the scabland wall to the north.

Esquatzel Coulee

Maps: Connell, Eltopia, Scooteney Lake quadrangles, U.S.G.S.; R4-5720, sheet 3, U.S.B.R.

(Bretz, Smith, and Neff)

Providence Coulee, entering Washtucna-Esquatzel at Connell (Pl. 1), is shown even by the 50-foot contour interval of the Connell 1 to 125,000 topographic map to have a pronounced narrowing below 1000 feet A.T. Providence Coulee crosses three formations. The valley is naturely open on the loess-covered higher basalt country; becomes a ravine across about 2 miles of Ringold (Paradise Flats topography); and, at its entrance into Washtucna, narrows to a trench across a back fill of gravel occupying the ravine mouth. Long uninterrupted fore-sets dipping diagonally up the coulee for the full height, about 40 feet, of a section along the Connell Branch of the Northern Pacific Railroad are clearly visible from the highway a mile distant. Neither these nor any others of the long, unbroken fore-sets listed above can be explained as parts of a gradually growing valley-train deposit. Can they reasonably be interpreted as erosonial remnants of deltas?[23]

Pits in this deposit show that the long fore-sets unconformably overlie finer gravel in which ordinary cross-bedding occurs in nearly horizontal courses about 2 feet thick. These courses dip about 5° NE. They may record earlier, nonflood deposition. But it is difficult to explain this trench if the gravel is pre flood unless the almost complete cleaning out of Washtucna is ascribed to flood erosion.

Connell stands on a fill of fine gravel which constitutes a divide in the old river valley (Connell quadrangle map) Drainage from Providence Coulee goes southwest down Esquatzel but run-off at Connell also goes eastward *up* Washtucna, descending more than a hundred feet in 7 miles to reach alkaline Sulfur Lake. It is 180 feet to basalt at Connell. However, the altitude of this mid-coulee divide, about 850 feet A.T., is far too low to allow consideration of this fill as the blockade which caused the Devils Canyon short-cut to the Snake beginning at 1250 feet, or the Palouse Canyon transection whose highest scabland is about 1400 feet. According to Flint's theory, the Connell fill can be only an erosional remnant of a valley deposit which originally must have reached to the highest scabland at that town, about 1100 feet A.T. A rising gradient of such a fill up-valley would account for the two canyoned divide crossings, Devils at 1250 feet and Palouse at 1400 feet.

Part of Connell is built on a low, rounded, gravel mound in mid-valley, composed largely of granule gravel and certainly not the deposit of a vigorous stream. Evidence of mid-valley, gentle-current deposition has been consistently sought. Lateral deposits in protected places were unacceptable. This site of Connell comes nearest to answering the demand. The transporting current, however, may not have come down Washtucna Contour maps by the U. S. Geological Survey and the U. S. Bureau of Reclamation show a flattish tract which descends eastward from the Othello divergence that enters the mouth of Washtucna and the head of Esquatzel. It begins about 5 miles west of Connell at 950 feet A.T. and descends 100 feet in reaching that town. Continued farther east up Washtucna, the slope descends another 100 feet in 7 miles to Sulfur Lake. Lack of adequate exposures along this 12-mile slope

[23] Oral suggestion from James Gilluly in 1927, as an attempt to escape from the bar hypothesis.

renders an interpretation speculative. But the nearly continuous and nearly uniform slope and the character of the deposit in pits at Connell suggest that it is a record of back-filling from Othello discharge subsequent to Washtucna's glacial river. This would help explain the Sulfur Lake depression. Silts overlying coarse scabland gravel at the lake may be contemporaneous with deposition of the barrier or may record a postglacial lake.

Supporting the view that the gravel at Connell and in the mouth of Providence Coulee came from the west (from Othello Channels) are strong eastward components in the long fore-sets dipping back up Providence and the occurrence of other eastward-dipping fore-sets in a small pit not far west of the railroad section.

One serious objection to this interpretation is that the Connell deposit is more like a valley bottom fill than a delta. Another is that the bedding in a shallow pit at Connell is fore-set westward. It is conceivable, however, that the divergent strand from Othello Channels was succeeded by renewed functioning of a glacial Washtucna which reworked the upper part of the coulee bottom deposit, giving it the aberrant slope and a superficial fore-set structure with westward dip.[36]

Unlike Washtucna, Esquatzel Coulee varies greatly in width, ranging from an eighth to three quarters of a mile between walls. The towns of Mesa (Scooteney Lake quadrangle) and Eltopia (Eltopia quadrangle) mark two narrow places, and there are three others less striking. Their significance lies in the massive gravel deposits constituting very local hills which constrict the old valley in these narrow places. They are not "perched" deposits. This difference between Esquatzel and Washtucna is a direct consequence of occupation, at least from Mesa southward, by one of the divergent strands supplied from Othello Channels.

Two of these gravel hills overlapping the coulee walls, one a mile south of Mesa, the

[36] A gravel deposit along the highway 4 miles directly south of Connell is only tentatively interpreted by Bryan (1927, p. 27), Flint (1938, p. 515), and the writers. It occurs on the slopes of Old Maid Coulee, a tributary entering Esquatzel from the east. Its altitude, 1050 feet A.T., is about that of the highest scabland in the larger valley. Flint reported a B soil horizon "consisting of 3 to 5 feet of calichified silt and firm pure caliche", underlain by a dominantly basaltic gravel ranging from granules up to boulders 3 feet in diameter, and overlain unconformably by Touchet silts. Quartzite and caliche pebbles and sand with feldspars, micas, *etc.*, occur in the considerably decayed basalt gravel. Fore-set bedding dips southwestward, down along Old Maid Coulee.

But there is no scabland in this coulee nor any scarp-bounded notch at the head where glacial water might have overflowed from Washtucna Coulee and introduced the foreign material. The caliche cap also sets the deposit apart from all scabland gravel ever described. Nevertheless, it probably records a meltwater stream across the plateau. Its 3-foot boulders indicate vigorous erosion somewhere enroute, and the caliche pebbles suggest a stream that overran surfaces above valley bottoms.

PLATE 13.—SCABLAND DETAILS

FIGURE 1.—Shoulder bar. Note parallelism of ripple marks with growing (northern) front of bar and their extension from summit down southern and western slopes to constitute the crenulations shown on Haas topographic map (*see* Fig. 21). Production and Marketing Adm. photo CCH-16-197.

FIGURE 2.—Part of bench between Babcock Ridge and Columbia River. Three contrasted surfaces are shown: (1) the northern part without scabland, (2) older scabland, and (3) younger scabland. TT—Trinidad or Crater terrace. WSD—Willow Springs Draw. G—gravel pit. B—gravel bar associated with older scabland. O—gravel marginal to younger scabland. Northward extension of the lower cliff up into the mouth of Willow Creek Draw shows that Columbia Valley and the Draw had present depths before any scabland was made on the bench. U. S. Army aerial photograph.

PLATE 14.—BARS NEAR MESA

FIGURE 1.—Interrupted panorama of terminal portion of bar south of town. Looking north. Fore-set bedding for full height of each pit dips as shown by arrows. Only slight gullying has occurred between bar on left and older gravel on right. Photo by H. T. U. Smith.

FIGURE 2.—Face of bar north of town. Looking west and showing the gulch across it, the southward slope of the summit, and the down-coulee tapering out of the deposit. Photo by H. T. U. Smith.

FIGURE 3.—Highway section through bar north of town. Looking south. Structure shows that valleyward slope can only be constructional. Photo by H. T. U. Smith.

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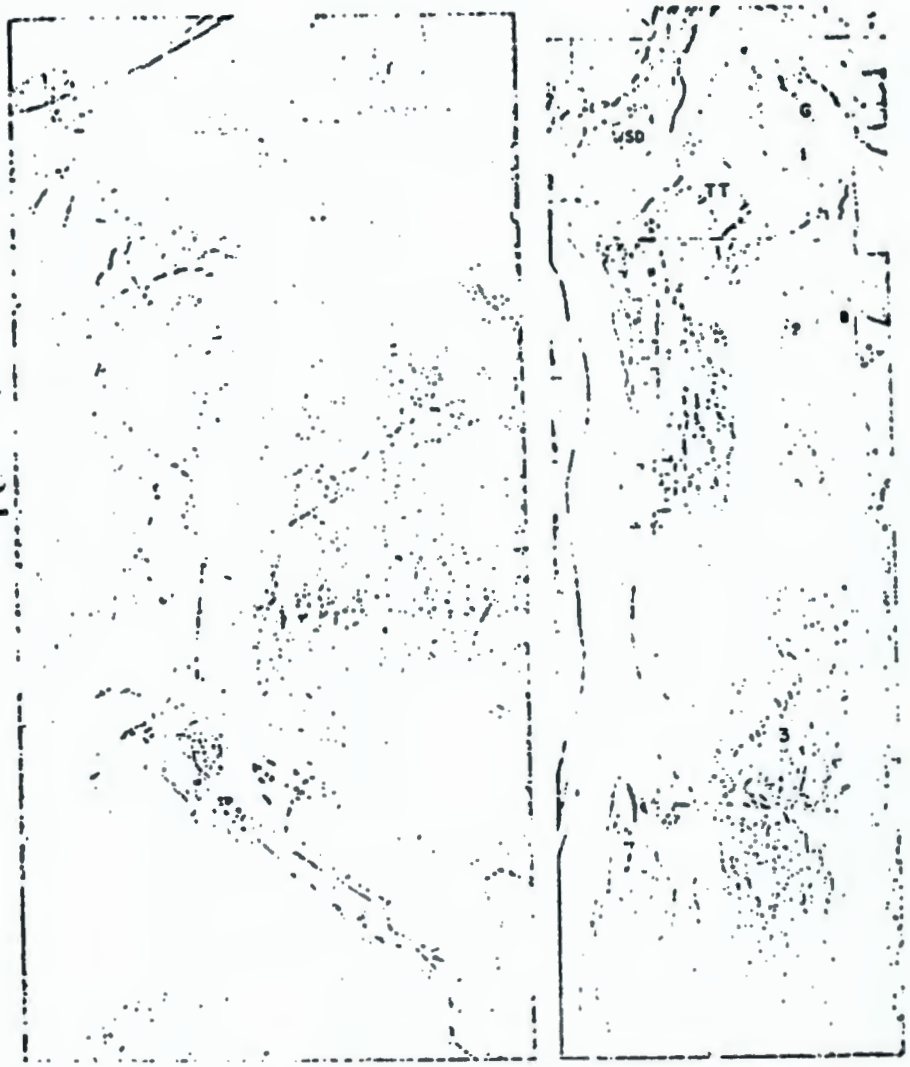

FIGURE 1 FIGURE 2

SCABLAND DETAILS

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FIGURE 1

FIGURE 2

FIGURE 3

BARS NEAR MESA

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FIGURE 4

GRAVEL BARS SOUTH OF SNAKE RIVER

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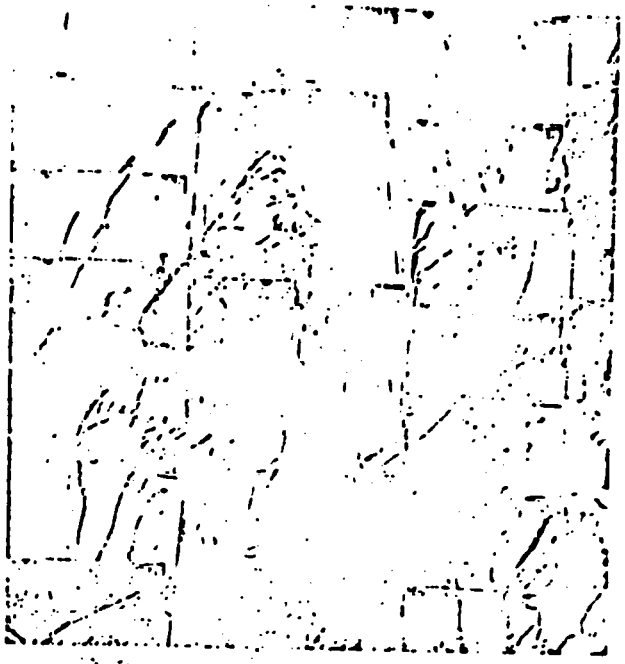

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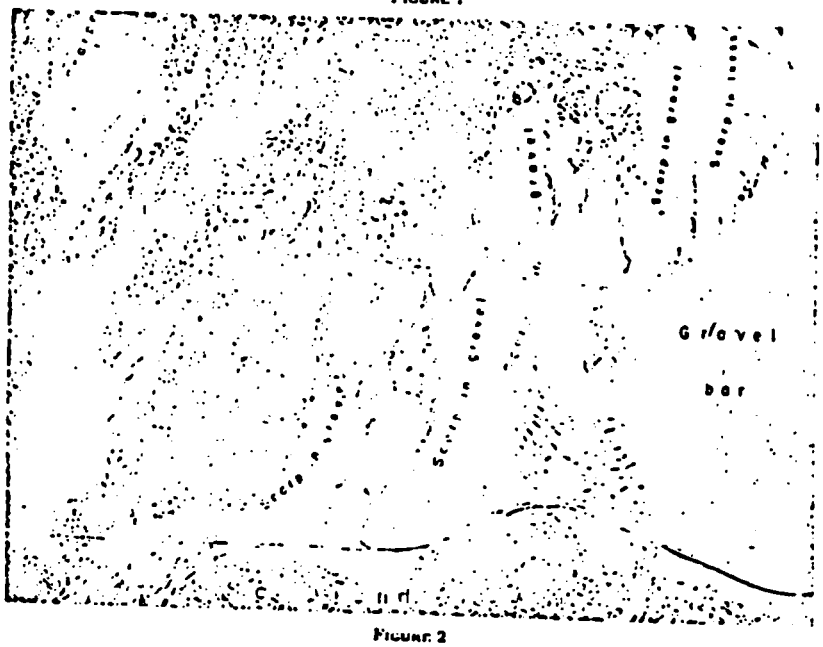

FIGURE 2

SCABLAND FEATURES IN MID-WIDTH AND MID-LENGTH OF CHENEY-PALOUSE TRACT

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other a mile north, have excellent sections (Pl. 14). The southern hill is 50 feet high at its blunt, downvalley terminus where it stands free from, but parallel to, the valley wall. On the valleyward side, the hill has three or four lateral lobations cut by the highway and one by the railroad. Even better sections are afforded by two large pits.

All these cuts show long, uninterrupted, deltalike fore-sets dipping downvalley. The larger pit wall (Pl. 14, fig. 1) shows 40 vertical feet of such beds dipping about 20° and striking essentially tangent to the curved end of the hill. There are no horizontal strata and no granule gravel, sand, or silt members. The gravel is all moderately coarse and moderately worn basalt, with some cobbles and a few boulders.

The form of the deposit is equally enlightening. The hill's elongated, rounded summit parallels the valley wall, a sag or fosse separating them. The unterraced valley slope against which the hill rests is of gravel, or at least is covered with gravel. It is marked by broad shallow gullies, features which the hill itself does not possess. Exposures in this slightly gullied valley slope show a fine-textured gravel with but few medium to large pebbles. The fine gravel is apparently older than the coarse. Yet there are definite constructional moundings on its slightly gullied surface, and both deposits are judged to be bars.

The deposit north of Mesa has a gulch cut through it (Fig. 15; Pl. 14, fig. 2). It is a hill of gravel built against higher, gravel-covered slopes, a fosse with its central part still undrained lying between. The hill summit

PLATE 15.—GRAVEL BARS SOUTH OF SNAKE RIVER

Photos by H. T. U. Smith

FIGURE 1.—Pit section in northwest part of shoulder bar. False and true fore-set bedding in lower left. One bevels the other. Note a fence (F) in Figures 1, 2, and 3.

FIGURE 2.—Pit section about half way down bar front

FIGURE 3.—Pit section at toe of bar

FIGURE 4.—Trickle bar south of Lyons Ferry

PLATE 16.—SCABLAND FEATURES IN MID-WIDTH AND MID-LENGTH OF CHENEY-PALOUSE TRACT

FIGURE 1.—Scabland with loessial islands. Scarified but not deeply channeled scabland with two scarped and prow-pointed loessial islands carrying unmodified minor preglacial drainage lines above flood limits. One of them also has a minor channel across it. Light areas are wheat stubble, dark areas are summer fallow or fields newly plowed. Part of T. 16 and 17 N., R. 37 E. From Production and Marketing Adm. mosaic 7, Adams Co., Wash.

FIGURE 2.—Giant current ripple marks. The local scabland "channel" is 1½ miles wide between two small loessial islands, part of each showing. A larger "channel," containing these islands, is 8-9 miles wide and is bounded by two larger islands. Overall width of the Cheney-Palouse tract at this place, downstream from all distributary routes except Washtucna Coulee, is about 15 miles. Figure 1 shows the general character of island and scabland relations a few miles farther south.

Width of the small "channel" of the particular "stream" which left the concentrically curved current ripples is a quarter of a mile, approximately that of Snake River in flood today. It appears to be the product of a later and smaller flood which here traversed and incised an earlier gravel deposit. On the right is a double scarp, the upper part in loess, the lower in the older gravel. This ripple-marked "channel" is only part of an anastomosis, the gravel scarp and ripples of a contemporary channel shown on the left. Relief of the ensemble demanded three curves in the railroad to reduce grades, two of them shown in the photo. The higher gravel deposit on the right is thus shown to have a broadly rounded terminus of bar, not terrace, character in the lee of the loessial island. Profile supplied by the C.M. and St. P.R.R., indicate that the railroad grade rises 20 feet in crossing from the west side of the area to round the tip of the bar to the east. Scaled from the photograph, the wave length of these ripples is 200 feet. Approximately Sec. 18, T. 18 N., R. 38 E.

Production and Marketing Adm. photo AAP-1G-125.

undulates through minor sags and swells that fall into a flattish profile when viewed from an equal height on the opposite side of the coulee. This profile descends southward, downvalley, with a slope of 4°. The hill narrows and lowers to its terminus, free from the valley slope. Overall length is 3000 feet.

The road along the gulch affords four good sections, all of which show delta-type fore-sets from top to bottom (Pl. 14, fig. 3) with dips prevailingly of 20° toward the valley bottom and strikes parallel to the frontal slope. Cobbles and boulders are not abundant, but pebbles are large almost throughout. A pit at the south, lee end of this valleyside hill shows rather fine gravel, with sporadic small boulders. It also shows a lens of silt and sand 3 feet thick, lying horizontally in the gravel. This could well be a deposit in a quiet water hole in the lee of the bar during its growth. A few days at the most would suffice for its settling.

