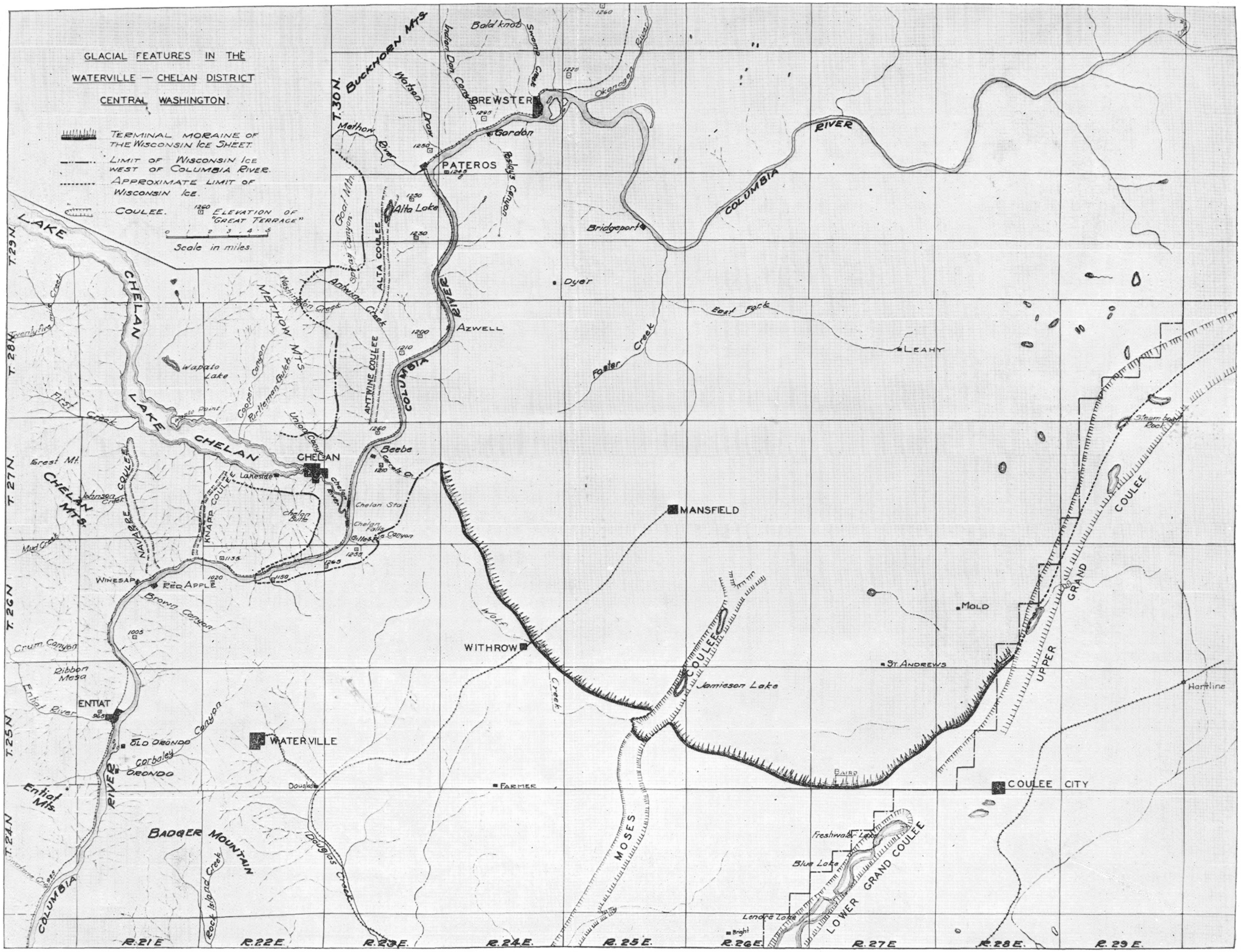

GLACIAL FEATURES IN THE
WATERVILLE — CHELAN DISTRICT
CENTRAL WASHINGTON.
TERMINAL MORAINE OF THE WISCONSIN ICE SHEET.
LIMIT OF WISCONSIN ICE WEST OF COLUMBIA RIVER.
APPROXIMATE LIMIT OF WISCONSIN ICE.
COULEE.
1260 ELEVATION OF "GREAT TERRACE"
Scale in miles.
BUCKHORN MTS.
T.30 N.
T.29 N.
T.28 N.
T.27 N.
T.26 N
T.25 N
T.24 N
Bald knob
Swamp Creek
Okanogan River
Indian Dan Canyon
Watson Draw
Methow River
BREWSTER
Gordon
PATEROS
Alta Lake
Goat Mtn.
ALTA COULEE
Bridgeport
COLUMBIA RIVER
Dyer
LAKE CHELAN
Antwine Creek
Washington Creek
METHOW MTS.
Wapato Lake
Twentyfive Mile Creek
First Creek
Cooper Canyon
Azwell
ANTWINE COULEE
East Fork
Foster Creek
LEAHY
Steamboat Rock
Union Canyon
Beebe
CHELAN
Lakeside
Chelan River
Chelan Sta.
Chelan Butte
Chelan Falls
Forest Mt.
CHELAN MTS.
Johnson Creek
NAVARRE COULEE
KNAPP COULEE
Mud Creek
WINESAP
RED APPLE
Brown Canyon
MANSFIELD
Wolf Creek
COULEE
GRAND
UPPER
MOLD
WITHROW
Crum Canyon
Ribbon Mesa
Entiat River
ENTIAT
ST. ANDREWS
Jamieson Lake
Hartline
WATERVILLE
OLD ORONDO
Corbaley Canyon
ORONDO
Douglas
FARMER
Baird
COULEE CITY
Entiat Mts.
RIVER
BADGER MOUNTAIN
Douglas Creek
MOSES
Freshwater Lake
Blue Lake
LOWER GRAND COULEE
Lenore Lake
Bright
Rock Island Creek
COLUMBIA
R.21 E.
R.22 E.
R.23 E.
R.24 E.
R.25 E.
R.26 E.
R.27 E.
R.28 E.
R.29 E.