It is argued here that the fore-set beds do not

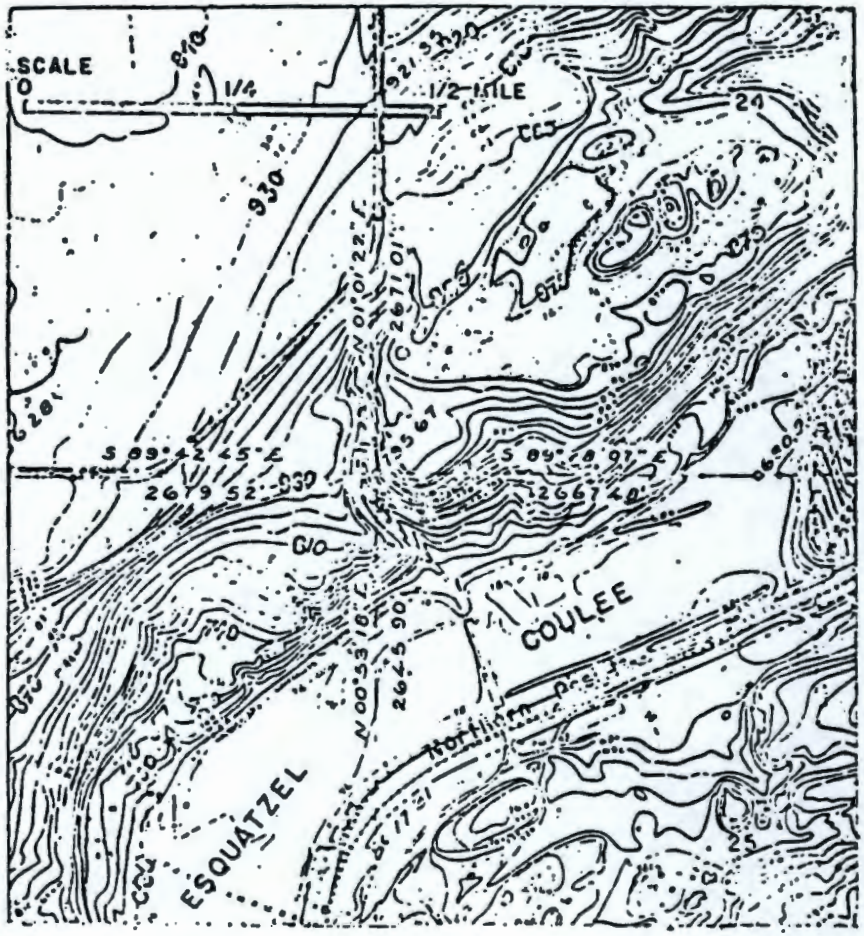

FIGURE 15.—BAR NORTH OF MESA

Showing the flattish free terminus (contours 700 to 740) and the undrained fosse (870 contour). Part of U. S. Bureau of Reclamation map G-5473, contour interval 2 feet.

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record addition of their gravel *down* the slope from *above*. The contributing current was flowing horizontally past the growing bar face; the gravel was travelling more largely *along* the slope than *down* it.

The irregularly mounded valley slope back of and above the fosse has broad, shallow gullies. The hill, which is interpreted as a younger deposit, has only a few narrow short gullies, other than the transecting gulch.

Neither of the Mesa bars has a scabland channel leading to it. The erosional pattern of the adjacent upland in both cases is elongated subparallel to Esquatzel and the two bars.

Just south of Mesa, Esquatzel Coulee breaks up into an anastomosing pattern of channels which at Eltopia, 8 miles farther downstream, is 5 miles wide. Jackass Mountain, an isolated Ringold hill in this complex, stands 200 feet above closed, channel-bottom depressions on both sides. The course of the preglacial Esquatzel margins the eastern side of the complex (Fig. 17). Most of these interconnected channels converge a little south of Eltopia, but here another break-up of Esquatzel makes two dominant, diverging channels, almost equally deep and separated by a broad hill of Ringold 5 miles long and 200 feet above its bounding channels. The eastern channel, deeply filled with sand and gravel (U.S.B.R. borings), apparently records the preglacial Palouse. Beyond this hill channels disappear in the blowsand of the Pasco lowland.

This complicated glacial-river channeling, well shown by 10-foot contours on the U. S. Bureau of Reclamation map R4-5720, sheet 3 (*see also* Eltopia and Wallula quadrangle maps, U. S. Geol. Survey), extends from 750 feet A.T. near Mesa down to an altitude of 500 feet in a distance of 17 miles; all of it is well below the high level of Lake Lewis as defined by Allison and Flint.

The two Mesa bars stand down on the main channel floor. Water in Pasco basin apparently did not then, nor later, reach the 1100-foot scabland channels at the summit of the Wallula watergap cliffs, 9 miles distant. Yet the complicated channeling was done by a very large glacial river after the Touchet silts were deposited, and probably when both Othello and Washtucna were contributing to Esquatzel. If Washtucna glacial river was then flowing, Upper Grand Coulee had not yet been completed or was temporarily blocked by the Okanogan lobe.

These channels clearly record a post-Touchet flooding down Esquatzel, and, if Allison is correct in making Touchet silts younger than the Snake Canyon gravel bars, Touchet (*i.e.* Lake Lewis) sedimentation, although glacial, must be interflood in age.

Pasco Basin

Maps: Coyote Rapids, Eltopia, Hanford, Pasco, Priest Rapids, Prosser and Wallula quadrangles; U.S.G.S.; and R4-5720, sheet 2, U.S.B.R.

(Bretz, Smith, and Neff)

All plateau scabland drainage, entering the Columbia to the west and the Snake to the south, converged to the Pasco basin, the largest and deepest of the structural-topographic basins of the region (Pl. 1). Nearly 500 square miles of it lies below the 500-foot contour. The Columbia River at its outlet, the Wallula Narrows across the Horse Heaven Hills anticline, is 300 feet A.T. Scabland extends up on the walls of this narrows to 1100 feet A.T. or more, but the basin upstream is largely empty.

Flint believed (1938, p. 517) the high Wallula scabland was made because the Pasco basin was filled with debris up to "at least 900 feet". This fill was of proglacial origin but was earlier than the rise of Lake Lewis, *i.e.*, earlier than the valley-filling, loess-scarping, scabland-making episode. It must have caused aggradation in tributary valleys back on the plateau, but about this Flint gave no details. However, most of this early basin and valley fill, its cause unspecified, was removed before the widely distributed lacustrine Touchet silts (contemporaneous with the plateau gravel) were deposited in Lake Lewis, therefore before plateau scabland erosion occurred.

The high Wallula scabland, although "well developed", is thus much older than any other in the entire region.

Allison (1941) asserted that the subfluvially molded gravel deposits associated with

scabland in Snake River canyon had been derived from "high-terrace remnants" of a single, great, prescabland terrace system which he correlated with "terraces" in the Pasco lowland and, with declining elevations, farther down the Columbia. He visualized this system as filling the basin up to 700 or 750 feet A.T. But he was unsure of the time of dissection. It could have occurred by "ordinary erosion . . . between two distinct glacial stages" or it could have happened "during a single stage of glaciation before the Lake Lewis-ice-jam stage was reached" (p. 71). "If Lake Lewis and the Touchet beds are later than much of the gravel, then the rise and decline of Lake Lewis cannot be the cause of the deposition-excavation sequence in Flint's fill hypothesis. Possibly Lake Lewis or equivalent appeared twice . . ." (p. 66), but Allison could find no evidence to support this idea. The cause of the earlier alluviation is not stated. An ice jam in Wallula Narrows is suggested for the (later) 1100-foot scabland and 900-foot gravel deposits at Wallula Narrows.

Because the Atomic Energy Commission had done much construction in the northern part of the Pasco lowland since the last field study there, permission to enter the restricted Hanford area and examine the open pits was secured prior to the present study. Because Bretz's earlier descriptions of forms and relations had not carried conviction to some geologists that the gravel hills there were giant river bars, it was hoped that perhaps composition and structures shown in the A.E.C. excavations would do so.[35] Most of the excavations seen were shallow and obscured, but data from them support Bretz's idea of bar origin. A pit in a high gravel tail to Gable Mountain (SE ¼ Sec. 28, T. 13 N., R. 27 E., Hanford quadrangle) showed that the flattish-topped deposit is composed of coarse sand of mixed basaltic and granitic debris, horizontally bedded, very evenly stratified, and carrying a cover of cobbly and bouldery gravel. It is an erosional remnant extending from about 650 feet A.T. down at least to 600 feet, its streamlined shape being the result of the glacial Columbia's erosion when the mountain was an island in the river that made the associated great bars. It is presumably of prescabland age and may well be correlative with the valley fill of granitic sand at and upstream from Crater. The coarse overlay on its summit and slopes is a derivative from the scabland of the mountain, acquired when the deep channels (400 and 425 feet A.T.) on either side of Gable Mountain were made and this deposit of fine gravel shaped. In this sense, it is a terrace, graded to bar form and armored with scabland gravel. The Columbia River surface just above Coyote Rapids, 4–5 miles upstream from these empty channels (*see* Bretz 1927b), is 400 feet A.T., and the streamlined gravel hills—*i.e.*, bars—which shut them off from the river are 100 feet higher. A spring in the bottom of the deepest depression (400 feet A.T.) fluctuates with stages of the Columbia River.

The "terrace" in the western part of the Coyote Rapids quadrangle[36] is shaped like a great spit projecting southeastward across ranges 25 and 26 E. into the lowland from a high basalt anticline (Umtanum Ridge) on the Priest Rapids quadrangle (Figs. 16, 17). At the west end, this "terrace" has steep scarps descending 200 feet toward the north and 125 feet toward the south. Its broad summit is 800 feet A.T. here but descends along its length about 100 feet, and its scarps become more gently sloped toward the southeast. In mid-length it is cut across by a channel 50–75 feet deep. Its length, 13 miles, projects more than half way across the Columbia valley bottom, separating the river on the north and northeast from about 50 square miles of lowland known as Cold Creek Valley to the south.

Three pits and one road cut afforded sections in this "terrace". Two pits showed well-worn, well-sorted pebble and cobble gravel, 50 per cent bluish-black basalt, with a few boulders. The bedding is horizontal without even shallow fore-sets. The highest of the three pits (approximately in NE ¼ Sec. 34, T. 13 N., R. 25 E.) on the brink of the 200-foot northward drop-off toward the Columbia has

[35] No maps were allowed in the restricted area, and the road system had been so greatly altered since the Commission took over that many locations could be only approximated. In addition, many roads were closed to private cars.

[36] Used by Allison in reconstructing his Pasco basin fill.

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FIGURE 16.—COLD CREEK BAR
From Coyote Rapids topographic map, U. S. Geological Survey. Contour interval 25 feet.

only long deltalike fore-sets dipping southward, away from the river and into the deposit. Much of its material is composed of fine-textured, dirty gravel alternating with clean, openwork cobble gravel. Boulders of basalt and granite 3 feet in diameter and one basalt boulder 8 feet in diameter indicate transportation by floating ice. Because the freshness of the material also indicates a scabland derivation, this "terrace" was added to, if not wholly built, during scabland history.

The lee slope could be examined in section in only one place, the steep drop-off away from the Columbia at the southeast terminus, approximately in NW ¼ Sec. 13 T. 12 N., R. 26 E. The long road cut here showed only loose, dark, coarse sand with few cobbles and boulders, material typical of lee slopes of scabland bars. No structure showed to check that interpretation.

The character of "Cold Creek Valley" on this Coyote Rapids quadrangle must not be neglected in understanding the origin of the "terrace". The creek, draining about 50 square miles of the high, arid basalt country to the west, has built a large fan where it enters the "valley", a fan that spreads out abruptly from a width of half a mile at the head to eight times that width in a distance of 3 miles; the creek becoming lost in its fill. These proportions (Figs. 16, 17) show that the "valley" is only a part of the lowland, a tract partially enclosed by the giant, spit-like form. It remains for objectors to show that Cold Creek Valley, the 50 square-mile area lying in the lee of this "terrace" (Coyote Rapids, Hanford, Pasco, and Prosser quadrangles), can possibly be an erosional product of Cold Creek, as it must be if the "terrace" is but a remnant of a valley bottom fill. It is significant that the great collection of iceberg mounds of glacial till on Iowa Flat (Bretz, 1930b, p. 410; Allison, 1941, p. 673) is less than 10 miles farther south, lying in the protected lee of this spitlike deposit and extending from 625 to 825 feet A.T. Cold Creek Valley was in existence when these bergs stranded at altitudes representing the full vertical range of the "terrace".

This extraordinary display of hundreds of till mounds, up to 50 feet high, and 100 feet or so in diameter, is unapproached by any other record of icebergs in scabland floods. Mounds are largest and most numerous close to their upper limit, 850 feet A.T. Above that are only stray erratic boulders, up to 1100 feet A.T. Two episodes of berg flotation thus seem indicated. Because even the massive bergs required for transporting the material of these larger piles would hardly ground in 225 feet of water, a prompt subsidence of the flood while bergs still survived in the Cold Creek ponding seems required. The abundance of bergs, the enormous size indicated, and the probable brevity of the episode appear to demand special conditions for release from parent glacial ice (a bursting Lake Missoula dam?) as well as special conditions for their transportation. The lithology of fragments in the till (Bretz, 1930b, p. 410) strongly suggests derivation from Beltian terranes of northern Idaho and western Montana. No route from Spokane across the scablands to Cold Creek valley could avoid cataracts and cascades where break-ups would be probable. It seems that the delivery of great numbers of giant bergs to Pasco basin must have required by-passing of the scabland river routes, therefore a trip along an unblockaded Columbia. Air and water currents probably caused their collection on the west side of both Pasco and Quincy basins.

The largest bar gravel deposit in Pasco basin lies a few miles upstream and across the Columbia from the Cold Creek bar (Fig. 17). It covers most of the northern half of the Priest Rapids quadrangle, and its contours nicely fit the inside of the uniform 90 degree curve made by the river. A summit area of about 20 square miles is enclosed by the 800-foot contour and reaches 860 feet A.T. more than 400 feet above the river. Except for the Columbia River undercutting along its southern margin (a 200-foot cliff) and at its upstream contact with Saddle Mountains (a 100-foot bluff), there are essentially no marks of erosion on its smooth, rounded form. No better place for survival of terraces cut during removal of a gravel fill in Pasco basin can be asked for. Yet two traverses and the 10-foot contours of the U.S.B.R. map reveal no such forms.

A pit on the 800-foot contour near the north end of this Priest Rapids bar shows a coarse, almost entirely basaltic gravel. Columbia River

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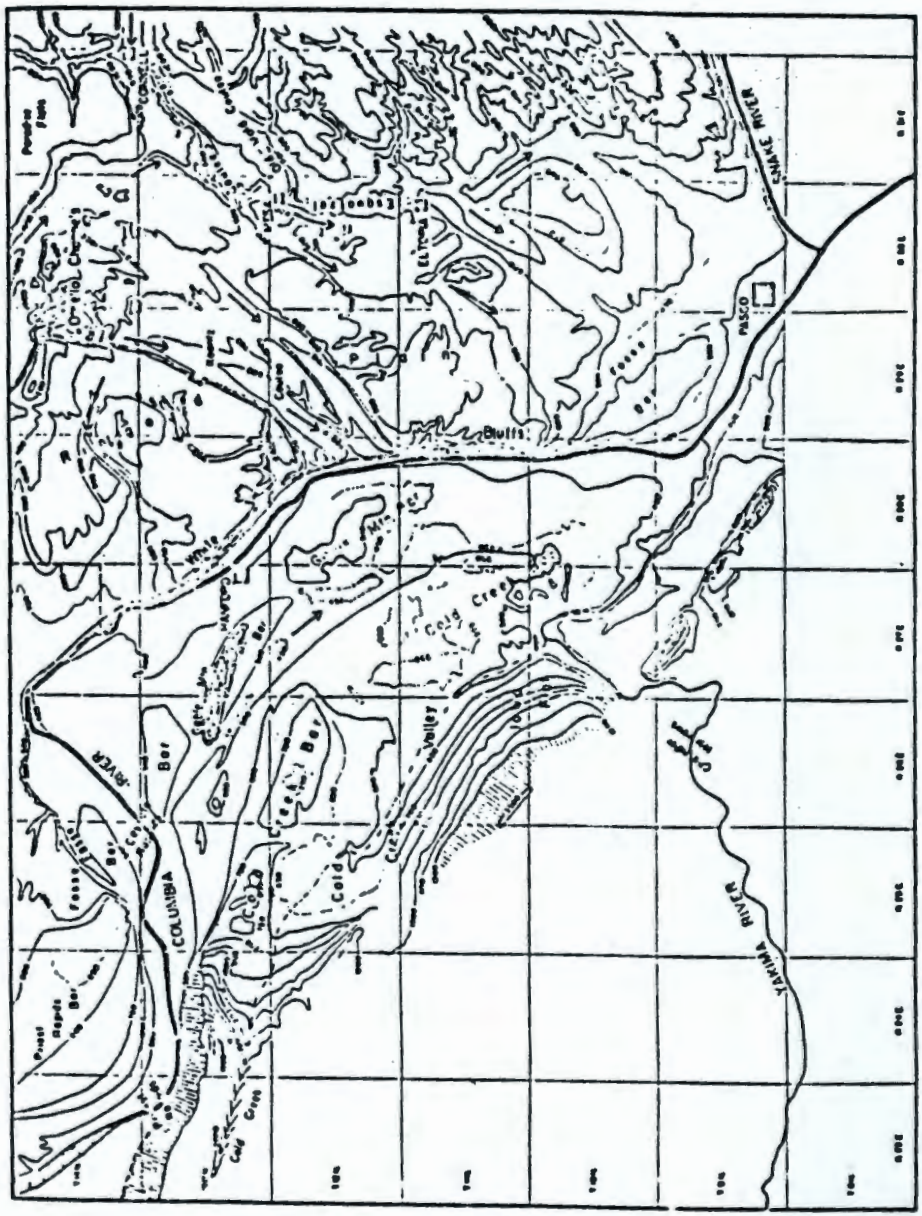

FIGURE 17.—CENTRAL PART OF PASCO BASIN

Contour interval 100 feet, locally 50 feet. From Connell, Coyote Rapids, Eltopia, Hanford, Pasco, Prosser, Scootenay Lake, and Wallula topographic maps U. S. Geol. Survey.

gravel immediately to the west is only 50 per cent basalt. Thus the glacial Columbia was carrying plateau, i.e. scabland, waste almost exclusively when the huge deposit was made. Sorting and wear of this gravel indicate sources more distant than walls of the Saddle Mountains water gap, 3–4 miles upstream. The gap therefore was already well opened and deepened when the massive gravel deposit was made.

A roadside cut near the southern end of the summit flat showed southeast-dipping fore-sets. A few borings show sand, gravel, and cobbles in the upper part of the bar but only gravel and boulders in the basal portion. At depths of about 100 feet these rest on Ringold clay and sand.

A.E.C. restrictions prevented examination of the southern cliff. If the deposit is a bar, stratification here should be either (1) steeply east-dipping, delta-type fore-sets, or (2) gently southwest-dipping beds parallel to the slope of the bar, with shallow fore-sets dipping into the bar, as in the Lind Coulee bar at the East Low Canal crossing. Construction of the Priest Rapids dam on the Columbia, now authorized, should resolve this question.

If this massive deposit be considered an erosional residual, the 18–20 square miles of lowland immediately beyond its east-facing scarp must be explained. That tract has no stream, and it cannot possibly be a meander scar made by the Columbia. Even the 25-foot contour intervals of the Geological Survey maps show clearly that it is another Cold Creek Valley in origin, an unfilled fosse behind a valley-margin bar.

This Priest Rapids bar is oriented and streamlined for the same great river that made the Cold Creek and Gable Mountain bars and in but one place shows signs of any smaller bar form superposed on its smooth riverward slope. Its thickness is approximately the height (75–125 feet) of the 4-mile-long lee scarp. The low area immediately east of it, underlain by Ringold, is obviously a remnant of the original surface on which the bar was deposited.

A smaller and lower bar, product of a later and smaller flood, trails about 4 miles downstream from the cliff in the huge bar's southern extremity. On the U.S.B.R. map, this younger bar top (125 feet above the river) is shown 60 feet higher than the dune-covered fosse between it and the low land east of the great bar. Yet the low area is 100 feet higher than the top of the younger bar.

Both the Cold Creek and Gable Mountain bars, separated by an undrained sag, can be identified farther south by linear elevations in the dune-covered central tract of Pasco basin (Fig. 17). The fosse of the Cold Creek bar determines the course of the creek to its junction with Yakima River.

Another conspicuous basin bar, also with a dune sand cover, lies just east of the Columbia and northwest of Pasco (Fig. 17). Its top is 200 feet above the river, its fosse 100 feet deep. Esquatzel Coulee's western channel enters the fosse, hanging 40–50 feet above its floor. Were the bar contemporaneous with the channel, the last 2 miles of the tapering form could hardly have been deposited.

These valley forms in the Pasco basin were never made erosionally during normal dissection of a complete valley fill.