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TERRACES AND COULEES ALONG THE COLUMBIA RIVER NEAR LAKE CHELAN, WASHINGTON [1]

BY AARON CLEMENT WATERS

(Read before the Cordilleran Section, April 8, 1932)

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INTRODUCTION

Near the close of the last century the region around the mouth of Lake Chelan was visited by several of the early reconnaissance parties.[2] Some-

[1] Manuscript received by the Secretary of the Society, December 5, 1932.

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

I. C. Russell: A geological reconnaissance in central Washington. U. S. Geol. Survey Bull. 108, 1893; A preliminary paper on the geology of the Cascade Mountains in northern Washington. U. S. Geol. Survey, Ann. Rept. 20, 1898-1899, pp. 89-210.

W. L. Dawson: Glacial phenomena in Okanogan County, Washington. Am. Geologist, vol. 22, 1898, pp. 203-217.

G. O. Smith and F. C. Calkins: A geological reconnaissance across the Cascade Range near the Forty-ninth Parallel. U. S. Geol. Survey Bull. 235, 1904.

what diverse interpretations of the glacial features, particularly of the broad terrace that hangs 600 feet above the Columbia, were proposed and the region became the subject of considerable controversy.[3] It was the writer's good fortune to spend most of the summer of 1931 in a portion of the Columbia Valley where the physiographic features associated with the advance and recession of the last ice sheet are well displayed. Although the investigation was primarily of petrologic character, it is believed that sufficient data regarding the glaciation of the district were gathered to be worthy of record, and that the observations here presented will be of assistance in evaluating some of the controversial interpretations.

Eliot Blackwelder has kindly read and offered suggestions regarding the manuscript, and the writer has also had the benefit of a brief visit from Professor Blackwelder and from Bailey Willis in the field.

Geologic Setting of the District

From its junction with the Spokane River in northeastern Washington, the Columbia River flows westward to its confluence with the Okanogan, and then swings southward in a broad curve that brings it past the city of Wenatchee. Throughout this part of its course the river flows in a deep canyon, which forms a natural boundary between two sharply contrasted geologic provinces.[4] To the south and east, enclosed in the great curve of the river, lies the nearly level surface of the Waterville Plateau, a part of the vast, basalt-floored Columbia Plateau. West of the river, bold ridges and serrate peaks carved from resistant metamorphic and plutonic rocks initiate the rough alpine topography of the northern part of the Cascade Range. The relief in this district varies between 3000 and 6000 feet. Lake Chelan, a narrow body of water over 50 miles long but averaging less than one and one-half miles in width, lies in a magnificent glaciated canyon transecting these rugged mountains. The outlet of the lake is only a few miles west of the Columbia River. North of the Columbia lie the Okanogan Highlands, a maturely dissected upland underlain by pre-Tertiary crystalline rocks similar to those of the northern Cascades.

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[3] W. L. Dawson: Op. cit.

I. C. Russell: The Great Terrace of the Columbia and other topographic features in the neighborhood of Lake Chelan, Washington. Am. Geologist, vol. 22, 1898, pp. 362-369; A preliminary paper on the geology of the Cascade Mountains in northern Washington. U. S. Geol. Survey, Ann. Rept. 20, 1898-1899, pp. 150-204.

G. O. Smith and F. C. Calkins: Op. cit., pp. 35-43.

[4] G. O. Smith and F. C. Calkins: Op. cit.

A. C. Waters: A petrologic and structural study of the Swakane Gneiss, Entiat Mountains, Washington. Jour. Geol., vol. 40, 1932, pp. 604-634.

Into these sharply contrasting but contiguous provinces—the one a flat pleateau; the other, a maturely dissected, rugged mountain mass—advanced the Wisconsin [5] ice sheet. The topographic modifications that it produced in each province are striking and distinctive but are as markedly different and distinct as are the provinces themselves.

Glacial Features on the Waterville Plateau

TERMINAL MORAINE

West of Grand Coulee the basalt underlying the southern part of the Waterville Plateau is covered by a thick mantle of aeolian soil which permits wheat farming. On the other hand, the northern half of the district is a broad expanse of rocky waste, most of which either still preserves its primeval sagebrush covering or is spotted with abandoned, weed-covered farms.

Separating these agriculturally different areas lies the terminal moraine of the Okanogan lobe of the last ice sheet. This lobe pushed south across the Columbia River, scooping the plateau free of its mantle of loess and piling up a huge moraine that forms an easily traceable line of hummocky hills. A few miles northwest of Coulee City the moraine disappears along the walls of Grand Coulee. From this point it loops southwestward to the vicinity of Baird and then trends northwest, terminating on the walls of the Columbia canyon in the headwaters of Corrals Creek (figure 1). A separate tongue from this lobe extended farther down the Columbia canyon, terminating a short distance south of Chelan Falls, and sending a lateral branch up Chelan Valley. Similar relations are found where the moraine crosses Moses Coulee, a dry river canyon carved by pre-Wisconsin glacial melt water.[6] A few miles from Jamieson Lake the vertical bluffs of basalt forming the eastern wall of the coulee are buried and masked beneath the terminal moraine. A narrow tongue of ice advanced about a mile farther down the coulee and there built a moraine on the coulee floor.

Throughout most of its course the moraine varies from 50 to 100 feet in height, but in the vicinity of Withrow it is much higher. Behind the moraine discontinuous, faintly developed, recessional moraines are locally seen. Glaciofluvial deposits are rare, both as outwash and as deposits

[5] In this paper, following the usage of Bretz, the term Wisconsin is used to signify the last ice invasion of the district. So far as the writer is aware, definite correlations with the Middle West have not yet been made.

[6] J Harlen Bretz: The channeled scablands of the Columbia Plateau. Jour. Geol., vol. 31, 1923, pp. 617-649; The channeled scabland of eastern Washington. Geog. Rev., vol. 18, 1928, pp. 446-477.

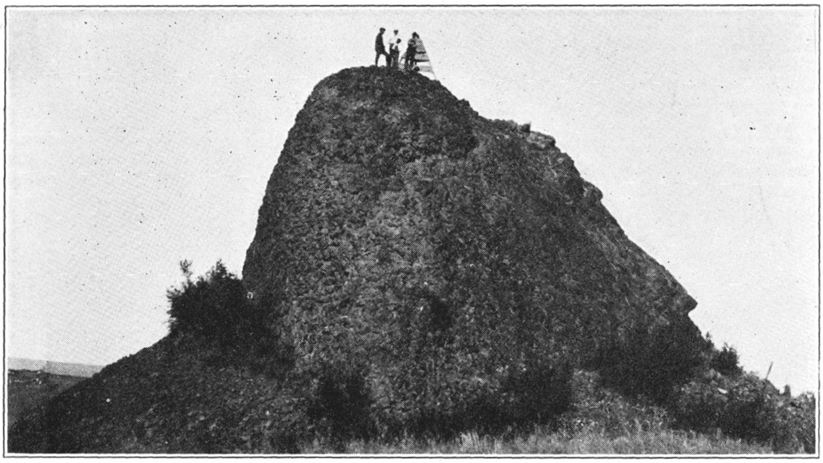

FIGURE 2.—*Basalt Erratic*

"Haystack Rock" on the surface of the Waterville Plateau near Coulee City. Photograph by O. P. Jenkins.

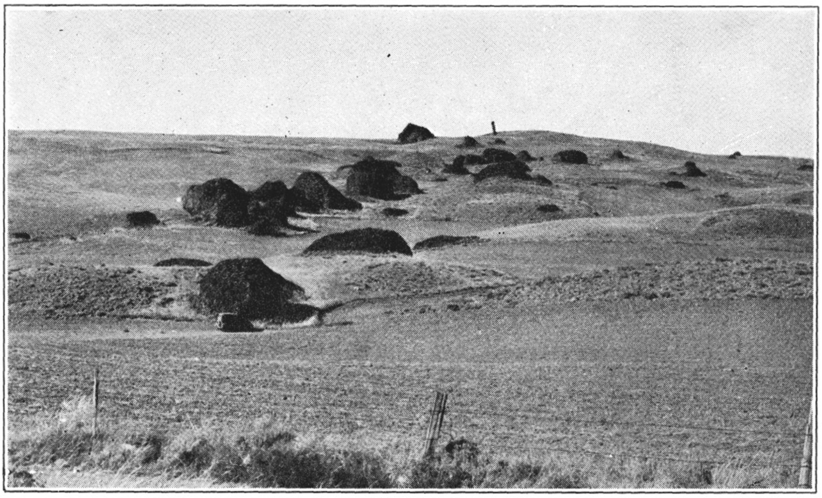

FIGURE 3.—*Group of Haystack Rocks on the Terminal Moraine near Corrals Canyon*

The automobile beside the rock in the foreground gives the scale. Photograph by Eliot Blackwelder.

behind the moraine.[7] The almost complete absence of an outwash apron is one of the most striking characteristics of the plateau region

BASALT ERRATICS OR "HAYSTACK ROCKS"

The moraine on the Waterville plateau is rendered especially conspicuous because its surface is studded with enormous erratic boulders, many of which are larger than an ordinary dwelling (figures 2 and 3). They occur by the thousands. Many of the boulders approximate a roughly rectangular or a nearly equidimensional shape, and from their rather striking resemblance to the stocks of wheat hay and straw erected by the farmers, they are locally called "Haystack Rocks." The "Haystack Rocks" are invariably composed of basalt. Granite, gneiss, and many other rocks occur in the glacial débris but never form enormous 60-foot erratics. Between Grand Coulee and the Okanogan the Columbia flows westward almost at right angles to the direction of ice movement (figure 1). The ice rode across the canyon and, in passing up the steep, southern wall, quarried under the horizontal flows of lava exposed in steplike cliffs along the side of the gorge, lifted great fragments of these flows bodily loose from their basement, and strewed them over the landscape.

Glacial Features West of the Waterville Plateau

PRELIMINARY STATEMENT

In the rough mountainous district west of the Columbia the advancing Wisconsin ice buried peaks and ridges that now rise 4000 feet above the river, but the main ice sheet did not pass over the summits of the Methow Mountains. Farther west, valley glaciers descended from the high Cascades. In the region overrun by the continental ice the most conspicuous evidence of glacial occupancy is the presence of suites of terraces that hang from the sides of the major valleys and completely block the minor tributaries. These terraces are commonly connected with flat-bottomed coulees or with narrow notches that cross spurs between adjacent valleys. In marked contrast to the plateau area there is a striking absence of morainal material of any kind, the deposits found in the mountainous district being composed almost entirely of stratified glacial drift.

HIGH TERRACES

Distribution.—Between the mouths of the Wenatchee and the Okanogan rivers the Columbia is incised in a steep-walled canyon which varies from 2000 to 4000 feet in depth. It is joined by no major stream

[7] O. W. Freeman has recently called the writer's attention to the presence of a rather extensive group of kame-like deposits behind the moraine east of the town of Mansfield.

from the east, but its eastern wall is sculptured by numerous small canyons that head 6 to 12 miles back on the plateau. On the western side, also, the canyon walls of the main stream are, for the most part, breached by rather small, insignificant tributaries, but Swakane Creek, Entiat River, Chelan River, and Methow River have extensive valleys (figure 1). A striking change in the character of these tributaries of the Columbia is noticeable in the vicinity of Chelan Butte. Down the Columbia from this point the walls of the tributary valleys are free and unencumbered save in their lowermost parts (figure 4). Upstream they are choked throughout their entire length by dozens of terraces, which convert each tributary

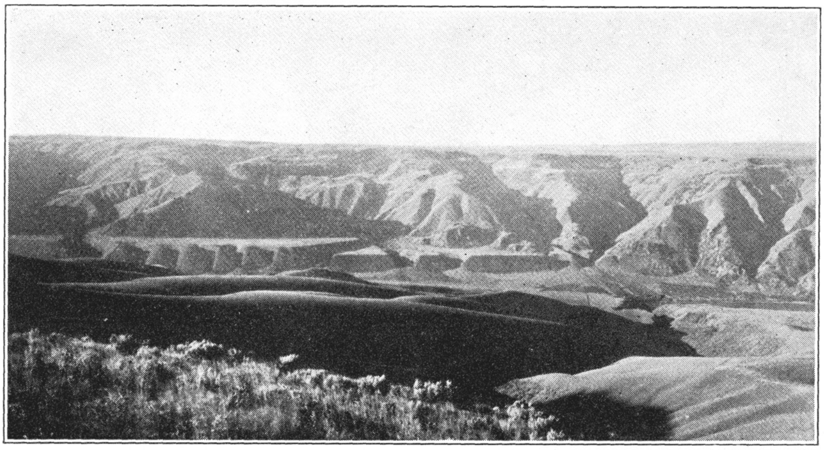

FIGURE 4.—*Terraces along the Columbia River south of Chelan Butte*

Note that only the lower parts of the tributary canyons are blocked by terraces. the ice tongue in the Columbia terminated approximately at the right margin of the picture and was less than 1000 feet thick throughout the length of the view.