The formidable problem of removing a fill in this basin, 16 miles wide between the 750-foot contours in the latitude of Pasco (Flint asked for the 900 foot contour), was handled by both Allison and Flint in the most general terms, with no comments on the surprising absence of extensive terrace remnants. Lower Yakima structural valley is another large basin which must have shared in this fill (Pl. 1). Its width is much greater in proportion to its stream than Pasco basin, but it likewise is empty and is unterraced except close to the river. It is quite unlike the strongly terraced Yakima Valley above Ellensburg. Flint and Allison said nothing about the place of lower Yakima Valley in their theoretical fills.[11] It is

[11] Flint ignored the scabland and upvalley fore-sets in associated gravel bars described and figured by Bretz (1930b, p. 412) in the Chandler Narrows at the mouth of this structural valley; and made no text comment on the pebbly silts veneering Yakima Valley slopes up to 1100 feet A.T. Allison (192[illegible], p. 678), placed an ice jam in the Narrows which, by growing higher, detoured the upvalley flood current onto successively higher surfaces and thus made possible the 450 foot vertical range of this very local scabland. Unaccountably, however, the lower (earlier) bars are still perfect. The superposition of the growing dam did them no harm.

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argued here that no such fills ever existed, and it is suggested that the supposed correlatives below Wallula Narrows are probably older deposits shallowly covered with fresher debris. Huge gravel mounds comparable to the scabland bars have been described (Bretz, 1925; 1928a) along the Columbia as far as Portland. No restudy of that region was possible during the 1952 field season.

Allison's Snake River gravel bars, although older than Flint's terraces, are also relics of former valley fills. They cannot be remnants of a Snake valley train. Consistency in the ice-jam hypothesis therefore should postulate a comparable prescabland aggradation in major valleys throughout the plateau with local thicknesses equal to heights of its largest bars. As they are prescabland, these valley fills must antedate the divide crossings. This, with their overwhelming percentage of basaltic and caliche gravel, requires local origin on the plateau. Thus plateau valleys unentered by glacial water should still possess records of this episode. None does. If the plateau scabland bars are deposits of glacial streams, the Snake Canyon bars should be accepted as of the same genesis.

The high Wallula scabland, 800 feet above the river and more than a mile wider than the top of the gorge, was accepted by Allison and Flint as channeled and accompanied by scabland gravel deposits. Although extraordinarily high, its altitude is that of the Yakima Valley and Walla Walla basin pebbly silts and drifted erratics and approximately that of upper-limit records along the lower Snake. To explain these facts, Bretz (1925, p. 257) proposed that Wallula Narrows had acted as a bottleneck for the combined volume of all scabland rivers, and even announced the discharge through the short canyon as 39 cubic miles per day. This proved to be the most shocking of all interpretations based on the flood hypothesis, and Bretz retreated subsequently, taking refuge in possible post-scabland anticlinal uplift or postscabland (and late scabland) deepening at the Narrows, for neither of which is there any known field evidence.

The scabland on top of the Wallula gorge walls apparently must be early, although it hardly suggests its age. It would seem to predate the development of the Quincy basin cataracts which, 100 miles distant, have brinks only 100 feet higher. It may be correlative with their earliest westward discharge at 1360 feet A.T. Allison's or Flint's fills would readily resolve the problem if only there were supporting evidence for them. But even the concept that scabland bars are erosional forms developed in former valley fills cannot be used with Pasco basin's and lower Yakima Valley's great empty widths confronting us. Nor can the high Wallula scabland, when compared with Drumheller, Othello, Palouse-Snake divide, Grand Coulee complex, and other contributing scabland, possibly be adequate for the ice-jam "run-around" concept. There may be some possible combination into an eclectic hypothesis which future study will bring out. If only one factor be involved, the bottleneck idea again seems most acceptable. At the rate computed in 1925, Lake Missoula's 500 cubic miles of water would pass through the Wallula Narrows in a little less than 2 weeks.

Columbia-Snake junction (Pl. 1) also has (1) gritty silts up to 1050 feet A.T. or more, (2) scabland-marked narrows separating it from the larger valley and (3) fore-set gravel containing foreign pebbles with dip upvalley away from the Columbia (Bretz, 1929, p. 531). Both men have ignored these features. No theoretical ice jam can explain this because the fore-set gravels lie on the floor of a marked broadening, 4-5 miles east of the narrows. In contrast with Yakima Valley, the Walla Walla basin contains thick deposits of silt and fine sand derived from a glacial Columbia, with marked contrasts between, and disconformities separating, different members. The basin appears to have repeatedly become a shallow post flood lake. Detailed study of these sediments may yield significant data regarding the glacial Columbia's flood and non-flood experiences.

Palouse-Snake Divide and Environs

(Maps: Haas and Starbuck topographic and geologic maps; U.S.G.S.)

(Bretz and Smith)

General

Glacial water, flowing south down the Cheney-Palouse tract, was in excess of the amount Washtucna Coulee could carry, and it widely overflowed a structurally determined

divide, escaping southward from Palouse River valley to enter the canyon of the Snake, making a scabland record on more than 80 square miles of the divide summit and producing the deep canyon (top width 1250 feet, maximum depth 440 feet) by which Palouse River now enters the Snake (Pl. 1). Interpretations of the conditions which caused this overflow and canyoning vary widely. Four new topographic maps of the U. S. Geological Survey (Benge, Haas, LaCrosse, Starbuck) and a complete coverage by aerial photography supply some pertinent new data.

Flint believed that any first-magnitude flooding across the divide would find, or make, a ponded Snake Canyon and would build "a large deltaic deposit whose foreset beds would have an amplitude of hundreds of feet" in the deep Snake River canyon (1938, p. 513). Because "nothing of the kind is found in the Palouse Canyon scabland", Flint believed that an earlier proglacial flow had occurred, finding "a very low route" already in existence across the Palouse-Snake divide to permit spill-over from "a comparatively thin fill" in the Palouse Valley. This gashed the divide to make the Palouse Canyon transection (1) before the major episode of filling occurred, (2) before backwater (Lake Lewis) began rising in Snake River canyon to cause the deposits at the Palouse-Snake junction which Bretz had termed bars, and (3) before any scabland had been made on the divide. These "bars" Flint viewed as erosional remnants of a slowly aggraded dam, comparable in character to the Chippewa River deposit in the Mississippi River which forms Lake Pepin. This dam (800 feet thick) formed "Riparia Lake" upstream in Snake River canyon. By coincidence alone, Lake Lewis was slowly rising at the same time, thus avoiding long delta fore-sets in the deposits. Such fore-sets, however, do exist. Flint saw them (1938, p. 479, 481) but did not explain them.

Scabland Features on the Divide

With reference to Flint's supposed "very low [preglacial] route", it is instructive to note that an east-west profile along the high northern part of this divide, drawn from the Haas and Starbuck quadrangle maps (Fig. 18), finds the entire 9-mile width on the summit scabland to be 1280 feet or higher, more than 200 feet above the present aggraded Palouse Valley floor, except for an eighth of a mile immediately adjacent to the canyon walls on either side, where it is 1200 feet. A mile south of the cross section the brink of the canyon walls is 1280 feet. The loessial scarps marginal to this cross section are 120 to 180 feet high, and at least 100 feet of loess probably covered the divide top when the first glacial spill-over occurred. There is also at least 50 feet of gravel in the bottom of the preglacial Palouse at this place. These facts require a thickness of not less than 350 feet (to 1325 feet A.T.) in Flint's "comparatively thin fill" to make the first crossing possible. His "very low route" never existed, and Palouse Canyon cutting belongs in the general scabland-making episode.

Flint minimized the size of the various cataract alcoves of this district, citing five examples on the divide, not one of which is deep enough to be shown on the new topographic maps. His argument collapses when the map of H U Ranch dry falls (Fig. 19) (Haas quadrangle S. W. ¼ Sec. 29, T 14 N., R 36 E.) is examined. The cataract cliff is 280 vertical feet from the lowest notch in the lip to the bottom of the plunge pool. Recession of the falls left the Davin gorge 1½ miles long containing a closed depression equally long and 128 feet deep.[20] The water that supplied the H U Ranch cataract even at its very last functioning had to cross the but slightly channeled scabland divide at an altitude of 1280 feet A.T. or more.

Inspection of the Haas and Starbuck quadrangle maps shows several such features far exceeding in magnitude the examples cited by Flint. One of these (Devils Lake, crossing Sec. 17, T. 14 N., R. 37 E.) has an 80-foot dry falls at the head of a recessional gorge about 2 miles long, more than 100 feet deep, and containing closed basins with 40–80 feet of closure. The largest and deepest of these terminates almost on the brink of Palouse Canyon, itself 200 feet deeper at this place.

[20] One of Flint's examples (1938, p. 490), is just west of the Davin Ranch where one may look northward up the gorge to the cataract cliff.

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Another dry falls (S.E. ¼ Sec. 1, T. 14 N., R. 36 E.) tunneled through by the Union Pacific R.R. between canyon and preglacial valley is 100 feet high.[89]

Were it not for late development of a short channel from the northeast, 80–120 feet deep above the H U Ranch cataract and thus an incision of its lip, the sheer drop here would be 350–400 feet. Figure 19 suggests that before this channeling occurred the cataract head was a cascade chute at the northwest end of the gorge. Alignment of this chute with the straight recessional gorge is determined by a vertical fault with 40 to 50-foot downthrow to the east. But the chute head is close to the western margin of the divide scabland, and the larger volume of water came from the northeast. The lengthening channel, therefore, left the fault trace and headed 2–3 miles to the northeast. The profile of the west wall of the Davin gorge shows that the cataract became markedly higher as it receded along the last half mile of its length by migrating out of a prescabland, minor valley along the fault.

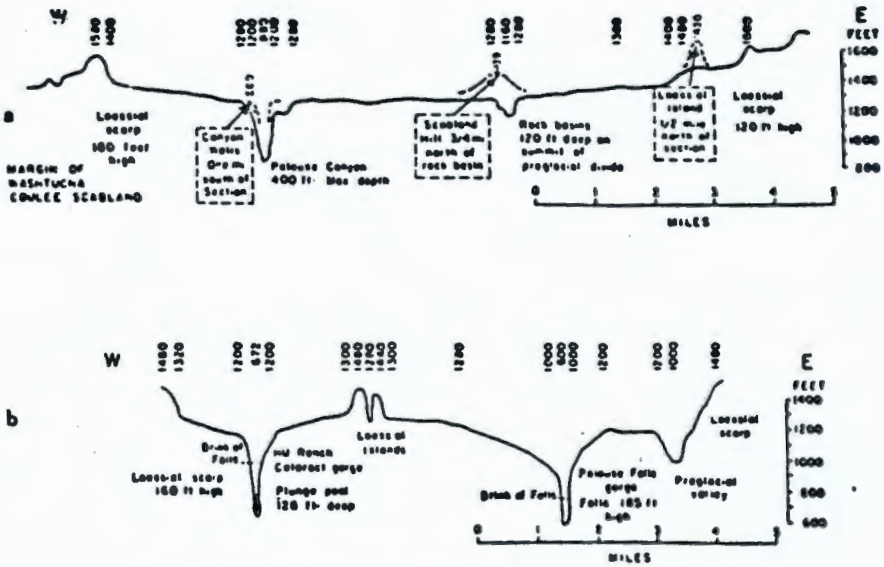


FIGURE 18.—PROFILES OF SCABLAND ON PALOUSE-SNAKE DIVIDE
a—Along the crest of the former divide
b—Immediately downstream from the two cataracts

Flint also minimized the depth of rock basins in this district, as elsewhere in the area of his study. He could never have seen the two basins 1½ miles directly south of Hooper Junction on the very summit of the divide scabland (Sec. 3, T. 14 N., R. 37 E.) (Fig. 20). The larger one is ringed by a 1240-foot hachured contour and is more than 120 feet deep, and the smaller one is more than 80 feet deep below the same contour. These great empty holes are impossible erosional products of Flint's streams that removed the fill. If they were pre-fill in age, they would now be full of gravel. They cannot be forced into the fill-and-cut strait jacket.

Bases of the loessial scarps bounding the Palouse-Snake divide scabland are 1400 feet A.T. or higher on both sides at the north end of the wide spillover. Flint got the vertical range of 120 feet or more in summit scabland

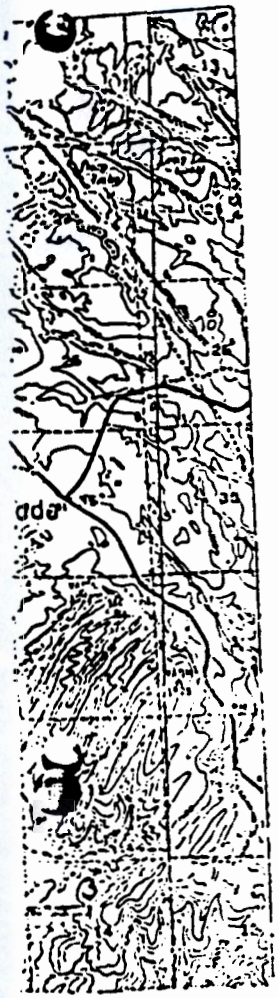
[89] Trimble (1950) noted a striking joint control of the shapes and orientations of many rock basins, "slots" and gorges in the Palouse-Snake divide scabland, some closed basins 100 feet in depth. He accepted them as scabland features, the erosional results of glacial water, but disclaimed any "attempt to explain the mechanics of their erosion."

FIGURE 19.—VICINITY OF H U RANCH CATARACT

Western part of Palouse-Snake divide scabland. Loessial topography in northwestern and southeastern portions of area, loessial islands in central part. Largest island is 1 mile long and 500–1000 feet wide, and its scarps are 150 feet high. Deep Lake gorge is tributary to Palouse Canyon a mile beyond eastern edge of map. Part of Haas and Starbuck topographic maps, U. S. Geol. Survey. Contour interval 40 feet.

by aggrading an equivalent amount so that a river whose "discharge was less than that of the Snake today" could reach successively higher and wider surfaces. However, his river did not make the scabland, it only scoured off the loess. The scabland relief was produced later, while the fill was being removed, and this occurred simply because original preglacial gradients were being restored, not because of any augmentation in discharge. If a normal valley train already existed in Washtucna, it could have been a factor in causing overflow, but the 80 square miles of scabland on the preglacial Palouse-Snake divide can never be explained by Flint's theory. The acid test, however, is in features on the south side of Snake River canyon.

Allison never specifically located any ice



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jam on the plateau scabland but was content with general statements regarding what would happen if they did form in a drainage system invaded by meltwater streams. For the Palouse-Snake divide's scabland, he would obviously have to block Washtucna Coulee (Fig. 2; Pl. 1) somewhere along its length to a height great enough to cause the first spillover, estimated as at least 300 feet above the present aggraded Palouse Valley floor, or 1325 feet. A.T. However, water reached an elevation of 1400 feet at the bases of the loessial scarps margining this 9- to 10 mile wide tract, and Allison's theory requires more ice jams not alone in the growing Palouse Canyon but also on the divide top itself to avoid the great volume. Where can they be placed on this great width so that water would have to rise to detour around them, make the higher scabland, and cut the loessial scarps? To the writers, such a mechanism is impossible here. Only in constricted or crooked valleys could jams ever grow to the required dimensions. Furthermore, in the Washtucna Coulee not a single favorable place was found for the jam called for nor any features like these Waters (1933, p. 818) interpreted as ice-jam records in Columbia valley north of the plateau. Still further, the loessial scarp bases along the 5 miles of Washtucna's length constitute a uniformly descending profile, impossible to explain if an ice jam interrupted the glacial stream's surface gradient.

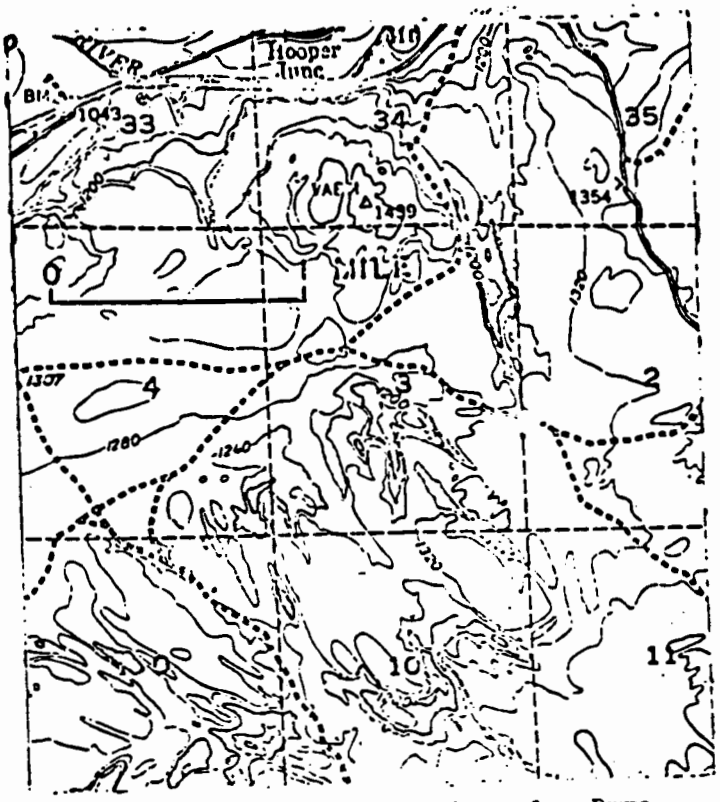

FIGURE 20.—ROCK BASINS ON SUMMIT OF PALOUSE-SNAKE DIVIDE
Basin in south-central Sec. 3 is more than 120 feet deep. Vertical range of scabland in this tract is 400 feet. Part of Haas and Starbuck topographic maps, U. S. Geol. Survey. Contour interval 40 feet.

To erode Palouse Canyon across the divide deeply enough to provide a permanent rerouting of the river, any ice jam in Washtucna

must have persisted (or been repeatedly renewed) while Allison's moderately sized, detoured meltwater river deepened more than 400 feet in basalt. The narrow new route was never (more than temporarily) clogged with the abundant floating ice while the dam in the much wider preglacial valley continued to be effective. How can rock basins 100 feet deep on the scabland summit of the divide be explained by Allison's hypothesis? How could buttresses of loess for the divide top's dam survive? How, when buttresses failed, could the dam grow laterally to close the gaps seized upon by the escaping water and thus eventually make the 9–10 mile width of summit scabland? The quantity of floating ice constantly required of a normally wasting ice front to maintain and extend a dam on this broad summit passes all credibility. Failure of a Lake Missoula dam might rapidly release the enormous quantities of berg ice demanded by this elaboration of Allison's concept, but no believer in moderately proportioned glacial rivers will ever accept that solution of the problem.

Bars in Snake Canyon

(Bretz and Smith)

At the Palouse-Snake confluence, Allison and Flint have reinterpreted the "bars" (Bretz, 1928a), disagreeing with each other as well as with Bretz. Field study in 1952, with the aid of the Haas and Starbuck topographic maps, has led to a vigorous reaffirmation of the original interpretation and a denial that any dam of debris or ice ever existed at this place in Snake River Canyon.

Bretz originally described two great bars at the junction, both on the south side of Snake River. One was a "mid-canyon bar" about 2 miles long on the floor of the canyon, deposited by glacial water flowing tumultuously *up* the Snake. The other was a high-lying "shoulder bar" in the mouth of Fields Gulch, a tributary from the south entering the Snake about 2 miles farther downstream. The shoulder bar was made by a detour of part of the flood southward across the Snake and thence westward around the south side of a big, "semi-isolated" basalt hill, there to reenter the Snake in the south wall of its canyon (Fig. 21).

Flint interpreted these bars as remnants of his Riparia Lake dam, a Snake canyon fill 800 feet thick, actually the toe of his 120-foot fill on the top of the Palouse-Snake divide. Lake Lewis, the cause of all this valley deposition, was supposedly rising downstream in Snake River canyon at the same time, and the rate of deposition at the dam site kept pace, so this dam never developed delta structure.