valley into a gigantic stairway, the flat tops and steep margins of the terraces forming the steps and risers, and the rocky ridges of the interstream divides furnishing the balustrades (figure 5). The higher terraces are almost invariably confined to a single canyon. Some of the lower ones may extend around a spur and coalesce with terraces in a neighboring tributary, but, with the exception of an extensive compound terrace that lies at an elevation of approximately 1250 feet above tide and that is known in the literature as the "Great Terrace of the Columbia,"[8] none of them is very extensive outside its own valley.

[8] I. C. Russell: A geological reconnaissance in central Washington. U. S. Geol. Survey Bull. 108, 1893.

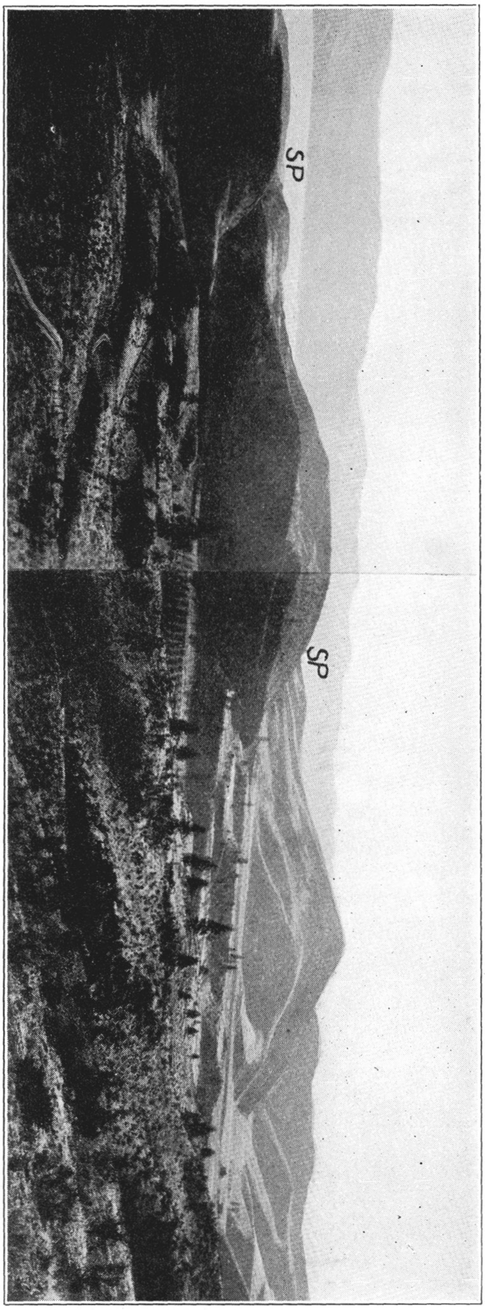

FIGURE 5.—*Terraces in the West Fork of Union Canyon*

Two spillways constituting the outlets through which the lakes in which the terraces were built drained into the Chelan Basin are shown. The higher one controlled the highest terrace in the canyon; the lower one controlled the terrace upon which the orchard is located. Lake Chelan in the background.

Nature of terrace material.—Excavations in the terrace fronts and tops reveal that they are composed of gravel, sand, silt, and clay, all of which are well stratified. Gravel and sand predominate. Several factors indicate that deposition took place largely in ponded bodies of water. The finer-grained materials are invariably bedded horizontally and show the paper-thin lamination characteristic of lacustrine deposits. The gravels are crossbedded in deltaic fashion, and delta foresets are locally seen, extending for more than 100 feet along the dip. At many places the foresets dip up or else directly across the tributary valley, indicating that the delta was built by a stream flowing in the opposite direction or else at right angles to the present drainage. The majority of the terraces have horizontal tops, indicating that they were controlled by a lake surface, but a few terraces have sloping or irregular tops.

The terrace material is obviously foreign to the valley in which it is now found. In Corrals Canyon the highest terrace is built against basalt walls, and Corrals Creek heads on the plateau where basalt and limy concretions in the loessial soil are the only coarse débris that can be obtained. Nevertheless, the boulders within this terrace are composed largely of granodiorite and associated plutonic rocks similar to those of the Chelan batholith, and there is only a very minor amount of basalt and limy concretionary material. Similarly, in Indian Dan Canyon, which drains only the Chelan granodiorite and its associated recrystallized roof rocks, boulders of basalt (figure 12) quartzite, and other rocks are found which could not have had their source in this valley.

The terrace material is clearly of glacial origin. Some of the boulders are faceted, and specimens may be found that preserve glacial striae. Most of the material has been partially rounded by transportation in glacial streams. Under the microscope, the fine silt grains show the ragged, irregular boundaries characteristic of glacial material, and they are of markedly unweathered character. Fresh feldspar is the most abundant constituent, and much undecomposed ferromagnesian material is also present.