Flint was a bit reserved about the composition of the mid-canyon bar, saying of the "rubbly, basaltic, cobble gravel with huge boulders, too little size-sorted to have distinct bedding" that "it strongly suggests torrential conditions" (1938, p. 513). The depression (fosse) between the bar top (241, not 150, feet above the Snake) and the basalt knobs and cliffs south of it, he said was "unusual" (p. 481) but appeared to be comparable to "'deeps' at the outside of bends in the river during dissection" of his dam.

Allison (1941, p. 69–70) said of the mid-canyon bar that its "top is constructional", its "flutings are primary", and the depression back of it is also primary, showing "no resemblance to deeps at the outside of river bends nor to plunge pools". "It represents the top of the fill made by the last outpouring of glacial waters from Palouse River Canyon". Although that "outpouring" of "torrential" water had to be *up* Snake River canyon, neither Allison nor Flint noted the fore-set beds at the eastern end of this bar. They dip *up* the Snake and toward the depression.* Allison thought the depression "was left unfilled—because the area was occupied by ice, driven against the cliff by force of water from Palouse River canyon and then protected from wasting by shadow". There is, however,

* With Lupher (1944), they have ignored the existence of such up-valley fore-sets, reported by Bretz to occur as far as Lewiston. Existence of the new Hay geological map (40-foot contour interval) and of State Highway 3 should encourage examination of the readily accessible Central Ferry "half mound bar" (Bretz, 1929, p. 411), 20 miles up the Snake from the mid-canyon bar. Despite the authority of the map, it cannot be correctly described as a Snake River terrace.

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FIGURE 21.—SCABLAND FEATURES ON SOUTH SIDE OF SNAKE RIVER AT CONFLUENCE OF PALOUSE RIVER

Fields Gulch preglacial course shown by dashed lines. Part of Starbuck and Haas topographic maps, U. S. Geol. Survey. Contour interval 40 feet.

no summer shadow on the area from adjacent cliffs.

From the mid-canyon bar minor dependent bars extend southward, *away* from the Snake and back in the mouth of a blocked, preglacial tributary that formerly entered the canyon across the north edge of section 6, T. 12 N., R. 37 E., and now is detoured westward to Fields Gulch. The headlands at the former mouth are marked scabland buttes rising above these southward extensions of the mid-canyon bar. Each butte has a long gravel ridge in its lee that tapers out and down *away* from the Snake. These gravel ridges are genetically part of the mid-canyon bar. Their existence, magnitudes, and space relations must not be ignored or slighted. The knobs reach 800 feet A.T., and the south-pointing bars are as high as the mid-canyon gravel hill, 731 feet A.T.

From Lyons Ferry at the junction of Palouse and Snake rivers (Starbuck quadrangle) a circuitous road may be followed to DeRuwe Ranch (Haas quadrangle), just south of the shoulder bar in Fields Gulch (Fig. 21). In the second and third miles of this road, one climbs from BM 547, entirely on nonterraced gravel, to BM 861 in the detoured drainage. Enroute, constructional forms are very obvious in the moundings and enclosed, undrained depressions. The striking little "trickle bar"[31] (Pl. 15, fig. 4) which descends the southwest slope of a scabland hill in SW ¼ Sec. 36, T. 13 N., R. 36 E. looks somewhat like a flattish debris cone or a steep detrital fan, but it is definitely ridged along its length, its lateral slopes are much too steep to harmonize with the gentler gradient along the crest, and its bulk is far in excess of what could be shed from the small section of the basalt hill that could contribute. The ridged fan or cone form mounts almost to the hilltop. The altitude of its crest ranges between 920 and 1000 feet. The deposit originally blocked local drainage off the hill. A gully across its low distal end has spared portions of the floor of the once-closed depression back of the bar. The valleyward lateral slope at the terminus descends 50 feet and flattens out in a 40-acre closed depression shown on the Starbuck quadrangle map. The deposit is composed almost entirely of little-worn basalt pebbles and boulders. A few well-rounded Snake River pebbles were found. The form is that of a small, local bar 390–520 feet up on the bar-mounded slope above Snake River but 300–430 feet below the level of Flint's supposed dam across Snake River canyon. The water that carried its debris southward down this hillside away from the Snake came over the top, 1010 feet A.T.

The shoulder bar and immediate environs (Fig. 21) were carefully examined during this field study. Renewed excavation in the old pit on the north side afforded good sections, and the topography of the entire deposit was seen by walking over it. The interpretation that it is a great gravel deposit essentially with original outlines and with long deltaic fore-sets dipping northward toward the Snake is here emphatically reaffirmed.[32]

The flattish summit of this shoulder-bar deposit is approximately 1000 feet A.T. over nearly half of Sec. 25 and more than half of Sec. 26, T. 13 N., R. 36 E. It is diversified by low linear ridges and swales, their relief 10–15 feet in places, impossible to explain as erosionally made by subsequent runoff. A few well-worn Snake River pebbles were found; otherwise the material is all little-worn basalt.[33]

Recognition of the true character of this minor relief on the summit (Pl. 13, Fig. 1) did not come until aerial photographs were studied after the writers had left the field, hence no measurements were made. Scaled from the

[31] Long narrow bars steeply descending preexisting slopes and appearing as trickles from a distance.

[32] Among Allison's comments on Flint's work is the statement that this shoulder bar "was built into water [525 feet deep] at the edge of Snake River Canyon by currents which left the major valley a short distance, [2 miles] upstream [and detoured around the south side of the semi-isolated hill, 1211 feet A.T.] when free flow down the valley was obstructed by ice jams."

[33] Allison's view that the gravel of the shoulder bar is largely reworked, old, high-level Snake River terrace gravel is untenable. The percentage of well-worn constituents is small, of nonbasalt fragments even smaller. Furthermore, Snake River canyon for nearly 75 miles upstream, where Allison's supposed old, high-level terrace system should be well recorded, has no such deposits at comparable altitudes above the river. The 20 miles of this canyon shown on the Hay and Starbuck geological maps (U.S.G.S. 1951) have but one patch of gravel (Qs-Quat. scabland) as high as 450 feet above the river.

.s [illegible]in a 40-acre closed de-
[illegible] Starbuck quadrangle
it is composed almost entirely
.salt pebbles and boulders. A
d Snake River pebbles were
n is that of a small, local bar
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river but 300–430 feet below
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photograph (Production and Marketing Adm., CCH 16-197), the crests of the giant current ripples are about 175 feet apart.

From this summit flat, the bar surface descends 200 feet southward and westward with a convex slope which the Haas quadrangle map shows as crenulated. Orientation of the ridged crenu[illegible]ons changes gradually from nearly south-pointing forms on the south side to west-pointing, even northwest-pointing, forms on the west side of the hill. A little gullying has occurred between the ridges low on the slopes, but, for the most part, they are original shapes of the bar surface.[34]

Sect[illegible]ns in the old railroad gravel pit on the Snake River face, cut deeply back into the deposit, show the bar material to be fore-set bedded almost throughout (Pl. 14, figs. 1, 2, 3). Parallel to the steep, riverward slope of the gravel hill, these long fore-sets are not a misinterpretation of pseudo-fore-setting due to slopewash. The 100-foot scarp trending northeastward from the pit for a quarter of a mile is the constructional front of the deposit, avalanching as in a dune. It is not an erosional scarp. Its strike parallels that of the long fore-sets in the pit (Flint, 1938, p. 481, to the contrary notwithstanding) and the elongation of the giant ripples. Water, not debris, or ice, filled Snake Canyon up to more than 1000 feet A.T. at this place when these fore-sets were deposited. Flint offered no explanation for them.

In this fore-set gravel is embedded a granite boulder 5[illegible] feet long, its outlines fracture-determined and only one surface showing pre-fracture abrasion. Flint (1938, p. 498) remarked that "In such shallow scabland streams as are indicated by the stratification of their deposits, only small pieces of glacier ice could be expected to travel down their lengths. . ." How small a piece of glacier (or river) ice could have held onto this granite boulder for the 75 miles it travelled down the Cheney-Palouse scabland river? And meandering added to that mileage![35]

This shoulder bar in the lower part of Fields Gulch *contains the delta fore sets Flint asked for* at the mouth of the Palouse, if the flood theory were correct! The mid-canyon bar is part of that "delta"; the bars tailing southward from the scabland buttes in sections 30 and 31, T. 13 N., R. 37 E., are part; the bars along the road south from Lyons Ferry are part; the "trickle bar" is part; the bars farther west, tapering southward from the same hill are part. The flattish summit of the shoulder bar with its giant current ripples is the *subfluvial* "delta top". All gravel forms are portions of a deposit made at the *bottom* of the great torrent which carried most of its debris *across* Snake Canyon and much of it *up* for more than 500 feet on the far side. Volume and velocity of the flood that made these bars were greater than anything that Flint objected to.

Allison, accepting this remarkable detour of glacial Snake River, made it possible by placing an ice jam in the canyon just below the mouth of the Palouse (Fig. 41). A slight constriction here might favor the idea, but the dam would have to be from three quarters of a mile to a mile wide (across the canyon), and, to allow the detoured stream to re-enter the canyon where it did, the dam could be only 2 miles long. Such a dam never could have had enough frictional grip on the canyon walls or among its constituent ice blocks to hold back a 500-foot head of water. Furthermore, there was equally deep water where and when the detour re-entered the canyon below his dam. Above the ice jam, there was only slack water, and through this the scabland gravel had to travel to cross the canyon and climb to the shoulder-bar summit. Allison's hypothesis really requires a scabland run-around canyon at this place, instead of a gravel deposit.

Allison needs another ice jam for his sequence of events at the Palouse-Snake junction. Plate 1 and Figure 19 show that the 4-mile wide Davis Ranch portion of the divide scabland, lying west of the isolated group of loessial hills, had to be effectively blockaded to make the detour south of the Snake possible. Otherwise, all

[34] A repeating character of the giant current ripples seen during the 1952 field season is [illegible] extension of the ridged forms of a bar summit down the slope toward the adjacent channel. Neither slopes down into a fosse nor erosionally scarped valleyward slopes have shown this feature.

[35] Another granite boulder, equally large, in the Cow Creek scabland 1½ m. [illegible]th of Hooper lies as high as the scabland [illegible] the divide. Still another and larger (9 feet maximum diameter) granite boulder lies 3 miles south of Ewan, 35 miles down along the Cheney-Palouse tract.

Cheney-Palouse glacial water would have entered the Snake below the site of A' 'son's canyon dam, and only Snake River water would have used the detour. Coming directly from a ponded Snake, it could have had no gravel load, and no shoulder bar could have been made.

Prescabland Fields Gulch

(Bretz and Smith)

The floor of Fields Gulch in the half mile between the shoulder bar and Snake River is very narrow compared to its proportions farther upstream (Fig. 21). It is a hanging-valley mouth, with a sharp entrenchment made subsequently. Its gradient is 200 feet to the mile in this stretch, six times as steep as in the next 5 miles upstream. It clearly does not record the stream that preglacially drained the 50 contributing square miles of mature topography lying to the south. E en if a partial damming of the gulch by the bar (Bretz, 1928a, p. 659, Fig. 8) interrupted the gradient, this narrowness and steepness would indicate that these great bar deposits have blocked a capacious lower course elsewhere, and have turned postscabland drainage into the present aberrantly narrow and steeply graded route. A reconstructed prescabland Fields Gulch (Fig. 21) would enter Snake Canyon where the mid-canyon bar and other higher bars obviously fill and block an earlier drainage way to the master stream. Compared with the valleys of neighboring Tucannon River and Kellog Creek, the width here between basalt hills is certainly adequate for the drainage area. And this blocked valley is twice as wide as the present one downstream from the shoulder bar.

Flint's Riparia Lake

(Bretz and Smith)

For the following reasons, the writers hold that Flint's Riparia Lake never existed.

(1) All roads crossing the region where the distal portion of Flint's 1300-foot dam (Fig. 21) must have lain were traversed, and a few miles of foot traverse was made across interroad tracts. No remnants of any gravel or sand deposit were found on the broad, thinly loess-covered, basalt uplands above the summit level of the shoulder bar, and no suggestion of debris from such deposits was seen in drainage ways. It is quite impossible that all that theoretical deposit could have been carried off these hilltops where it was originally 100–300 feet thick.

Only wind, rain, and slope wash are available agents. Had they been thus effective, there would be no remnants of Flint's fill elsewhere, nor of Bretz's bars, to theorize about.

(2) The Haas and Starbuck geological maps (U. S. Geol. Survey, 1954), made for engineering use in proposed dam construction on Snake River, show no gravel deposits above about 1100 feet A.T. on the area covered by Flint's hypothetical 1300-foot dam. The highest part of the shoulder bar's gravel is 1120 feet. Along the east side of Flint's fill on the Snake-Palouse divide, altitude of which he showed as 1350 feet, the Starbuck map shows a ragged pattern of local drainage gulches in basalt, with loess-covered interfluves (but no gravel remnants) descending to and below 1200 feet A.T.

(3) The giant ripple marks covering the shoulder bar's square-mile summit flat record a constructional surface, the original top of the deposit, 325 feet below the altitude of Flint's delta surface at that place.

(4) Flint's Figure 9 (1948), showing the delta-dam gradient as about 13 feet per mile, also shows a remarkable steepening downstream to 30 feet per mile. The distal margin of the supposed dam had to be at least 1300 feet A.T. for 10 miles west of the Palouse junction in order to impound Lake Riparia. The upper limit of Snake Canyon flooding 5 miles farther downstream is only 1200. (*See* Flint's Fig. 11.) Hence the incredibly steep gradient!

(5) Half a dozen gravel-covered tracts of 160 acres or more, lying on the Palouse-Snake divide scabland, are shown on the Haas and Starbuck geological maps. Two closely associated ones, just east of Palouse River about 2 miles above its mouth (Starbuck map), partially bury interfluve spurs of the preglacial basalt topography. Where nearest each other they are separated only by a small streamway draining from higher loess-covered country farther east. Two tributaries join, just above

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this narrow place. Their 75-degree divergence upstream (eastward) outlines another basalt interfluve spur of comparable size, lying between the two. As shown in Flint's Figure 3 (which has some considerable altitude errors) this spur has no gravel cover. The map distance between the two gravel patches is a tenth of a mile at the west where the tributaries join and increases upstream to three quarters of a mile across the gravel-free spur.

"A single course of fore-sets [at least] 35 ft. thick" (Flint) in the northern deposit, described by Bretz (1928a, p. 655) and confirmed by Flint (1938, p. 479), dips N. 68° E. Bretz read this upvalley dip, away from the Palouse, as recording introduction of the pebble gravel diagonally across the top of the buried spur and considered both deposits as essentially bars, their form and location conditioned by the underlying topography and direction of current. To Flint, they were erosional remnants of his Snake Canyon dam whose flattish tops (terraces) now lie 125–285 feet below its original surface at this place.

The outstanding objection to Flint's interpretation here is the impossible survival of the closely contiguous "terraces" which, down in the united stream valley, 290–330 feet below the lowest portions of the flattish tops and 600 feet below the original surface of his fill, are only 500 feet apart. By his interpretation, half a square mile of original gravel cover for the scabland spur, 125 to nearly 600 feet thick, has been removed through that constricted gap without widening it.

(6) Flint's Riparia Lake received the Snake River of that time as well as glacial water from the Palouse. Its outlet must have been a considerable river. Nothing in Flint's text deals specifically with this outlet. His Figure 9 has an arrow marked "Lake outflow" near the southern margin of the delta. Traced on the Haas and Starbuck geological maps, it traverses a basalt topography ranging from 810 to 1200 feet altitude! The arrow therefore indicates an entirely hypothetical channel across the vanished delta. Figure 9 also shows four "conspicuous abandoned channels" across the site of the dam, two of them about a mile back from its low southern edge, the others even farther back. One does not exist. Two are misinterpretations of unaltered, preglacial saddles, related to his lake only in that they lie below its level. The fourth (in SE ¼ sec. 28, T. 13 N., R. 36 E.) is truly a small scabland discharge route through a preglacial saddle at 1000 feet altitude, a mile northwest of DeRuwe Ranch and 3 miles back from his delta's distal margin. It is 325 feet below the top of the supposed dam at this place. There are good minor bar forms at intervals from the aggraded flat at the ranch buildings (800 feet A.T.), (which also has bar forms) up to the col. There are even unfilled depressions close to the summit, compounded of small scabland knobs and bar knolls. Obviously, a current of flood water crossed this saddle at 1000 feet, a part of the overflow when the shoulder bar was being built. But obviously also it did not spill thence down the steep ravine toward the Snake. The scabland notch is not a channel and does not record any Snake River course during dissection of the dam. Furthermore, its small capacity falls far short of Allison's needs, should he try damming Snake Canyon below Fields Gulch but above the mouth of the preglacial tributary on the far side of the saddle.

(7) With a gradient of 13 feet to the mile for the Cheney-Palouse fill and the top-set beds of hypothetical Riparia Lake dam (Flint's estimate), the lake's outlet must have been forced to skirt the far southern edge of his Snake Canyon deposit. This Flint recognized. Snake River today, therefore, should be in a post-dam canyon superimposed on the basalt upland at that same place, and the preglacial canyon's dam should still exist. Palouse Canyon (made before his episode of filling) should still be buried in gravel, and Palouse River should be following its Washtucna Coulee preglacial route. Instead, the Snake has inexplicably flowed *up* the eastern front of his delta, the lake outlet climbing 30–35 feet *against* the delta's lateral slope to relocate and re-excavate the preglacial canyon 3 miles north (*see* Flint's Fig. 9) of the only place the glacial Snake could have crossed the delta when at its maximum growth. The irregularly hilly basalt topography shown in Figure 21 forbids any notion that the post-dam Snake could, while re-excavating, have slipped laterally back into its preglacial course. The hill summit between the DeRuwe notch and Snake Canyon is 1160 feet A.T. Once caught in the notch, the river never could have escaped.

(8) There are no shore lines for Riparia Lake,

even of the faintest detectable character, on the soil-mantled gentler slopes of Snake River canyon upstream from the dam, although there was ample opportunity for them to develop during the gradual trenching of that deposit at the mouth of the Palouse. Most of Flint's Cheney-Palouse scabland gravel was "leisurely" carried off during that same time.

(9) There are no lacustrine deposits on these slopes. There is, however, a widely distributed mantle of unsorted, unstratified silt containing abundant grains of fresh basalt with nonbasaltic pebbles and boulders extending up to 1300 feet altitude (Bretz, 1929, p. 407–418). No Riparia Lake type of ponding in Snake Canyon can explain the up-valley transportation for nearly 75 miles of this pe' 'y silt from its source, the Cheney-Palouse scabland river. Vigorous surging up the canyon is required.

(10) Snake River valley alongside and below the summit of the mid-canyon bar is only 1000 feet wide, and one bluff is all gravel. By the fill-and-cut hypothesis, this is all the widening the river has been able to do in the canyon bottom since Riparia Lake was drained. In contrast, Washtucna has a bottom width of 2000–2500 feet for many miles, made by a small divergent strand of glacial water. No postglacial stream has used the coulee. Harmonizing these facts with Flint's concept is quite impossible.

Devils Canyon

Map: Connell Quadrangle, U.S.G.S.

(Bretz)

Streamless Devils Canyon, 15 miles west of Palouse Canyon, transects the same Washtucna-Snake divide and is subequal in width and depth. Cataract or cascade recession here, as at H U Ranch falls, made the 4-mile gorge along a preglacial tributary of the Snake. The glacial stream made no scabland on top of the walls, and it ceased to flow before recession had completely cut through the divide. A rock sill at the canyon head, nearly 100 feet above Washtucna's floor, is tunneled through by the Spokane, Portland, and Seattle R.R. between canyon and coulee. Summit of the sill is more than 950 feet A.T., and the bottom of the canyon a mile to the south has an 800-foot depression contour. The canyon is empty thence to the Snake, but its flaring mouth has an unterraced, knolled, and ridged gravel mound rising nearly 300 feet above the Snake to the south and about 50 feet above a once undrained depression to the north. This mound projects more than a third of the way across the bottom of Snake Canyon and is entirely of gravel. The highest part stands nearly in midwidth of Devils Canyon. Figure 3 of Plate 9 shows a train of giant current-ripple marks half a mile long across it.