Local nature of the high terraces.—The field relations of the terraces indicate that they were built in lakes whose valleyward margins were dammed by ice that still occupied the Columbia Valley.[9] Gradual melting

[9] Although the so-called "Great Terrace" of the Columbia has been described in a number of reports, the smaller and higher terraces that block the upper reaches of the tributaries of the Columbia have been neglected in the literature. Smith and Calkins (U. S. Geol. Survey Bull. 235, 1904, pp. 38, 39) emphasize their importance and correctly state that the terraces in Washington-Antwine Creek (called Peters Creek in their report) are "in the nature of a delta deposit laid down in a tributary canyon dammed by the Okanogan glacier." Willis (U. S. Geol. Survey, Prof. Pap. 19, 1903, p. 59) also advanced this explanation for the high terraces on the north shore of Lake Chelan.

of the ice barrier caused the lakes to drop to successively lower and lower levels. Melt water, running marginally along the tongue of ice, filled these successive lakes with débris, which was left as terraces blocking the valleys upon complete withdrawal of the ice. Such a local control of lake levels through damming of the tributary valleys by ice explains the fact that the terraces in the different valleys occur at varying elevations. If we assume that the terraces were formed by some process of alluviation that filled the Columbia Valley with gravel from side to side and that later re-excavation of this fill has occurred, the terraces in the various tributary valleys, and particularly the topmost terrace, should lie at the same level in all valleys or else should change in level in a regular, orderly fashion. There is, however, no correlation of the terrace levels in adjacent valleys. Measurements of the elevation of the terrace tops, in all the valleys tributary to the Columbia between Knapp Coulee and the mouth of the Okanogan, are compiled for examination in Table I. The striking independence of the various tributaries with respect to the levels at which terraces are developed is brought out by the table. The elevations of terraces in the two forks of a single valley rarely coincide. In the upper part of Swamp Creek valley, terraces occur at elevations greater than the surface of the plateau on the east side of the Columbia.

TABLE I

Canyon	Elevations at which terraces occur (feet)
Gillespie	1255, 1405, 1705.
Corrals	1130, 1210, 1400, 1690, 1830, 1950, 2210, 2270, 2350.
Union	1415, 1660, 1795, 1875, 1915, 2125.
Washington-Antwine	1210, 1260, 1340, 1540, 1690, 1790, 2005, 2100, 2220, 2300, 2560, 2620.
Watson	1250, 1435, 1575, 1705, 1810, 1985, 2090, 2125, 2425.
Indian Dan	1295, 1405, 1555, 1655, 1775, 1895, 2170, 2405, 2485.
Paslays	955, 1105, 1325, 1455, 1695, 1845, 2025, 2235, 2590, 2720.

Terrace margins and tops.—Many of the terraces show, by the peculiar character of their fronts and tops, that they were built against ice. In the majority of cases it appears that the ice was in motion, but terrace fronts are found that seem to have been built against ice that was practically stagnant. Terraces with river-carved margins are found locally, but these have developed through lateral planation of ice-built fronts after melting had exposed the edge of the terrace to the river's attack.

The terrace margins that were built against moving masses of ice commonly cross the tributary valley in a straight line or are slightly convex upstream. The terrace top may end against a lateral moraine composed of glacial till and dotted with large erratic boulders. In places, as along the margins of the higher terraces in the East Fork of Union Valley, this morainal accumulation rises above the top of the terrace (figure 6), but more frequently it lies partially or wholly buried by the glacio-lacustrine material deposited in the adjacent lake. In the latter case, excavations in the terrace front reveal an indiscriminate jumble of till and stratified

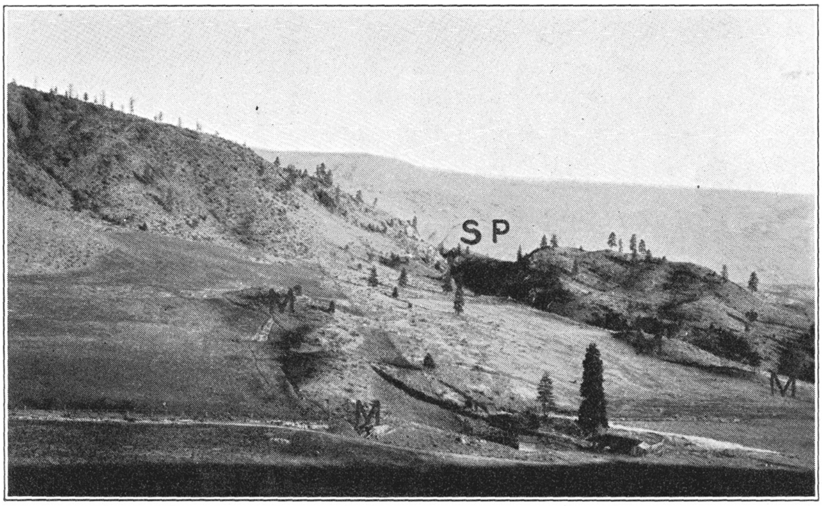

FIGURE 6.—*Looking east across two Terraces in the East Fork of Union Valley*

M-M indicates a lateral moraine covered with erratic blocks which forms the margin of the upper terrace. After this terrace was built the ice withdrew to a lower level, building the lower moraine M'-M', and furnishing a dam to hold the lake water in which the lower terrace was built. The ridge notch (S P) through which the debris-laden water entered these lakes from the Columbia Valley is also shown. This spillway continued to function after the two terraces were completed as can be seen by the fact that it has been lowered below the level of the lower terrace.

drift. Locally the stratified drift at the terrace margin is much contorted, having been pushed backward and broken by advance of the ice. Along the margin of the terrace at an elevation of 1660 feet in Union Valley, the stratified drift has been thrust bodily backward up the tributary by the advancing ice until it has been piled along the margin of the terrace in a high ridge which resembles a lateral moraine (figure 8) but differs from the more common type of moraine in being composed almost entirely of contorted and disrupted stratified drift instead of till.

An excellent example of a terrace built against moving ice is found at an elevation of 1795 feet on the south shore of Lake Chelan, just above Lakeside. The terrace front is straight and regular on a large scale but is hummocky and irregular in detail. It is composed of till and is the lateral moraine of an ice tongue, to be described subsequently, which ad-