Flint derived Devils Canyon in part by falls retreat during removal of fill, originally 1300 feet A.T. at the canyon head. On this fill, the Devils Canyon distributary from the Washtucna distributary initially descended 100 feet in 4 miles (Flint, Fig. 11). Eventually it cut through about 400 feet of basalt at the head to leave the 150- to 200-foot cataract-cascade descending from the 100-foot sill. Then the canyon route was "suddenly" abandoned (Flint, 1938, p. 512). Thereafter, all Washtucna distributary water continued down along preglacial Esquatzel, subparallel to the Snake.

Downcutting in both the Snake and Washtucna-Esquatzel fills was controlled by Lake Lewis. At highest stage, the lake was only 21 and 25 miles distant. When lowered to Pasco basin altitudes, the subparallel routes were respectively 38 and 41 miles long.

To provide an adequate gradient for erosion of Devils Canyon, by falls or by uniform deepening, the Snake obviously had greatly to outrun Washtucna-Esquatzel in removing Flint's fill while, about the same distance down along each route, Lake Lewis was the common base level, and both streams had only gravel to erode. This is hardly an acceptable interpretation. That his Devils Canyon divergence ever could have continued deepening, once it encountered basalt, is likewise unacceptable. That the gravel mound semiblocking the canyon mouth is a terraced residue of either Snake or Devils gravel is denied by all its characteristics. It is another scabland bar. The empty and rock-bottomed gorge was indeed "suddenly" abandoned but by a stream far exceeding a distributary strand from a distributary strand of a river no larger than the Snake.

To use Allison's ice-jam theory specifically for Devils Canyon, we must (1) block discharge

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across the Palouse-Snake divide, (2) construct another ice jam in Washtucna west of the head of Devils Canyon, (3) keep the narrow canyon head open while nearly 400 feet of deepening in basalt occurs, (4) have an ice jam down the Snake or Columbia higher than 500 feet A.T., and (5) remodel an older terrace into the gravel mound in the canyon mouth. These are difficult requirements.

Flint's Derivation and Disposition of Scabland Debris

(Bretz)

According to Flint (1938, p. 483), "very little" of the gravel fraction of the Cheney-Palouse glacial-river load was carried far enough down the Snake to reach Pasco basin. Deposition began promptly in Washtucna Coulee and Snake Canyon; the detritus being derived from "scoured basalt on steep gradients, mainly along preglacial drainage lines" (1938, p. 468) already down in basalt. These would have to be limited to Cow Creek, Rock Creek, Palouse River, and a few tributaries, and would involve but a small area compared with the nearly 1000 square miles eventually swept by glacial water in the tract of Flint's study. He visualized this fill as gradually extending upstream and finally reaching the channel heads. Because all channel-bottom basalt had by that time become buried, the channel-head deposits (required for his westward diversion of the northernmost distributaries to Crab Creek drainage) [illegible]d to be supplied directly from the ice. Yet their "remnants" are 65 per cent basalt (Flint).

In Flint's succeeding episode of erosion of the fill, the rejuvenated glacial streams "notched and channeled the newly exposed basalt extensively" (1938, p. 468), making most of the scabland he studied. This erosional episode must have produced far more basaltic debris than did the earlier scouring. Most of the gravel already deposited, mingled with this newly made detritus, was carried across the Palouse-Snake divide to join the wastage from the 800-foot-thick Riparia Lake dam. Some entered Washtucna. All this gravel eventually went down along the Snake and Washtucna toward Pasco basin.

About 30 miles below Flint's dam site, the scabland upper limits (Secs. 20 and 21, T. 10 N., R. 33 E.) are 500 feet above the valley bottom. (Here Flint believed that scabland gravel graded into Touchet silts.) An average thickness of 650 feet for the 30 miles is therefore conceivable. A generous estimate of the average valley width involved is half a mile, thus a gravel-storage capacity of 2 cubic miles. If none entered Pasco basin, this represents all the basalt waste removed from nearly 1000 square miles of scabland. Evenly distributed over the Cheney-Palouse tract, it would account for about 10½ feet of erosion. Allowing for 10 per cent or less (Flint's estimate) of glacial drift in the gravel, and using Flint's porosity factor of 25 per cent (1938, p. 483), the amount of basalt eroded is about 7½ feet, barely enough to remove the weathered zone under the loess. By using Washtucna for additional storage and by leaving small "remnants" in the channelways, we may retain the estimate of 10½ feet. But this is much too small to produce the relief ma[illegible] by the scabland streams. One cubic mile of gravel distributed over the 80 square miles of scabland on the Palouse-Snake divide alone would provide a fill only 66 feet in average thickness[14] about half as deep as Flint's theory requires.

This computation assumes that Snake and Washtucna valleys were originally empty and that they received capacity fills. Nothing remotely approaching this quantity of gravel is in them today. Flint's theory requires removal down along the Snake as Lake Lewis subsided. Where has it gone if it did not enter and pass through Pasco basin? And how could it be carried across the Touchet deposits, during subsidence of Lake Lewis, without leaving a record? The complicated channeling in lower Esquatzel is not that recorded for Washtucna. Allison, finding Touchet beds only above scabland gravel, denied the contemporaneity

[14] The preglacial gradient of the Cheney-Palouse tract was 20-25 feet per mile. Flint's estimate for the slope of his fill was 13 feet per mile. Thus the deposit at Hooper (60 miles from channel head and 1112 feet altitude) had to be 420 feet thick (1530 feet A.T.) before any aggradation began at the head. By the time aggradation was completed, it was thus 275 feet thick on the divide summit (1250 feet A.T., 2 miles south of Hooper) and therefore had to lap an impossible 1[illegible] feet up on the bordering loessial scarps. A minor error in his Figure 8 is the bar scale by which the 60 miles of length measures 120 miles.

that Flint claimed. With this denial, the writers agree.

An outstanding infelicity in Flint's concept of a Cheney-Palouse fill is the quantity of debris demanded before the scabland was made. An average thickness of 100 feet on the 800-square-mile tract north of Hooper would require a volume of 15 cubic miles. Subtracting for porosity and glacial contributions, this still remains a fantastically impossible quantity to derive from subjacent basalt before scabland was eroded.

When Upper Grand Coulee's cataract receded through the monoclinal uplift, the new channel head thus afforded was 800–900 feet lower than any other in the complex. All other scabland channels then ceased functioning, unless for a possible very brief late closure of Grand Coulee by glacial ice. Hence the removal of Flint's valley fills must have been completed before the opening of the low Grand Coulee route.

A dozen separate valleys east of Grand Coulee led glacial water to Quincy basin (Pl. 1). Their supposed fillings must have been carried off to that basin before Grand Coulee's capture of their rivers. If we grant that there was time enough for this, was there sufficient capacity in Quincy basin to contain their debris in addition to what the great Coulee itself contributed?

The profusion of granite boulders along Rocky Ford and Willow Springs channels in Quincy basin gravel indicate that they were in use before Upper Grand Coulee's receding cataract had reached the Columbia valley. Drumheller Channels were well deepened by Rocky Ford and Willow Springs discharge, and Quincy basin's initial storage capacity was correspondingly decreased. Yet there is clear evidence that Upper Crab Creek glacial river was still functioning. By Flint's reasoning, it was still discharging gravel into Quincy basin.

Neff estimates (from U.S.B.R. data) that a "bare minimum" of 11 cubic miles of rock was eroded in making Grand Coulee and associated distributary coulees, all of it carried into Quincy basin. He finds that, if this debris had remained in the basin, it would have made a fill three or four times as thick as the existing deposit of scabland gravel. Thus this basin's fill, even if restored to a pre-channeling plain, cannot possibly represent the total debris contributed alone from Grand Coulee and its scabland complex. Great quantities must have gone on out by way of Drumheller, Othello, Koontz, and Lower Crab Creek. Add what was yielded by erosion in these deeply bitten dischargeways. Consider that all are largely empty today. Note that Pasco basin, also largely empty, lies almost immediately downstream and its highest "remnant" of Flint's or Allison's fill, Priest Rapids bar, 860 feet A.T., forbids a gradient for contemporaneous erosion of virtually all these channels. Where has this debris of the hypothetical fill gone if not into, and through, Pasco basin? Lake Lewis did not coincide with any scabland floods.

Repetition of Floods

(Bretz)

If floods of comparable volume repeatedly swept down the Cheney-Palouse tract, scabland making on the Palouse-Snake divide would be resumed each time along the pattern left by the preceding flood. This behavior would be changed only after Palouse Canyon's upper falls (now only 20 feet high near the head of the 200-foot canyon) had retreated across the divide and only if later floodings could be carried off through it and the old Washtucna Coulee route. Did more than one flood cross the summit of the divide?

One approach toward an answer lies in relations of Palouse Canyon to the bars south of Snake River at the junction. The top of the mid-canyon bar is 130 feet higher than the foot of lower Palouse Falls, only 5 or 6 miles distant, and 60 feet higher than the foot of extinct H U Ranch cataract. Were these "waterfall" canyons eroded *beneath* the deep torrent that made the bars, or are they products of a later flood?

Matthes (1918, p. 258–259) has described the intense, quasi-vertical, vortex suction in turbulent streams (his Type III) as kolk action, calling it "probably the most important macro-turbulence phenomenon in natural streams" and "the most powerful form of concentrated energy at work on stream beds." Once the unparalleled magnitude of scabland streams is realized, the kolk, which is essentially a subfluvial tornado in structure and in velocity relative to surrounding turbulence, can readily

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petition of Floods

(Bretz)

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Matthes notes that the most effective plucking action of a kolk occurs on downstream-facing vertical faces where cavitation is at a maximum. Celilo Falls, at the head of the Dalles of the Columbia, is 20 feet high in low-river stages but disappears during floods when it becomes a "subfluvial cataract" with maximum kolk action on the same rock in which the many scabland falls were developed. Can this idea be extended to include the production of subfluvial erosional forms which, after the stream has vanished, look like abandoned waterfall cliffs, plunge pools, and recessional cataract gorges?

The lack of continuous marked channels leading across the Palouse-Snake divide to the several abandoned cataracts is comparable to the relations of cataracts on Trail Lake anticline's southeastern limb. It debars any reasonable interpretation of such cataracts made by individual streams across either divide. Development beneath a wide sheet of water is demanded, and this would require subfluvial origin by kolk action.

If H U Ranch and Palouse falls and their recessional gorges are not explicable by the kolk concept, then there must have been some marked change in conditions, particularly in the level of water or debris in Snake River Canyon, after bar building and before completion of scabland canyons, a change at least suggesting two episodes of flooding across the divide.

Another approach toward an answer is suggested by the much smaller proportions of the short channel leading to the H U Ranch cataract than those of the cataract itself before the notching of its lip. It is comparable to the minor channeling above the lip of Potholes cataract and suggests the same thing, a later and smaller flood.

The lowest brink of H U Ranch falls has the same altitude as the top of the shoulder bar, although 7 miles farther up the glacial stream. Most of the rim of the Davin gorge is only 50 feet higher. Unless the cataract and gorge are of subfluvial origin, or adequate lowering of water or debris in Snake Canyon occurred during a given flood, this third approach indicates that two episodes of flooding are required for these relations, the shoulder bar dating back to an unnotched brink of the falls.

A fourth approach lies in scabland canyon relations in the vicinity of Davin Ranch (Fig. 19), west of the large group of residual loessial hills interrupting the summit scabland of the divide. Several square miles of prescabland Palouse loess topography is between Palouse Canyon on the east and the H U Ranch cataract and Davin gorge on the west, and extend south to the brink of Snake River canyon. A small scabland coulee crosses this residual tract, from northeast to southwest, and enters the gorge at the Davin Ranch. It heads in a group of irregular channels which are cascade-chutes rather than cataract alcoves. The last mile of this coulee is wide and gravel-floored. It obviously is a modified, minor, preglacial tributary of the Snake, as also is the last 3 miles of the Davin gorge.

This tributary's gravel flat hangs, without any notching, about 140 feet above the adjacent gravel-covered floor of Davin gorge. This seems too great to ascribe entirely to excess depths of water in the main channel over that in the tributary. It seems obvious that the gorge floor was lowered after the tributary ceased to flow. Although water for both the tributary cascade and the main cataract had to cross the unchanneled divide summit at 1280 feet A.T. before entering either one, the channel to the cataract headed 3 miles farther upstream than did the cascade channel. Also three other cascade or cataract gorges, tributary to Palouse Canyon, head at this altitude within a mile of the H U Ranch channel head. All must have operated after Davin's tributary cascade chute ceased to function.

A fifth approach lies in two sets of glacial river-bottom records, separated by a vertical interval of 150 feet or more. A channel around the southern slope of the semi-isolated hill and its appended shoulder bar (Fig. 21) has a floor at 810 feet A.T., approximately the same altitude as the Davin gorge floor at the junction of its hanging cascade-chute tributary. Like

[27] Mr. Matthes permits us to quote from a letter that "as regards kolk action, the negative pressures involved would easily account for effective plucking, especially in the case of columnar basalt whose shrinkage cracks would facilitate plucking." He adds "I like your comparison of a kolk to a tornado".

tances to the Snake are 2 and 1½ miles, respectively, and the mouthings in Snake Canyon are only 2 miles apart. In contrast, the shoulder bar's flattish summit (at 1000 feet A.T.) is 160 feet above the channel to the south, and the cascade chute's gravel fill (between 960 and 1000 feet A.T.) is 120–160 feet higher than the Davin gorge floor. These relations strongly suggest that two floods crossed the Palouse-Snake divide, the earlier one making the shoulder bar and the cascade-chute fill, the later one finding lower levels (of ponded water or a debris fill) in Snake Canyon and consequently scouring out the channel south of the bar and lowering the floor of the gorge. The abundance of large boulders on the brink of the Davin terrace overlooking Snake River and the unfilled plunge-pool trench at the foot of the falls (Fig. 19) testify that H U Ranch cataract was operating at high efficiency to the very end of the second flood.

Cheney-Palouse Tract North of Palouse-Snake Divide

Maps: Benge, Haas, LaCrosse, Starbuck and Washtucna quadrangles; U.S.G.S.

Multiple Scarps

(Bretz and Smith)

A traverse from Sprague to Washtucna (Pl. 1) and a re-examination of the Willow Creek bar constitute all the study given to the tract north of the Palouse-Snake divide in 1952. The traverse was made to find multiple scarps in the bordering loess bluffs, features which Flint had stressed as "conspicuous" evidence for his episode of dissection following the aggradation. Bretz had no notes or memories regarding such things.

Four possible multiple scarps were seen in this 50-mile traverse. The lower member of each double scarp was a rounded form, not a sharply cut bench, appearing low on the slope and having a narrow tread. Time did not permit examination on foot, and comments here are only suggested alternatives to Flint's explanation. One suggestion is that low gravel bars deposited against the base of the loess scarps and subsequently scarped in turn would produce this effect of erosional terracing in the loess (Pl. 1[illegible] fig. 2). Another suggestion is that masked basa[illegible] ledges may be responsible.[38] Another is base[illegible] on Culver's report (1937, p. 58) of probabl[illegible] Ringold remnants in the basal portions o[illegible] "prow-pointed hills." Another, thought to b[illegible] supported by other features of a particular case is that they are remnants of the prescablanc[illegible] erosional topography, so situated that the upper, steep slope appears to belong to the scabland ensemble. A fifth suggestion is born of finding buried, calichified zones elsewhere in the Palouse loess. Such, being more resistant, could produce the effect of multiple scarps where subjected to lateral erosion. A sixth alternative comes from locating Flint's most convincing double scarp (his Pl. 6, fig. 1). It is a mile back up a narrow nonscabland tributary of Washtucna Coulee and 250 feet higher than the coulee floor. Although loessial scarps facing the coulee along this stretch have bases a little higher than this, only back filling could have occurred here. At the entrance to Washtucna, this tributary has a heavy gravel deposit almost as high as the base of his double scarp. (*See* Haas geological map.) The feature he illustrated is, as he admitted, a record only of the local stream's work, which surely is post-scabland.

However, double scarps could be produced by glacial-river strands which did not, in their first operation, cut down to a basalt floor and hence had opportunity in a later flooding to deepen in loess. This procedure would be favored if an adjacent larger strand had been deepened sufficiently during the first episode to give exceptional gradient to the smaller one in the second. Indeed, eight of the double scarps listed by Flint are closely associated with such small

[38] Bryan (1937) figured a loessial island in the Cheney-Palouse tract near the Ralston divide crossing; his *figure A of Plate 1*, shows 50 feet of basalt in the lower slopes of its scarp. Bretz studied that hill after Bryan had called his attention to it. To get 50 feet of basalt requires measurement from the bottom of a closely associated scabland channel, and only the northern end of the hill has any basalt in the scarp. A low, south-facing ledge of prescabland origin, traceable for a few miles laterally out across the scabland on either side, provides this basalt. Enough retreat of the ledge occurred under the scabland river's erosion to leave a foundation of basalt in the lower part of the scarp. Bryan notes masking of the basalt in the scarp "by slump of soil from above."

channels separating small loess islands, and only three face large channelways.

Although Allison (1941, p. 55) described no such topographic forms, he accepted Flint's statement regarding their common occurrence but derived the multiple scarps from local ice jams.

Meander Scars

(Bretz)

Loessial islands are strikingly streamlined with the glacial-river courses (Pl. 16, fig. 1), and most of them have sharp prows pointing up the gradient; obviously they have been made by glacial-stream erosion. But do these narrow, elongated, residual hills and the narrow, elongated channels separating some of them fit the pattern that would be left by a stream (or streams) as small as the Snake, meandering on "great areas 10 to 20 miles wide"? Where are the meander scars in the loessial scarps?

Flint did note four examples of "crescentic undercut faces and slipoff slopes" (1938, p. 475) in the scabland deposits, none of which remotely approaches the Moses Lake pattern, but he did not state, as he did for multiple scarps, that there are "scores" of cases. There is no comment in his paper indicating that the "scarps and benches streamcut in the 'Palouse soil' . . . , recording streams cutting laterally on various profiles" (p. 472) bear any meander scars. Topographic maps, aerial photographs, and field inspection have revealed none to the authors.

Flint's "leisurely streams with normal discharge" began their work of degradation in many places on a fill banked up high (90 feet in his fig. 4) against confining loessial slopes. Removal of such fill to expose and in most places to scarp, the buried loess apparently involved no normal meandering. Indeed, he found places where the relatively coarse stream fill had been removed and pre-fill, *unscarped* slopes of the fine-textured loess "exhumed by rinsing rather than by the more drastic process of lateral planation" (p. 486). This process of "rinsing" is not quite convincing.

Eardley (1938) was impressed by the "magnitude and manifest rapidity" of Yukon River meandering. Reports of residents and ages of trees in abandoned channels led to his estimate of 1000-2000 years for a meander loop to shift across the 10 mile (average width) flood plain. He judged the Yukon to be degrading its valley floor in the process. Concomitant widening, where meanders undercut valley walls, is largely in frozen "Yukon silts", and the greatest width attained is 35 miles.

The loessial bluffs undercut by Flint's Cheney-Palouse glacial river may well have been similarly frozen, but his stream's load was much coarser than is the Yukon's, its gradient much greater, and volume of water much less. Any possible meanders therefore were smaller and less active. One wonders how long this scabland river's meanders required for removing the great fill of Flint's hypothesis—*i.e.*, how slowly the Lake Lewis dam wasted away. Valley glacier and landslide dams in historic time have had very brief lives compared with Eardley's estimate for one valley-wide meander sweep. Epeirogeny as first choice for the cause of the fill-and-cut sequence would have escaped this particular criticism.