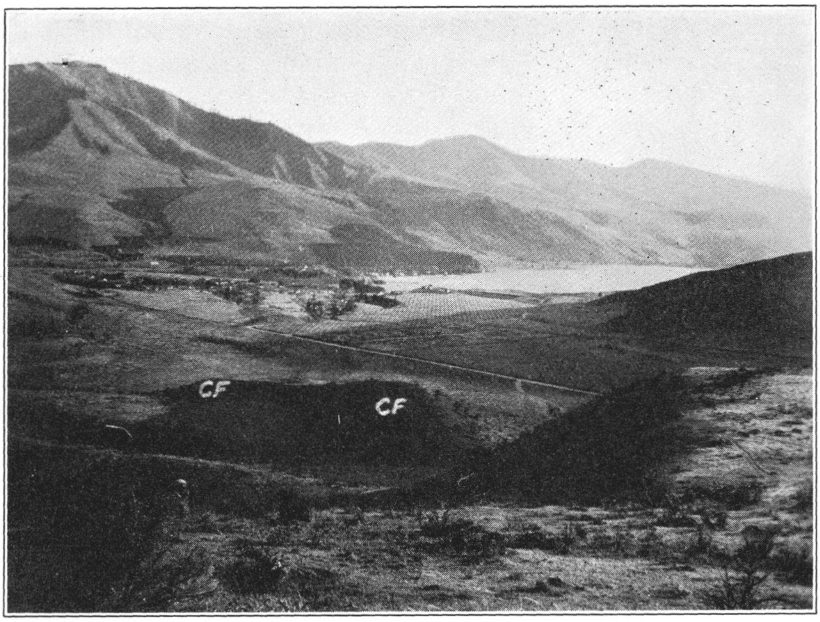

FIGURE 7.—*Margin of the 1660 Terrace in Union Valley (foreground)*
Shows an ice contact slope and a crevasse filling (CF). Note the boulder littered margin of the terrace.

vanced from the Columbia Valley up Lake Chelan. In the re-entrant formed by the canyon that mouths at Lakeside a lakelet developed behind this combined moraine-ice dam, which was then filled with a deposit of stratified drift. Numerous erratic boulders perch on the top of the lateral moraine, and just above Lakeside there is one of the "Haystack Rock" variety, which weighs many tons. Terraces of similar nature are found in Indian Dan Canyon, in the valley of the Methow, on the north side of Antwine Creek, and at several other localities. In most of these, however, the lateral moraine is largely or completely covered, and near the top of the terrace, glacio-fluvial material was deposited directly against the surface of the ice.

A small number of terraces have frontal margins that appear to have been built in contact with stagnant, rotten, highly fissured ice masses. These terraces have highly crenulated margins, although the terrace front, on a large scale, may pursue a fairly straight course across the valley. From the terrace front, striking fingerlike masses of stratified drift extend out, terminating in the open valley beyond. The terraces also commonly show pitted tops, and near their outer margins there may be a veritable maze of kettles. The edges of the kettles, as well as the margins of the terraces, are littered with erratic blocks that sloughed off the melting ice against which the glacio-lacustrine deposits were built (figure 7). Apparently, at the time these terraces were formed, the lake water was dammed by a highly fissured, débris-laden, rotten mass of stagnant ice, against whose front the stratified deposits came to rest. Material washed into the long, narrow fissures formed the fingerlike crevasse fillings,[10] and isolated blocks of ice, detached from the main mass by differential melting, were surrounded or, in some cases, completely buried by sediment washed into the lakes, and, upon melting, left characteristic kettles.

The stagnant condition of the ice responsible for the building of these features appears to have been entirely local. There is no evidence that the entire ice sheet stagnated at this locality, although recent work by the writer in the Okanogan Highlands, to the north, shows that widespread stagnation of the Wisconsin ice occurred in the more mountainous parts of the region during the period of deglaciation. In the Chelan region the evidence indicates that, at some localities, change from activity to stagnation, or vice versa, has occurred during the building of a single terrace. For example, in Union Valley the terrace at an elevation of 1660 feet is dammed by a lateral moraine at one point, and a stream excavation in the front of the terrace shows that the lacustrine sands and gravels along the terrace margin were disrupted, broken, and pushed inward by the thrust of the ice. On the west side of the valley, near the spillway that controlled the terrace, an additional terrace fill has been built beyond the zone of lateral moraine and disrupted strata. This newer fill is pocked with kettles and ends in a highly irregular ice contact slope (figure 8). Clearly, the main part of the terrace was built against active ice, but in the last stages of lake-filling a condition of stagnation ensued which persisted until the

[10] R. F. Flint: Eskers and crevasse fillings. Am. Jour. Sci. (5), vol. 15, 1928, pp. 410-416.

lake was drained. Change from activity to stagnation and vice versa has actually been observed in modern Alaska glaciers.[11]

SPILLWAYS CONTROLLING THE TERRACES

The attention of the observer who travels up the Columbia in the vicinity of Lake Chelan is attracted by the terraces blocking the tributary valleys of the river, because these terraces are so completely out of adjust-

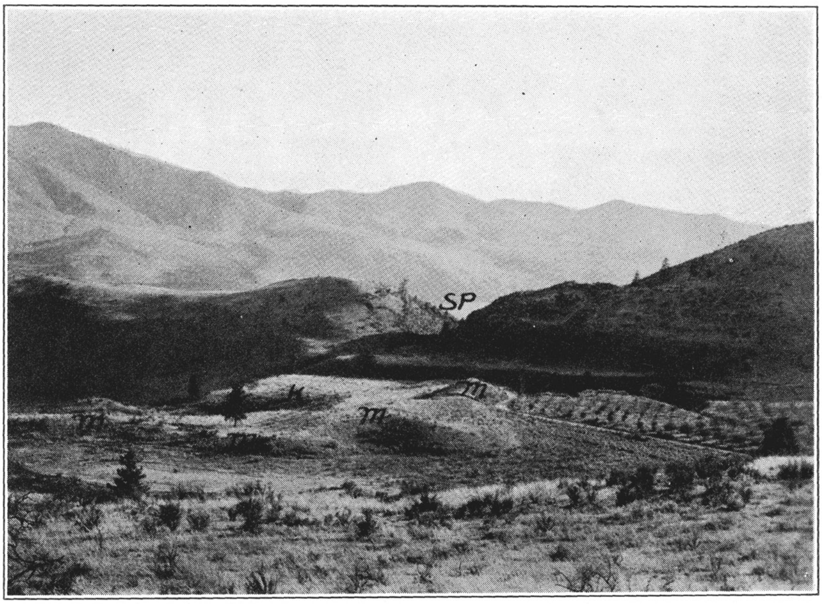

FIGURE 8.—*Margin of the 1660 Terrace in Union Valley*

The hummocky ridge marked m-m-m-m is a moraine composed largely of disrupted and contorted stratified drift. After the building of the lateral moraine and the terrace behind it, the ice withdrew a short distance down the valley and became practically stagnant, resulting in the building of a narrow kettle-pocked terrace with a highly irregular margin. Part of this terrace is shown just to the left of the moraine. K indicates a kettle on this new fill, and Sp indicates the ridge notch that formed the outlet of the lake. Beyond the spillway notch the surface of Lake Chelan is visible, and Chelan Butte forms the high mountain in the left distance.

ment with the other physiographic forms with which they are associated (figures 4, 5, 13, 18, 20). If these terraces should be removed, the long, sloping curves of a maturely dissected region would meet the eye on

[11] R. S. Tarr: Some phenomena of the glacier margins in the Yakutat Bay Region, Alaska. Zeit. für Gletscherkunde, vol. 3, 1908-1909, pp. 81-110.