We can accept heavily laden, braided, aggrading streams with gradients of 13 feet to the mile (Flint's figure) but not degrading rivers approximating the size of the Snake which meandered on gradients increasing to 20–25 feet per mile. Allison (1941, p. 56) called "impossible" Flint's concept for removing the fill he postulated. The writers agree. Furthermore, they believe that such streams could not have eroded the bedrock scablands, even with their final hydraulic gradient doubled.

Willow Creek Bar

(Bretz)

The new Benge and LaCrosse quadrangle maps show that Willow Creek flows from a typical, mature Palouse loess topography into a flat nearly a mile wide south of LaCrosse. The creek skirts this flat in a ravine about 50 feet deep and thence enters a narrow valley, which it leaves to traverse scabland to the Palouse. The creek still follows its prescabland course, but the marked valley widening south of LaCrosse is due to convergence there of six or seven lateral glacial channels from the north, separated by elongated loessial islands (Fig.

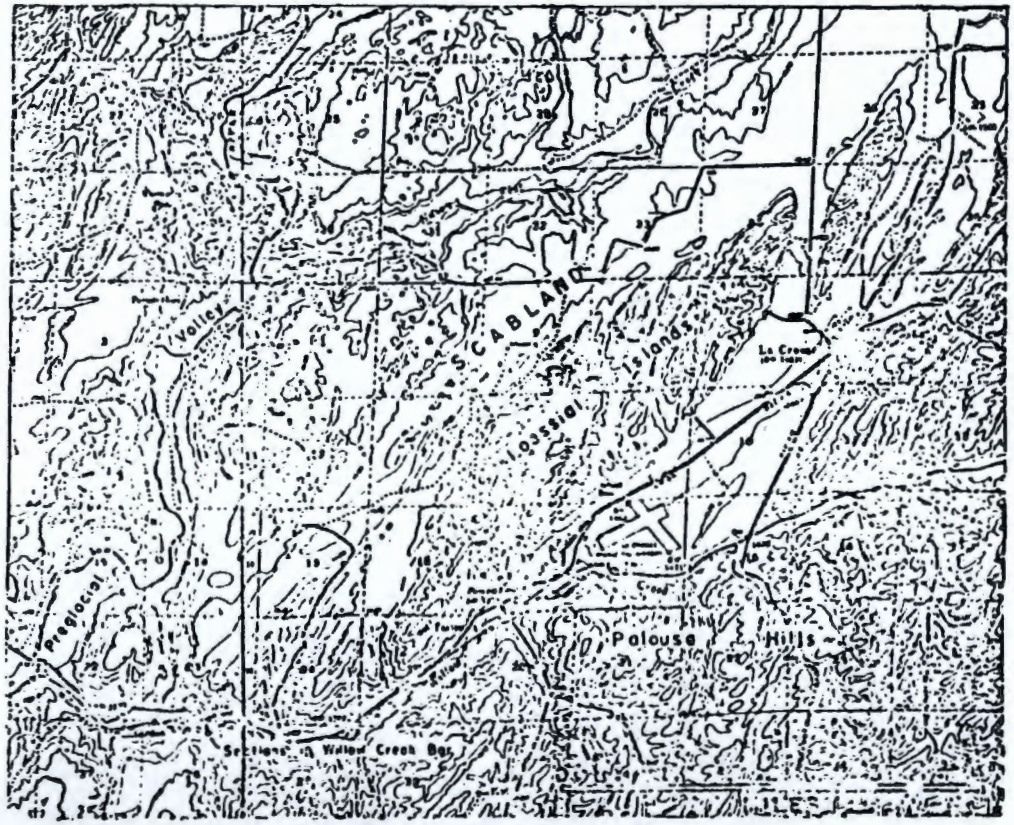

FIGURE 22.—LOWER WILLOW CREEK AND VICINITY

Showing loessial islands, glacial-river channels separating them, part of Cheney-Palouse scabland, and location of Willow Creek bar. Part of Benge and La-Crosse topographic maps, U. S. Geol. Survey. Contour interval 40 feet.

FIGURE 22.—LOWER WILLOW CREEK AND VICINITY
Showing loessial islands, glacial-river channels separating them, part of Cheney-Palouse scabland, and location of Willow Creek bar. Part of Benge and LaCrosse topographic maps, U. S. Geol. Survey. Contour interval 40 feet.

22). Three of the channels are bottomed on basalt at their heads and the broad flat is surfaced with basalt gravel.

The Willow Creek bar lies almost at the valley's entrance into scabland, in sections 23 and 26, T 15 N., R. 38 E. Bretz (1928a, p. 617-618) described it as a ridged gravel deposit once built across the creek valley and subsequently trenched through by a narrow, postglacial gulch. Flint (1938, p. 478)—finding (1) cut-and-fill recorded in lenses of silt included in this deposit, (2) fore-sets dipping both up and down stream, and (3) failure of some to dip parallel with the surface slopes—claimed that this valley barrier was "a remnant of a formerly continuous fill."

Allison (1941, p. 68-69) agreed with Bretz that the bar is constructional and wondered "how ordinary streams could have removed [Flint's] fill in the scabland west of the bar and yet have left the numerous Palouse islands and the seven channels across the divide west of LaCrosse except under conditions of ice blockade"—conditions which he did not specify. One unavoidable condition was that the ice blockade must have been 10 miles from end to end across the entire Cheney-Palouse tract (with one central interrupting loessial island) and about 400 feet thick in the deep preglacial Palouse River and Cow Creek valleys on either side of the island. Another limiting condition was that the supply of floating ice must have been abruptly terminated on completion of the dam, or the dam must have promptly failed; otherwise the seven narrow channels could not have escaped similar blockading.

As shown by fore-sets in highway, railroad, and creek trenches, the Willow Creek bar is composite, composed of basalt gravel brought upvalley from the west, and sand and light-brown silt brought downvalley from the east. A marked disconformity shows that there were two episodes of deposition separated by an interval of erosion.

The form of the earlier deposit no longer exists. Its exposed gravel is largely horizontally bedded but has eastward-dipping fore-sets locally. It dammed Willow Creek, causing later deposition of silt on the upstream (east) side, lenses of which tongue out westward into gravel rehandled by the creek during the erosional interval. The creek subsequently cut a ravine through the deposit and, as shown in the highway section, made a steep, east-facing bluff.

During the second depositional episode, scabland water from Palouse River valley swept up lower Willow Creek, eroded the west slope of the first deposit, tossed gravel over the top and down the face of the stream-cut bluff to build the conspicuous, long, east-dipping fore-sets that occupy the whole vertical range of the east half of the highway cut. The bar thus reconstructed a barrier to the creek, one that the stream has again succeeded in breaching. The earlier deposit may also have been a bar, or it may record a prescabland Palouse-Washtucna valley train, here built back in deltaic fashion into a tributary valley's mouth.

If the bar form were only a remnant of a former continuous fill in Willow Creek valley, why is it lingering in this narrow place[30] where six or seven glacial channels from the north discharged across it and where the drop today is 80 feet along the creek, and 200 feet from the bar top, to the Palouse 1½ miles away? It should long since have disappeared as did most of the glacial-river deposits under which Flint buried the whole, broad, flattish Cheney-Palouse tract. Its location is the last place to expect a lingering remnant.

SLACKWATER SILTS NEAR PALOUSE-SNAKE JUNCTION

(Bretz)

The fill-and-cut or ice-jam theory may appear to find support in the slackwater silts back in valleys tributary to the scabland and in the Snake and its tributaries upstream from Palouse River junction (Bretz, 1929; Lupher, 1944). These silts are similar to the Touchet beds, although commonly they record currents flowing up the tributaries. They do not occur near the

[30] At 50 feet above the creek, the ravine across the bar is a third to a quarter as wide as the creek valley for the next 4 miles upstream, and at 100 feet above, it is less than half as wide. Summit of the bar ridge is about 30 feet higher than the creek at the transection, and less than 1300 feet A.T. Flint's fill was nearly 450 feet thick here (1938, p. 478), reaching 1700 feet A.T. Thus more than 400 feet has been eroded away to leave a mile-wide valley bottom just upstream from this constricting ridge at right angles to the valley length.

torrent-made bars in the region of the Palouse-Snake junction, suggesting that they are contemporaneous. Bretz has no very definite interpretation to make, except that (1) they clearly are deposits from glacial water that was flowing back up the tributaries from the Cheney-Palouse scabland and Snake River canyon, (2) they record some rhythm or repetition of conditions, and (3) they are only mantles ranging through a maximum of 700–800 vertical feet on the slopes. They are not terraced remnants of a continuous fill to their upper limits which are essentially close of floated erratics upstream in Snake River canyon, 1300 feet A.T. Some exposures in valley bottoms probably are in materials reworked by postglacial streams.

Fresh highway sections were available in 1952 in the bottom of lower Tucannon River valley, which enters Snake River just upstream from the mid-canyon bar. Here a massive silt without current bedding appears to be the basal member. It could be a turbidity-current deposit. Disconformably overlying it is a fine sand with scattered pebbles, some consisting of the massive silt, and with some thin gravel units. At the base of this member may be a breccia of the massive silt. Channel cut and fill is common along the disconformity. Fore-sets record an upvalley current. Coarser material lies above and intertongues with this member. This also contains upvalley fore-sets. Sorting is very good locally in this third member, and there are some silt lenses and pebbles of foreign rock.

Equally significant but somewhat different records of a surge from scabland channels back up preglacial tributaries with no other access to glacial water exist in every valley entering the Cheney-Palouse tract for 50 miles north of Snake River canyon (Bretz, 1929). The deposits constitute a mantle of loess-derived silt with abundant angular grains and granules of unweathered basalt, a scattering of pebbles of foreign rock, and some erratic boulders. Commonly this mantle is unsorted and unstratified except locally on valley floors. Where bedding exists, it commonly records upvalley currents from the scabland. The upper limit in any one tributary valley corresponds to the upper limit of glacial-river water at junction with the main dischargeway. The deposits are thickest and coarsest in the tributary debouchures to scabland, and any stratification in such places is prevailingly fore-set out of the scabland and up the tributary. In numerous places, they are mounded scabland gravel deposits with long delta fore-sets comparable to the bars already described.

The outstanding feature of this backwater silt is the record of repeated upvalley currents during deposition of as much as 40 feet of material. No record of downvalley currents, except where postglacial rehandling is probable, have been found. A bursting dam farther down the Snake or Columbia would inevitably make strong currents downvalley. The coarser character of the material near the valley mouths and its gradation, in the farthest upvalley deposits, into a fine silt without sand or granule gravel units seems to indicate that it is gradational with scabland sediments, but neither the fill-and-cut theory nor the ice-jam theory can account for the reverse currents, the mantle-like character of the deposits, or the succession of events recorded. Repeated upvalley surges from the scablands could leave such a record.

Perhaps two kinds of backwater episodes are recorded in these deposits, both with upvalley currents. The well-sorted, well-stratified valley-bottom deposits may be the consequence of meltwater 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 requires a Palouse canyon, an Allison ice dam, or a Flint fill in order to cross the divide.

Glacial Lakes Missoula and Coeur D'Alene

Maps: Greenacres, Medical Lake, Oakesdale, Packsaddle Mtn., Priest Lake, Rathdrum, Spokane 1911 and Spokane N E 1950 quadrangles: U.S.G.S.

(Bretz)

The Pleistocene history of the region is still only sketched, but the writers believe it reason-

ne [illegible]sits are thickest and [illegible]ary debouchures to [illegible]y stratification in such places [illegible]re-set out of the scabland and [illegible]. In numerous places, they [illegible]abland gravel deposits with [illegible]sets comparable to the bars [illegible].

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[illegible] LAKES MISSOULA AND COEUR D'ALENE

[illegible]res, Medical Lake, Oakesdale, [illegible] Mtn., Priest Lake, Rathdrum, [illegible] and Spokane N E 1950 quad-[illegible] G.S.

(Bretz)

[illegible]ete history of the region is still [illegible] but the writers believe it reason-

able to postulate that Glacial Lake Missoula's history included several dammings and several burstings. Pardee (1942) has described giant current ripples, huge bar deposits, and greatly scoured salients along and north of the narrow Clark Fork Valley portion of the Lake Missoula basin, produced by "a sudden failure of the ice dam that blocked this valley" and the escape through it of a large volume of water impounded in the Rocky Mountain Trench. He calculated the discharge as nearly .91 cubic miles per hour, and his title, "Unusual currents . . ." is a fine example of understatement. Continuous discharge at this rate would empty the lake in about 2 days. But Lake Missoula could not have been emptied across the plateau until Upper Grand Coulee's cataract recession was completed. Extensive, thick, varved silts and clays, with glaciated stones dropped from bergs, probably tell of long-continued occupation of the deeper portions by a much smaller glacial lake or lakes. The varved sediments in the Bitterroot Valley portion lie a few hundred feet higher than comparable deposits in the Rocky Mountain Trench, yet are farthest from any lobe of the Cordilleran ice-sheet. There are outwash gravels above silts and similar gravels beneath silts, and relations vary in different arms of the very irregularly outlined lake. Pardee's illuminating discoveries[a] are only the beginning of what eventually should be a series of detailed studies of glacial pondings in western Montana.

Bretz has examined the mountain summit at the extreme northern end of the Bitterroot Range where the Clark Fork and Pend Oreille valleys diverge southward, (Figs. 23, 24) and against which the glacial dam for Lake Missoula was built (Priest Lake quadrangle map, Idaho-Montana). There is no notch at 4200 feet where Davis (1921, p. 140) speculated on an outlet. The aneroid read 4800 feet for the lowest saddle seen on the ridge, a saddle that has no channel features.[a] No suggestion of glacial ice above 3550 feet was found in the northwest branch of Johnson Creek valley, the route followed to the summit. The highest record found, a granite boulder, may have been berg-floated. The summit of the cliffed northern end of the range is 2000 feet above Pend Oreille Lake surface only a mile away. The steepness of the ice front here makes feasible a concept of catastrophic emptying of the lake, once weakening of the dam began and hydraulic quarrying under a head of 2000 feet of water took over. Lake Missoula probably never had an outlet, other than channels across, leakages through, and failures of its glacial dam. Had the dam remained intact through any one glacial episode the lake certainly would have risen to the lowest saddle. Discharge there would have channeled it and made a striking cascade chute down the western slope.

The multiplicity and very immature development of Lake Missoula's shore lines argue against a long stillstand at any one level. Although the highest of the series is no stronger than any others, the universal faintness may be due in part to submergence as the basin became filled. If there were several fillings and emptyings, the weak and close-set shore lines may constitute a composite aggregate of later mountainside scorings interpolated among earlier ones, the vertical sequence not being one also of time as Eakin and Honkala (1952, p. 1361) conceived it to be.

Although the late Wisconsin (Polson) moraine in Flathead Valley may have been built subaerially when no Pend Oreille glacial dam existed, and the shore lines on this moraine inscribed later (Nobles, 1952), it does not follow that there had never been any earlier pondings in the Lake Missoula valleys. The Elmo moraine at the head of Dayton Bay, on the west side of Flathead Lake and contemporaneous with the Polson moraine, has a few faint Lake Missoula

[a] G. A. Thiel (1932, p. 452-458) has described giant current ripples made by an observed abrupt emptying of a Minnesota lake. The ripples were 30 to 50 feet apart. They showed size sorting; coarser fractions of the debris were left in the troughs as winnowing carried the finer gravel forward to the crest of the ripple. Fore-set bedding in the ripples conformable with the lee slope was not reported, although Pardee noted and figured such structure in his Lake Missoula giant ripples. This item of fore-set structure is lacking also in the argument of the present writers because no sections were found in the scabland ripples, and there was no opportunity to make any. Neither were lag-cobble collections seen in the troughs among the scabland ripples, perhaps because of inconspicuous display, perhaps because the rippled gravel was already well size-sorted.

[a] Packsaddle Mountain quadrangle map, U. S. Geol. Survey, published subsequently, shows a lower saddle farther south, but it is 4600 feet A.T., 400 feet higher than the lake's highest shore line.

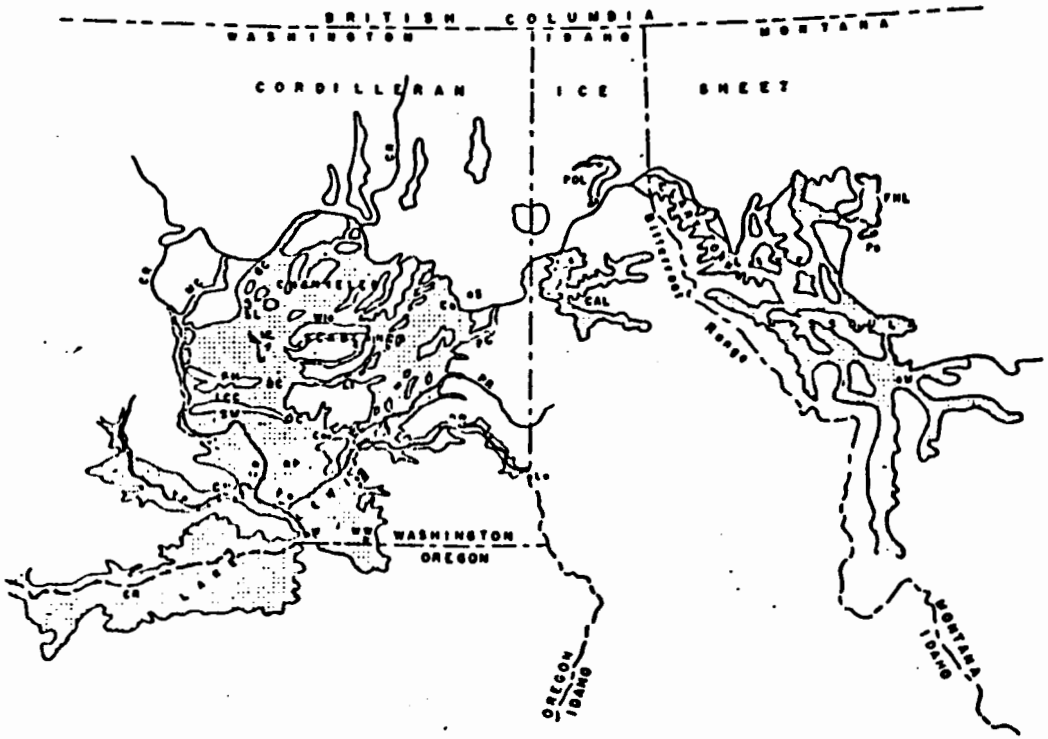


FIGURE 23.—MAP OF GLACIAL LAKE MISSOULA AND CHANNELED SCABLANDS

C—Cheney	FHL—Flathead Lake	Pa—Pasco	SM—Saddle Mtn.
CAL—Coeur d'Alene Lake	GC—Grand Coulee	PC—Pine Creek	SN—Snake River
CN—Chandler Narrows	LCC—Lower Crab Creek	Po—Polson	W—Wallula
Co—Connell	Le—Lewiston	POL—Pend Oreille Lake	WC—Washtucna Coulee
CR—Columbia River	M—Missoula	PR—Palouse River	WiC—Wilson Creek
DC—Drumheller Channels	MC—Moses Coulee	RP—Ringold Plain	WW—Walla Walla
E—Elmo	ML—Moses Lake	S—Spokane	YR—Yakima River

FIGURE 23.—MAP OF GLACIAL LAKE MISSOULA AND CHANNELED SCABLANDS

shore lines, whereas the valley slopes just outside the moraine are well scored with numerous fairly definite shore lines, certainly older than the moraine. Furthermore, outwash from the moraine occupies a trench cut in a valley floor of lake silt. There may have been no Lake Missoula in the southern part of Flathead Valley when the Polson and Elmo moraines and the Elmo outwash were deposited, but there was one before and one afterward.[a]

One critical region for the theory of a Lake Missoula catastrophic burst is the southwestern prong of the Purcell Trench. It extends from the site of the dam to the deep Spokane and Columbia valleys which skirt the northern edge of the plateau where overflow into the scabland channels occurred (Fig. 24). The trench, confined by highlands rising above the plateau level, contains remnants of basalt flows that were backed up into it. It also contains a great gravel deposit for its full length southwest

[a] W. C. Alden's long-awaited *Physiography and glacial geology of western Montana and adjacent areas* (U. S. Geol. Survey, Prof. Paper 231) was distributed just before the manuscript for the present study was submitted. Alden's (1953) comments on glacial lakes Missoula and Coeur d'Alene and the plateau scablands involve the following items.