R. S. Tarr and L. Martin: Alaskan Glacier Studies. National Geographic Society, Washington, 1914.

every hand, save that in the more alpine regions bold cliffs and rugged promontories serve to break the monotony. Deep U-shaped valleys, cirques, and other evidences of glacial cutting are entirely absent. The ice mass modified the original form of the valley only moderately through erosion, the principal effects being to round off and smooth the minor irregularities of the sides and the valley floor, without extensive cutting. Some of the higher peaks were planed off and lowered by glacial abrasion. There is, however, no evidence of extensive valley-deepening, such as occurred through the action of the valley glacier that occupied the site of the

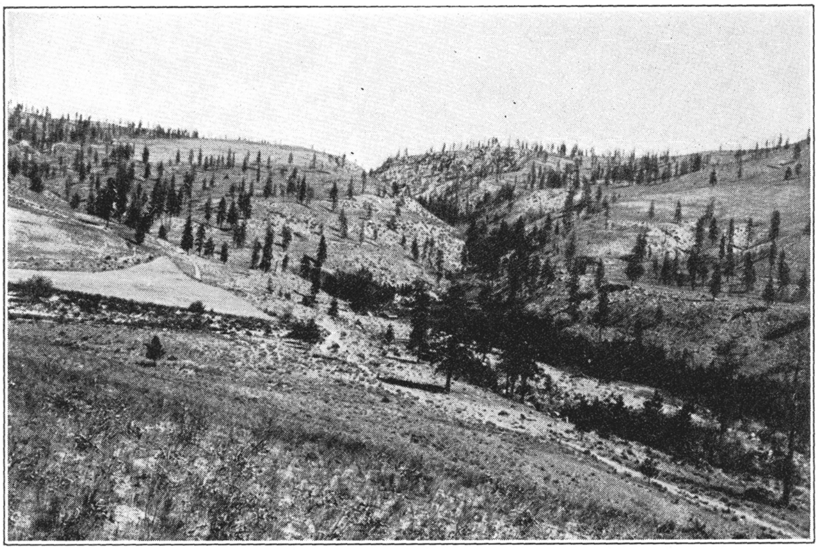

FIGURE 9.—*Mouth of a Spillway*

Looking northward into the mouth of a spillway east of Knowlton Butte (see map, figure 10) which formed the outlet of a lake at an elevation of 2850 feet in Swamp Creek.

present Lake Chelan, and if the terraces were removed, the Columbia Valley, above the limit of glaciation, would show only minor differences from the valley below the limit of the ice.

There are, however, certain unique topographic features other than the terraces that commonly occur in the area overrun by the ice, but which are not commonly encountered in the unglaciated districts. These are the narrow, flat-bottomed coulees and the smaller ridge notches, which pass across divides separating tributary valleys of the Columbia, and which are strikingly out of adjustment with the smooth, uninterrupted ridges that