(1) (p. 155) The 4200-foot saddle or col across the summit of the Bitterroots that Davis thought might be a Lake Missoula outlet was similarly interpreted by Alden. This idea is based only on study of the 1913 Priest Lake topographic map (scale 1:250,000 and contour interval 200 feet). Neither man could have made a field examination. Alden was "certain that the glacial ice dam was more than high enough to have held a lake up to the level of this col" (p. 143), but he obviously never had studied the Packsaddle Mountain quadrangle map.

(2) (p. 142) "There were probably at least three glacial invasions of the Purcell Trench".

(3) (p. 143) "It is probable that every time the Rathdrum [Pend Oreille] lobe of the Cordilleran ice advanced southward along the Purcell Trench, it crowded southeastward from Pend Oreille Lake basin into the valley of Clark Fork whose drainage became completely dammed . . . [forming a Lake Missoula]."

(4) (p. 155) "There seems to be no doubt that the mouth of the gorge of Clark Fork was dammed at least twice near the Idaho-Montana line. . . ."

(5) (p. 143) Glacial ice "must have crowded against the lower slopes of the mountains west of. . . . Lake Coeur d'Alene and must have overlain the 2500-feet basalt bench west of Coeur d'Alene [town]."

(6) Grand Coulee as a discharge route for water from Lake Missoula is mentioned (p. 146) under "Pre-Wisconsin Glaciation", its sill at the head noted as 1600 feet A.T. There is no comment on the time or conditions of Grand Coulee's origin; only the tacit assumption that the great gash then already existed at full depth. Under "Wisconsin Stages of Glaciation" Grand Coulee is again mentioned (p. 149) as part of the discharge-way for "another filling of glacial Lake Missoula", and it is also stated that glacial water may "have spilled over the part of the basalt plateau south and west of Spokane if the Grand Coulee was not open".

(7) (p. 155) "The relatively slight amount of wave work recorded along each of the . . . delicate shore lines of Lake Missoula would seem to indicate that no one stand of the lake was of long duration. The close spacing of the shore lines seems to indicate that the lake level fluctuated a number of times". Abrupt release of water from "lowering of the ice dam . . . might result in floods of great magnitude . . . even if Lake Missoula were only partially drained. Each may, *perhaps*, have been the origin of many violent floods that *are supposed to have* swept over the scablands. . . ." (italics ours). Thus Alden retreated slightly from his 1927 position.

(8) (p. 165) The Polson moraine "may have been deposited in the lake".

(9) Concerning Pardee's giant current ripples, Alden said (p. 96) of the "somewhat puzzling features" that "some of the numerous small ripples are beach ridges or bars . . . and some . . . may be due to moderate erosion of coalescent alluvial fans . . ." No genesis for the large ripples, up to 50 feet high, was proposed. The most desperate efforts to escape the flood hypothesis can hardly dare use the above ideas for the current ripples on scabland bar summits.

(10) Alden admitted (pp. 96–97) that one of Pardee's channels (Rainbow Lake gap), contemporaneous with his current ripples, "looks as though it were at some time traversed by a river but its open eastern end now hangs hundreds of feet above the floor of the Camas Prairie Basin on the east and above the bottom lands bordering the Little Bitterroot . . . to the northwest". Instead of Pardee's explanation, Alden favored either a glacial river marginal to a possible Camas Prairie lobe (for which lobe existence he admitted that he could find no field evidence), or a normal river in Pliocene or early Pleistocene time, its drainage coming from the surface of a vanished basin fill of Tertiary sediments. But Pardee described the channel as "severely scoured, exposing the bedrock which remains bare. . . ." and as possessing "channel depressions, several of them holding ponds or marshes". Rainbow Lake, 1½ miles long, is the largest unfilled depression. A Pliocene or early Pleistocene age for the channel is very doubtful indeed.

(11) The massive "high eddy deposits" of Pardee, earlier called deltas by Campbell (1913, p. 142) and lateral moraines or morainal embankments by Davis (1921), Alden (p. 159) considered them to be gulch mouth fills or "lacustrine bars" made at different times during Lake Missoula's history. But harmonizing their bulkiness with Lake Missoula's "delicate" shore lines is impossible. The ridged valleyward margins of their summits and the undrained depressions farther back in the gulch mouths were explained as due to "settling and deepening" as "percolating water may have carried some of the finer material down into the interstices . . . [of the coarse material of the deposits]". Disposal of coarse contributions to these basins from subsequent gulch erosion was not discussed.

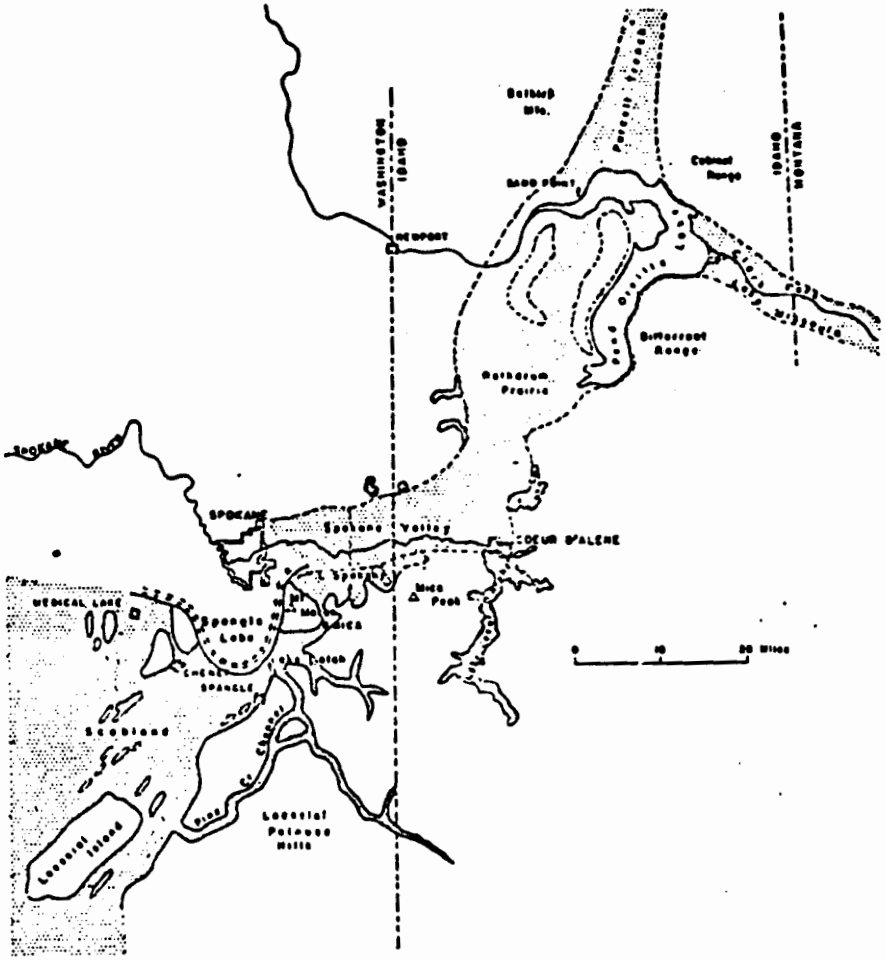
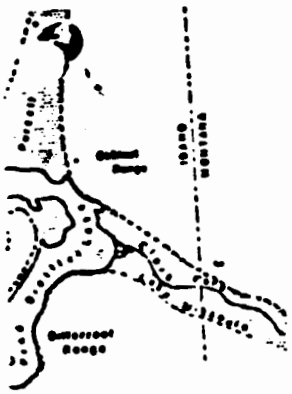


FIGURE 24.—REGION BETWEEN LAKE MISSOULA AND CHANNELED SCABLANDS

of the dam. This region has been examined only in reconnaissance fashion.

Lake Pend Oreille, at the site of the dam, is relatively shallow north of the entrance of the valley (Clark Fork) which contained Lake Missoula's westernmost portion, averaging less than 200 feet and containing several islands South of this junction, the basin of the lake deepens abruptly to reach more than 900 feet in depth for nearly 15 miles along the length and more than 1140 feet for more than 5 miles. (*See* Packsaddle Mtn. quadrangle map.) Its maximum depth is reported to be 1800 feet. The lake surface is 2051 feet A.T. (2048 in 1946), and the bottom is therefore 900 feet or less A.T. in the southern part. This is 1000 feet lower than the brink of Spokane Falls nearly 50 miles downvalley to the southwest and is actually lower than the bedrock foundation of Grand Coulee dam more than 60 miles still farther west.

This deep part of the lake, constituting two-thirds of its total length, closely margins the western side of the northern tip of Bitterroot Range, one buttress of the Lake Missoula dam. A clean-cut mountain wall rises in 2 miles from



ASNELED SCABLANDS

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lake bottom to average altitudes of 4900 feet A.T. in Green Monarch Ridge. The lowest saddle in this ridge is 4600 feet A.T. (Packsaddle Mtn. quadrangle map). This deep basin can hardly be anything but an erosional product of its glacial experiences, its southern part now deeply filled with gravel which rises steeply 400 feet above the water, its slopes kettly and mounded from deposition against glacial ice (Pend Oreille lobe) then occupying the lake basin. The fill obviously is younger than the trough.

Between the site of Lake Missoula's dam and the plateau scablands, the large basin of Lake Coeur d' Alene (Fig. 24) extends southward from the Pend Oreille-Spokane valley, the southwestern prong of the Purcell Trench. Striated erratic boulders at many places around this lake up to 2700 feet A.T. obviously were berg-carried to position (Anderson, 1927). But field examination of the southern and western slopes enclosing Lake Coeur d' Alene shows that it never had an outlet directly to the plateau. Its highest level is to be associated with upper limits of the scabland channel heads west of Spokane, approximately 2500 feet A.T. The lake, at 2700 feet, had at least four times its present area of 60 square miles and was 575 feet deeper. It may have served as a great surge basin.

Glacial ice has apparently reached southward down this southwestern prong of the trench as far as the drift dam at the north end of Lake Coeur d' Alene 23 miles distant from Pend Oreille Lake. This portion, now deeply gravel-filled, is streamless Rathdrum Prairie. At Lake Coeur d' Alene the course of the trench turns more directly westward (the Spokane Valley) and opens to the basalt plateau at the city of Spokane. Here another lobe (Spangle) crossed the mouth of this trench, reaching some 15 miles south of the city, out on the plateau. Probably the Spokane Valley part of the trench was also ice-filled at this time.

At Spokane superposition of the river on a remnant of the basalt tongue that originally backed up the trench has made the Falls and protected the gravel fill upvalley from deep dissection. The fill does not, however, have a simple profile. In the Rathdrum Prairie section it is traversed by an empty channel 100 feet or more in depth and a mile wide, leading from Pend Oreille Lake as far southward as Lake Coeur d' Alene where Spokane River, the lake's outlet, enters it. In the Spokane Valley section, which extends thence westward to the Falls, terracelike deposits of stream gravel, fore-set away from the main valley, block the mouths of tributaries, making swamps or lakes in them. In the Rathdrum Prairie section, comparable ponding of tributary mouths has also made lakes (Coeur d' Alene being one), but the blockades are in part morainic and they stand higher than the Prairie surface.

Flint (1936, Pl. 6) considered that the inner valley followed by Spokane River has been eroded in an original fill which, still intact in Rathdrum, remains in Spokane Valley only in the gravel blockades to tributary mouths. This erosion entrenched the early fill at Spokane Falls about 150 feet and at the junction of Spokane and Columbia rivers, 45 miles farther downstream, as much as 200 feet. He also considered that the upper profile never extended farther down the Columbia but ended at or a little below 2000 feet A.T. because a lobe (Columbia) of Cordilleran ice blocked further transportation. How the meltwater passed the blockade and where it escaped were not specified. The lower surface, he believed, continued down the Columbia from this junction as a silt and sand deposit almost without gradient. The ponded water was discharged through Grand Coulee (after Steamboat Falls had receded through the monoclinal uplift) while the Okanogan lobe blocked Columbia valley farther west. Flint considered the Rathdrum Prairie portion of the Purcell Trench fill as the still-intact surface of the original fill.

Although it seems more probable that the lower profile in Spokane Valley is continued upvalley as the empty Rathdrum Prairie channel (not noted by Flint) than that the two profiles converge eastward to become one near the Idaho-Washington line, as he thought, all altitudes and characteristics of the deposit show that the entire sequence is postscabland, except for late functioning of Grand Coulee.

There are still higher stream deposits, however, lying in and marginal to the scabland channel heads a little west of Spokane; their altitudes are as much as 500 feet above the

upper profile in the mouth of the trench. If the trench east of Spokane contains correlative deposits, they must be the isolated outwash patches shown on Flint's Plate 6 (1936), 150–350 feet above his upper profile. The highest of these fall within the altitude range of the near-by scabland channel heads. The trench between the Lake Missoula dam and Spokane carries no other known deposits that might record glacial water on its way to any scabland channel head except Grand Coulee.

Although all the Cordilleran lobes which crossed to the plateau east of the Okanogan Valley must have stood somewhat short of maximum extent when the scabland channels functioned, the deep canyons of the Spokane and Columbia must still have been buried under glacial ice. It seems entirely probable that the Rathdrum-Spokane valley then also contained glacial ice and therefore that the flood discharge traversing it left no identifiable valley-bottom deposits.

There remains the possibility of *erosional* records, lying higher on the slopes. Five spurs on the southern slope of Spokane Valley and one saddle across the granitic hills separating that valley from the plateau to the south appear to be significant. One spur is a basalt bench just west of the north end of Lake Coeur d' Alene, at an altitude of 2400–2500 feet A.T. Its surface, 2 miles long and nearly a mile wide, has typical scabland topography of knobs and buttes and ridges separated by anastomosing channels elongated parallel to the higher valley wall, their total relief about 50 feet. That it is not a glacially plucked surface is clear from the character of glaciated surfaces on two other basalt benches much nearer Pend Oreille Lake, and in many places along the northern margin of the plateau. Glacial ice smoothed the Columbia basalt; it rarely plucked except where forced to climb north-facing slopes. This local scabland, 200–300 feet lower than the highest drifted erratics in near-by Lake Coeur d' Alene valley but equally higher than Rathdrum Prairie, appears to demand glacial water escaping westward between ice on the north and the valley wall on the south.

Glacial debris on this bench (see footnote 42, item 5) is probably contemporaneous with that in the lake basin's dam 2 or 3 miles farther east, and therefore belongs to the Rathdrum Prairie glacial drift of postscabland (except Grand Coulee), valley-fill age.

Four northward-projecting granitic spurs between the State line and Spokane possess scoured and channeled notches close to the higher, steeper valley slopes. Floors of the notches range from 2200 to 2480 feet A.T. The distal ends of the spurs are severely scrubbed whereas higher slopes are not. The spur nearest Spokane, a ridge that locally narrows the valley to about half, is just south of Dishman (Spokane N.E. quad.). Its terminal mile lies between 2000 and 2500 feet A.T. and is mostly bare and fairly fresh rock with a very irregularly rugose surface. South of it rises a steep cliff. Above that, the ridge has a cover of soil with protruding ledges of deeply weathered gneissic and granitic rock. The bare-rock part of the spur carries several transverse notches, some nearly 75 feet deep and containing marshes. As with the basalt ledge at the north end of Lake Coeur d' Alene, these features are ascribed to glacial water flowing westward between an ice mass in the valley and the rocky mountain side margining it, and escaping across the scablands. No argument for great volume can be advanced for these channeled spurs, but neither can it be denied.

The saddle across the range of old hills protruding through the basalt south of Spokane Valley is a broad sag containing two col notches a dozen miles southeast of Spokane, between Mt. Moran (3700) and Mica Peak (5205) (Fig. 24). The railroad station of Mica marks one col, from which drainage goes north into Chester Creek and southwest into California Creek (Greenacres quadrangle map). There is some channeling by glacial water in the deeply decomposed granitic rock at the cols, but obviously no marked current has ever traversed the saddle from Spokane Valley on the north to the plateau to the south. Erratic material is common up to 2550 feet A.T., but none was found higher.

Flint (1936; 1937) mapped the Mica saddle and most of the drainage area of California Creek as "drift-covered"—*i.e.*, glaciated—with Mt. Moran as a nunatak. It seems much more probable that the scattered erratic boulders and patches of till on which he based his inter-

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FIGURE 25.—SCABLAND CHANNEL HEADS NORTHWEST OF CHENEY

The hills are of granitic and metamorphosed sedimentary rock projecting through the basalt of the plateau. Fish Lake Channel, used by three railroads, has the only basin eroded in basalt and the lake surface is 200 feet or more below the channel floor to the southwest, also on basalt. Thus there must have been fairly deep prebasalt notches across this ancient divide, much of their depths unobliterated by the lava flows and waiting for the glacial water that sharpened and channeled them. Glacial ice has never been over these hills, but it has covered the plateau to the north and has been in the channel heads since the scablands were made. Part of Medical Lake topographic map, U. S. Geol. Survey. Contour interval 25 feet.

pretation were berg-carried to position. They fall far short of a "cover" for California Creek drainage, and their upper limit is nowhere known to be above 2550.

The ponded water for this flotation was named Lake Latah (Bretz, 1923, p. 582) under the impression that it was dammed by the Spangle lobe at maximum extent. It has long since been reinterpreted as a part of an elongated body of water just north of the plateau divide which supplied all the scabland channel heads. The "outlet" for the "lake" was the easternmost channel of the scabland complex (Oakesdale quadrangle) (Fig. 24; Pl. 1), discharging southward from the flooded valley of north-flowing Latah Creek by at least three subparallel and subequal routes across the plateau divide to southwest-flowing Pine Creek and leaving a well-marked glacial river course (Fig. 24) thence for 20 miles down Pine Creek to its entrance into the Cheney-Palouse scabland tract. The combination of features from Mica to the mouth of Pine Creek channel may be interpreted as the record of an early flooding out of Spokane Valley before much deepening of the Cheney-Palouse channel heads had occurred.

The four heads northwest of Cheney (Fig. 25) contain nine named lakes in rock basins and a multitude of rock-basined swamps and smaller lakes. Five of these lakes lie essentially on the plateau divide. Altitudes of channel-head floors range from 2300 to 2424 feet A.T. With other channel-head deepening, later floods may not have risen to the bottom of the Mica col, 2475 feet.

Nevertheless, a marginal meltwater lake must have existed back of the plateau divide, and the abrupt arrival of a Lake Missoula flood must have produced some gradient to its surface. Upper limits of the "Lake Latah" part should, therefore, theoretically be higher than those farther west. Interpretation of Mica col remains uncertain.

Evidence submitted in this paper for great volume of glacial water discharging across the scabland-scarred part of the Columbia Plateau debars any view that it came from excessive melting because of climatic amelioration. Despite the present lack of convincing evidence for torrential discharge between the Missoula dam site and the scabland channel heads, there is no evidence to contradict the hypothesis that enormous volumes of glacially derived water were abruptly discharged across this part of the plateau. Acceptance of Lake Missoula as the source involves no further assumptions to defend the idea.

Tempting speculations arise from the concept of a Lake Missoula dam burst. They include:

(1) abundance of floating ice riven by the dam's collapse;

(2) magnitude of individual bergs (Bretz, 1930b, p. 410);

(3) character of turbulence (excluding the kolk), as conditioned by local channel volume and load and by inherited gradient and valley shape;

(4) varying velocity of advancing front along different channelways, as conditioned by differing channel lengths, proportions and gradients;

(5) differing time of arrival of flood fronts and crests at various convergences;

(6) lag in initiation of channels with higher original sills at heads;

(7) differential yielding of various basalt flows as conditioned by both original and superimposed structures and by varying volumes and gradients of individual streams;

(8) possibility that waning stages of a flood made records suggesting successive floods;

(9) possibility that subglacial leakage from Lake Missoula made the excessive depth of Pend Oreille Lake.

The writers have endeavored to avoid *a priori* speculations as much as possible. Almost every argument for great volume starts from adequate field evidence. The cataract cliffs, alcoves, and plunge pools, and the huge rock basins on preglacial divide summits exist. The enormous, stream-lined piles of fore-set gravel on channel floors are a verity. The giant current ripples are, we believe, unchallengeable. The upvalley currents in tributaries cannot be denied from the record. The scarped loessial islands allow no interpretation other than ours. Furthermore, there was a Glacial Lake Missoula, 90 to 175 miles distant from, and 1700 feet above, initial scabland channel heads, and it was emptied by continuous valley routes directly toward those channel heads.

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Summary

(Bretz)

Bretz's Flood Hypothesis (1923–1932)

The greatly scarred linear tracts of denuded basalt interlaced in a complicated pattern and elongated with the dip slope of the otherwise loess-covered plateau of eastern Washington have been made by glacial floods entering a maturely developed normal drainage pattern. The adjective "channeled," first proposed by Bretz (1932b), and used in a dozen later papers implies that an enormous volume of water transformed the invaded valleys into gigantic river channels. Such great quantities could continue to arrive only for a brief time, and a large volume of ponded water, capable of being abruptly released, is needed for this interpretation. Lake Missoula's volume of 500 cubic miles (Pardee) back of a glacial dam with one buttress most vulnerably situated for a catastrophic failure is argued as the source. Even then, repetition of the cataclysmic flooding seems indicated by the amount of work done by the short-lived glacial rivers. This paper presents new field evidence believed to be consonant only with the interpretation of repeated floods. Its leading theme is that the associated mounded gravel deposits have constructional forms, are gigantic river bars.

But the demand for unprecedented volume has seemed outrageous to conservative geologists, and other hypotheses have been advanced to explain the extraordinary erosional and depositional features of the Washington scabland. Two of them possess sufficient apparent applicability to have secured adherents

Allison's Ice-Jam Hypothesis (1933)

Allison (1933) argued that the scabland phenomena resulted from a damming in the Columbia River gorge across the Cascade Range, more than 100 miles downstream from the plateau scabland. His dam was initiated by a landslide and composed of berg ice and river ice. Once started, it grew upstream by successive increments, eventually ponding the deep major valleys that bound the plateau and allowing glacial stream water of normal volume to cross low places in divides of the plateau's preglacial drainage system. The complexity of the scabland pattern required many other ice jams to provide for divide crossings farther back up the plateau slope. Water bypassing these ice jams in "run-around" lateral channels gashed into the blocked valleys' slopes to make high-lying scabland and remodeled older terraces to form "perched" bars.

Allison admitted that his Cascade Gorge dam must have been 900–1100 feet high but did not point out any field evidence for its precise location nor for its great "run-around" bypass channels in the gorge walls. Nor has he dealt adequately with the resultant flood down the Columbia (1932) below the dam when that great obstruction finally failed. He never located any smaller dams back on the plateau although he wrote about the excellent records left by stranded bergs in the widest ponding of glacial water in the region, the Pasco basin.

Allison's greatest dam lengthened upstream along the Columbia for 100 miles or more above its inception in the Cascade gorge. It thickened as it lengthened, and many diverted lateral strands of the glacial Columbia cut notches and channels across interfluves between entering tributary valleys and made gravel and rubble "dumps", "deltas", "fans", and "bars" in water ponded in these valleys. Several may occur at different altitudes in one locality, but, taken as a whole, they fall into a general descending profile for this valley stretch (Bretz, 1925). Eventually this ice jam was so thick that the Columbia became a series of ponds in these tributary valleys, standing at about 1100 feet A.T. for the entire distance (Allison, 1933, p. 722). No diversion channels were made at this altitude; only pebbly silts and berg-rafted erratic boulders attest the maximum flooding. How the glacially swollen river traversed this 100 miles of individual lateral pondings on no gradient is unexplained. How the diversion channels and gravel deposits near the main valley escaped modification while the dam was growing to full thickness is a puzzle for the deeper part of this long stretch of Lake Lewis was then almost solidly full of ice. The high-lying silts and rafted boulders may not date from the episode of diversion channels and gravel deposits. Leaving out the 1100-foot records, Allison's picture for this 100 miles of Columbia Valley is appealing but lacks any

positive records of the ice blockade itself or of a downvalley rush of water when it failed.

Search was made at Washtucna Coulee, Esquatzel Coulee, Lower Crab Creek, Upper Crab Creek, and Palouse Canyon, where divide crossings or lateral canyons seemed to suggest detours caused by ice jams in the glacial streams. No favorable constrictions and no records of stranded bergs were found. Instead, the upper limits of the glacial rivers, recorded in steepened slopes of the bordering loess, possess uniformly descending profiles along such glacial river courses.

Local ice jams may have occurred in the making of the scabland but no evidence for any has been found. Allison implied that downvalley floods from the inevitable bursting of such dams made the great mounded scabland gravel deposits (remodeled older terraces) which he recognized had largely constructional forms.

Allison also theorized on a deep fluvial fill in the capacious Pasco basin. This basin was undoubtedly occupied by glacial water up to the limits specified, but the only deposits which might conceivably record his detrital fill are huge, elongated mounds, 100 feet or more above the bottoms of closely associated depressions, both forms streamlined like the bars he identified in Snake Canyon, but lying out in the middle of a river valley more than 15 miles wide. The largest depression contains a closed basin 5/10 mile long and more than 50 feet deep. He found only one terracelike gravel deposit in the basin to fit his theory.

Flint's Fill Hypothesis (1938)

Flint (1938) proposed that the many divide crossings and the abundant scarps in loess-covered tracts bordering the scablands had resulted from deposition in the valleys invaded, a common procedure of laden glacial streams but continued here until low divides were crossed and the plexus was outlined. Raising of base level to produce this deposition was presumably because of a dam in the Columbia gorge, formed probably by a great landside or a local valley glacier pushing down into the gorge. This dam was as inferential as Allison's. Flint's glacial streams across the plateau were shallow and "only small pieces of glacier ice" ever floated down them. During wastage of the dam, the glacial streams gradually removed their fills to leave remnants (15 per cent of original deposits—Flint) which he called terraces modified by creep and slopewash; "in various states of [subsequent] dissection." Every high-lying minor unit of the plexus was as well cleaned out as the larger, deeper ones. Wide-swinging meanders were a feature of the dissection on the broader (10–20-mile) tracts. The rugged basalt scabland, including the numerous and spectacular rock basins, was made largely during this removal.

This Columbia gorge dam must have wasted away very slowly, for the nearly complete removal of the fill in scabland routes was all done with moderate quantities of glacial water while also the valley bottom basalt was being scarified (by meandering streams!) into the butte-and-basin topography characterizing scabland.

Flint's interpretation of the gravel deposits associated with the scabland routes as "non-paired, stream-cut terraces", cannot be accepted. Many of the "remnants" are ungullied hills of gravel standing out in mid-valley, possessing stream-lined forms, having associated closed fosse depressions between them and valley walls, containing bouldery accumulations for the transportation of which his "leisurely" streams never could be held competent, displaying internal structures of long fore-sets parallel to the slope for the entire height of the deposit, and carrying gigantic current ripples on their summits and channel-side slopes. Allison, in a later paper (1941), recognized these gravel piles as subfluvially shaped individual forms made in favored places.

There are divide crossings inexplicable by Flint's rising fill (Drumheller, Othello, Devils Canyon, Palouse Canyon); there were contemporaneously functioning spillways out of basins (three cataracts and Drumheller from Quincy basin, Dry and Long Lake coulees out of Bacon syncline) which, even with adequate fills, required far greater volume of water than Flint allowed.

Flint reported that many loessial scarps margining the scabland river routes were "multiple" and argued that the benched slopes

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recorded stages in removing the fill, overlooking any alternative possibilities.

The extraordinary pattern of islandlike, scarp-margined, prow-pointed residual hills of loess isolated in wide areas of scabland and cut through by narrow, subparallel accessory glacial river channels was to Flint the consequence of his widespread aggradation. But in the cleaning out of all the filled valleys by lateral planation, no meander scars were ever left in the loessial scarps.[40] Furthermore, Flint's mechanism "breaks down utterly" (Allison, 1941, p. 56) when catharsis of all the high-lying minor divergent strands is required of it.

Flint's arrow went widest of its mark at the place where Allison specified an ice jam in Snake Canyon at the junction of the Cheney-Palouse scabland river with the larger valley. For this district, Flint listed several dry falls and rock basins, stressing their small dimensions (too small to be shown by the 40 ft. contour intervals of the subsequently published topographic maps) as typical. Unfortunately, he missed seeing dry falls 100 to nearly 300 feet high, empty recessional gorges with closed depressions in them more than 100 feet deep, and rock basins equally deep on the rocky summit of the preglacial divide where a width of 9 miles was swept clean of its loess cover and 9/10 of its 80-square mile area has no remnants of his fill.

Flint hypothesized a debris fill completely blocking Snake Canyon just beyond this ravaged divide summit. To make a lake (Riparia) to account for high-lying, berg-rafted erratic boulders farther up the Snake, the fill had to be 800 feet thick. The outlet of the lake had to be around the southern low periphery of the fill. In the subsequent dissection of this dam (during the slow wastage of his Columbia gorge dam), Snake River unaccountably abandoned the low marginal bypass route, where it should have become entrenched, and returned to its buried preglacial gorge. The fill is almost all gone, and the exhumed, rugged basalt topography forbids any concept of a lateral shifting to bring the Snake back.

[40] Before one commits himself as skeptical of the interpretation of the present study, he should examine the Benge, Haas, LaCrosse and Starbuck quadrangle maps. A topography probably without close approach to parallelism in his experience with maps or terrain is depicted on them. Some of the "islands" (minor prescabland interfluves) have had one side so largely removed that little valleys draining to the opposite side have been beheaded.

Character of New Evidence (1952)

The new evidence for torrential discharge comes from detailed topographic maps (10 foot and 2-foot contour intervals) by the U. S. Bureau of Reclamation; from new topographic maps by the U. S. Geological Survey; from 175 miles of main irrigation canals excavated, in large part, in scabland gravel deposits; from dozens of large, recently opened gravel pits; and from aerial photographs not available during any earlier study.

The aerial photographs reveal giant current ripples on mounded gravel deposits interpreted as gigantic river bars, essentially unmodified subfluvial constructional forms.

Long, deltalike fore-set bedding parallels the slopes and extends throughout the body of many of these bars. The large quantity of transported boulders in some bars and their huge size are impossible products of Flint's streams.

Records of repeated debaclelike floods have been found well distributed throughout the whole scabland complex. The western part of the scabland (Grand Coulee, Quincy basin, adjacent Columbia valley) has had at least seven floods, five down Grand Coulee and two affecting the Columbia valley alone. These are accounted for by repeated burstings (and reconstructions) of the glacial ice dam of Lake Missoula in the mountains of western Montana. Altitudes and topographic relations between the lake and the plateau are in consonance with the idea. Striking records that the lake was abruptly emptied (giant current ripples, severely scoured salients, huge barlike deposits, Pardee 1942) strongly support that interpretation.

Flood Correlations

(Bretz)

Correlations of all the postulated floods are not yet feasible. The latest flood across Quincy basin came from Grand Coulee alone, only after that deep canyon had been cut com-

pletely across the plateau's high northern edge and only when the Okanogan lobe, holding an advanced position across the Columbia valley, prevented escape of the glacial water around the northwestern part of the plateau. This event is generally considered to be of late Wisconsin age. At that time only deeper Drumheller and Othello channels and Lower Crab Creek operated downstream from Grand Coulee. Backfilling in the mouth of Upper Crab Creek and perhaps in lower Washtucna Coulee was contemporaneous with it.

Bretz has argued that all channels in the scabland complex functioned contemporaneously until Grand Coulee's great gash was completed. With this interpretation, Flint has agreed (1938, p. 46). But the new evidence of deepening of some channels during a succession of floods renders that concept invalid for later occupations. The idea is not yet to be dismissed for the earliest recorded flooding. It is based on altitudes of upper flood limits at the channel heads on the high northern edge of the tilted plateau. About a dozen definite channel heads are distributed along about 85 miles of this divide, and the upper-limit altitudes (highest scabland, loessial scarp bases, and ice-rafted erratics floated back in minor valleys in the loess) lie between 2450 and 2550 feet. A.T. (Bretz, 1928b, Pl. 5). Although these are not precise markers, there is no cumulative decrease in their altitudes either east or west. Part of this range may well be ascribed to aneroid errors.

The conclusion that the first recorded flooding used all channels can be avoided if the sites of the western channel heads were originally sufficiently lower than the eastern ones to take all the first flood water and (2) in some subsequent flooding, either these heads were closed by an advanced edge of the Cordilleran ice sheet so that higher eastern channels were initiated or eastward down-tilting had occurred since the preceding flood. This sequence can be reversed by blocking the lower western channel heads at the time of an early flood with an expanded Columbia lobe so that only the higher Cheney-Palouse route operated and then in later floods which found a shrunken Columbia lobe, bypassing that eastern route. Postscabland east-west tilting would again be necessary to bring all channel-head upper limits into the same horizontal plane. An eastward down-tilting, however, would remove the present difficulty with altitudes at Mica.

The channeled summit of Steamboat Rock in upper Grand Coulee carries glacial striae and a moraine ridge, both clearly later than the channeling (Bretz, 1932, p. 35). A silt-covered bouldery ridge on the coulee floor close to the cliffs of Steamboat is perhaps morainic. The eastern margin of the Okanogan lobe apparently has invaded the coulee head since cataract recession passed the Rock. If this completely closed the coulee, it must have caused renewed discharge of flood or normal meltwater through the deeper of the eastern scabland channels. Such an episode must have been brief, for very little retreat of the Okanogan lobe would again open Grand Coulee. A flood down Columbia valley west of the scablands followed the last Grand Coulee discharge, its record indisputable in West Bar's giant current ripples and the Beverly bar. Bursting of the Okanogan lobe's dam (Waters, 1953, p. 617), perhaps as a consequence of another Lake Missoula dam burst, may well have supplied the water for this latest glacial river flooding of the Columbia Plateau.

The writers do not believe that successive Lake Missoula emptyings are to be correlated strictly with successive Pleistocene glacial episodes. Dam failures probably came when increasing hydrostatic pressure in front of the Pend Oreille lobe coincided with weakening of the ice front. Decreased alimentation of the lobe would accompany sub-periodic climatic warmings when wastage would also be excessive. Repeated failures[44] may have occurred during any one glacial cycle. This would be comparable to recorded modern glacial lake bursting in Alaska, British Columbia, the Himalayas, the Alps and elsewhere (Kerr, 1934; Klebelsberg, 1948; Stone, unpublished).

The steep scarps in weak loess can hardly be survivals from early Pleistocene glacial floods. If, therefore, they were made in relatively late Pleistocene time, either there were no earlier Lake Missoula pondings and outbursts or the

[44] Pardee's giant ripples (1942) record a lake surface at least 3450 feet A.T. when the dam burst.

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scarps record a late flood greater than any earlier ones.

It is significant that the closed basins of the scabland are largely unfilled. Their making was not followed by a dwindling flow of debris-laden meltwater incapable of keeping them flushed out. Flow seems to have ceased abruptly. For Grand Coulee's basins, this may have been caused by an abrupt failure of the Okanogan lobe dam but not for the hundreds of other empty basins in channels of all ages in the complex. If the scabland streams were supplied by lake water, instead of meltwater directly from the ice, they would have had only a minimum load. If they were supplied by a catastrophic failure of the Lake Missoula ice dam, an abrupt cessation would be expectable.

Ordinary valley trains along main scabland channels may have been deposited before flooding or in intervals between some floods. But, if so, these were largely destroyed by succeeding floods. None was made after the last flood to traverse any one channel.

All features of the Columbia plateau scabland are too intricately interrelated to dream of unlike agents or markedly different sequences for different parts. If any theory is correct for the Cheney-Palouse tract, it is correct also for Crab Creek, Grand Coulee, Quincy basin, Othello Channels, Pasco Basin, and the Columbia Valley farther downstream.

However plausible the fill-and-cut or ice-jam theories may be in any particular place, they must be equally applicable everywhere in the complex. The writers are confident that only the flood theory can successfully meet this test.

Recapitulation of Inferred History

(1) Miocene basalt flows (Columbia River formation) spread widely over, and almost completely buried, a mildly rugged topography of ancient crystalline rocks. Along the eastern and northern margins, bounded by highlands of these rocks, isolated peaks and ridges projected through the basalt and tongues of basalt penetrated back into deep valleys in the highlands.

(2) Lacustrine and fluvial sediments (Ellensburg, Latah, Early Ringold) were spread over at least parts of the region.

(3) Snake and Columbia rivers established courses across the basalt plain.

(4) Uplift with deformation down-tilted the region southwestward, warped and locally folded and faulted the basalt. These structures are strongly expressed in present topography. Snake and Columbia rivers held antecedent courses across some of the local uplifts.

(5) Weathering and erosion occurred.

(6) Later (?) Ringold sediment (Pleistocene lacustrine) was deposited on the eroded surface in the largest of the warped basins (Pasco), in southwestern part of the region.

(7) Loess was deposited on the plateau concomitant with continued erosional development of Columbia, Spokane and Snake valleys. Weathered zones and caliche layers in the loess record pauses during accumulation. Caliche developed also on basalt and sedimentaries where not loess-covered.

(8) Glaciation occurred. Canadian Cordilleran ice reached the northern edge of the plateau perhaps two or three times during the Pleistocene.

(9) Glacial water crossed the plateau when the deep Columbia valley along the high northern edge was blocked by lobes from northern highlands. Perhaps valley-train gravels were deposited in valleys across the plateau, their remnants now lying at or above upper limits of scabland gravels, or buried beneath them.

(10) Damming of Clark Fork and tributary valleys in Montana by a Cordilleran lobe in Purcell trench formed Glacial Lake Missoula. The Columbia valley was dammed by a similar lobe in Okanogan trench, presumably during Wisconsin time.

(11) The Lake Missoula dam failed before water had risen to the lowest col in Bitterroot Range. The lake's highest surface was about 4200 feet A.T., its depth close to the dam was 2000 feet. A recorded catastrophic emptying of Clark Fork portion demands similar emptying of the entire water body down nearly to 2500 feet A.T. This water escaped southwestward down Spokane Valley toward heads of scabland channels. Upper limits of channel heads range about 50 feet on either side of 2500 feet A.T.

(12) The great volume of glacial-lake water discharging down the dip slope of the plateau eroded its pre-existing minor valley system,

chiefly in loess, into a network of scabland buttes and rock basins in subjacent basalt. In deeper or broader places, deposits of basaltic and caliche gravel grew into huge bars. Some *de novo* divide crossings made by the flood became cataracts hundreds of feet high; Grand Coulee is the outstanding example. Depth and velocity (because of volume) enabled these rivers to quarry large columnar masses of essentially fresh basalt and transport them for miles. Giant current ripples left on bar summits indicate depth of rivers to have been considerably greater than heights of bars.

? (13) Repeated reconstruction of dam with repetition of dam failures and consequent floods took place.

(14) Deepening of some channels in basalt during later floods allowed scarping of bars already formed and growth of lower bars close to scarp bases. These also have great current ripples. In Quincy basin, adjacent Columbia valley, and environs, seven successive floods are recorded, five of them while the Okanogan lobe dam forced the discharge to cross the plateau by way of scabland channels.

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