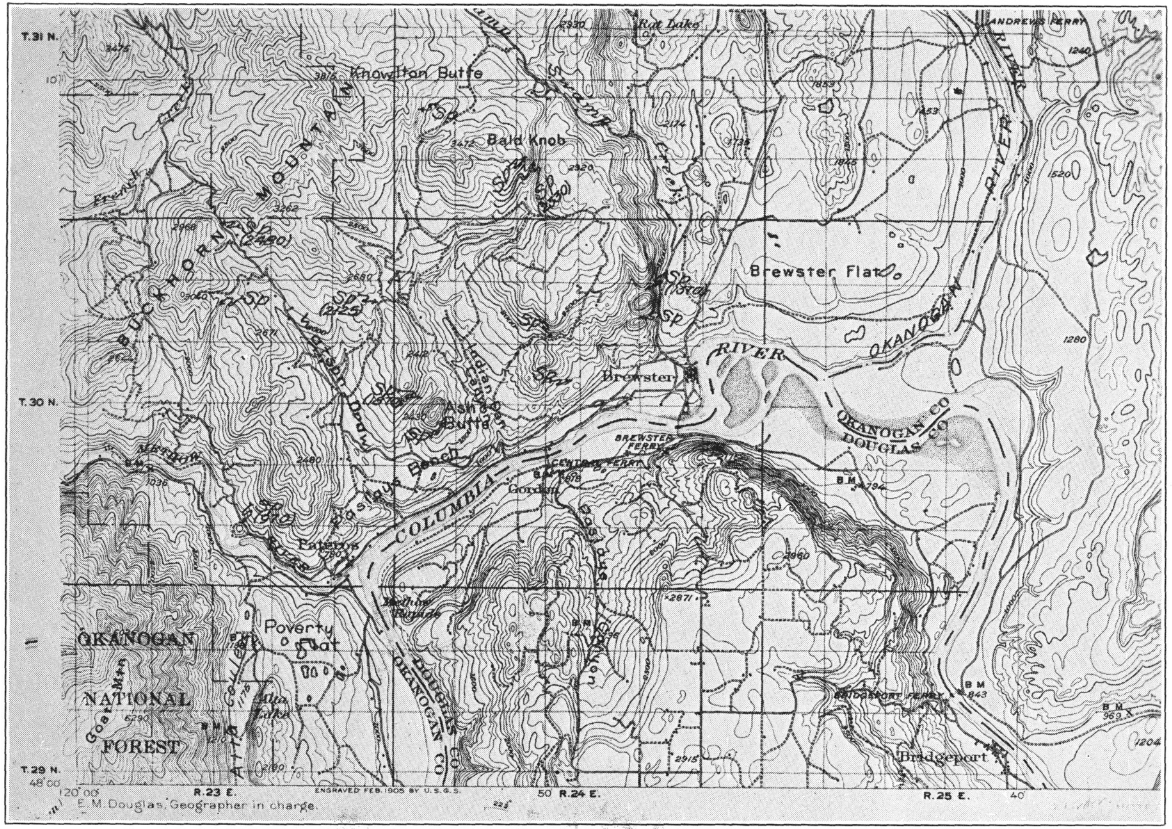

FIGURE 10.—*Southwestern part of the Okanogan Quadrangle, Washington*

Note the large expansions of the "Great Terrace" in Brewster Flat, Poverty Flat, and Paslays Bench. The head of Alta Coulee is also shown. Several rock notches, or spillways, are indicated by the symbol (2125) SP. The number in parenthesis indicates the elevation of the spillway. Contour interval, 100 feet.

they transect (figure 9). They show evidence of recent formation, for their walls are nearly perpendicular, unscalable cliffs at many localities. The walls of these coulees and ridge notches are so abrupt and, in many cases, are so close together that they resemble great open fissures crossing the divides. In fact, the ones at the east end of Chelan Butte near the confluence of the Chelan and the Columbia were so considered by both

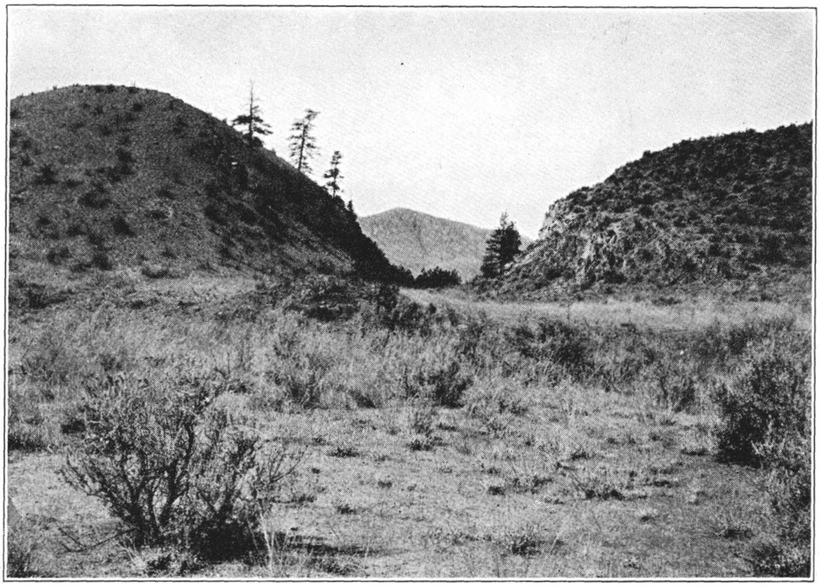

FIGURE 11.—*Ridge Notch on the West Side of Union Valley*

Note how the former saddle has been cliffed and lowered by the glacial water. The terrace that the spillway controlled occupies the foreground.

Russell [12] and Dawson,[13] the part of the ridge lying nearer the Columbia being interpreted by them as a fallen landslide mass. A recently constructed tunnel of the Washington Water Power Company passing under this notch, however, encountered solid rock all the way. Evidence is here presented to show that these, and other notches and coulees in this district, were cut by heavily loaded streams of high velocity that flowed marginally along the tongue of ice occupying the Columbia Valley.

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[12] I. C. Russell: A geological reconnaisance in central Washington. U. S. Geol. Survey Bull. 108, 1893, p. 80.

[13] W. L. Dawson: Glacial phenomena in Okanogan County, Washington. Am. Geologist, vol. 22, 1898, pp. 203-217.

SMALL RIDGE NOTCHES

The short notches transecting divides are well exemplified by a number of trenches that cross the ridge between Swamp Creek and Indian Dan Canyon (figure 9) and by others that cross the divide between Indian Dan Canyon and Watson Draw. These notches are shown on the Okanogan topographic sheet, a part of which is reproduced in Figure 10, but the 100-foot contour interval masks the precipitousness of their sides and makes them appear far more like normal stream valleys than they really are.

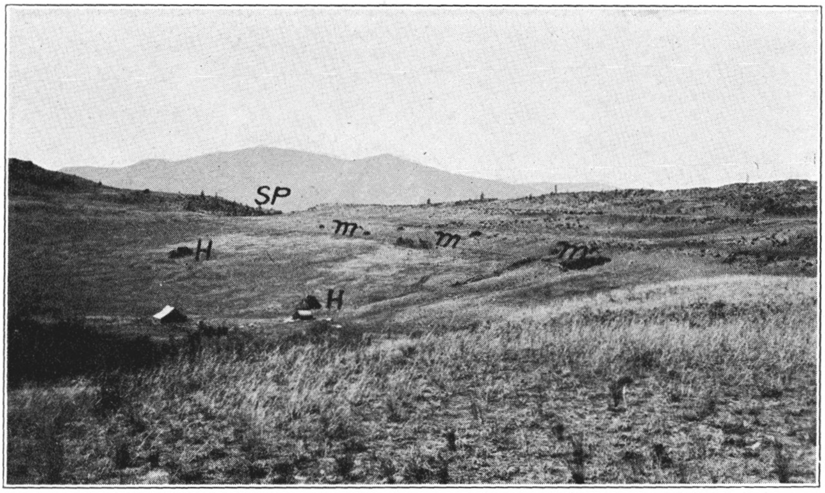

FIGURE 12.—*Ridge Notch (Sp) on the Divide between Indian Dan Canyon and Watson Draw*

The terrace that the notch controlled in Indian Dan Canyon lies in the foreground. The area between the terrace margin and the spillway was blocked by ice at the time the terrace was deposited. The position of the ice margin is clearly outlined by the mass of debris containing many erratic blocks along the line m-m-m. An older shoreline, marking an earlier stand of the lake before the spillway was cut to its present level, is faintly shown above m-m-m. The letters H-H indicate two, large, basaltic erratics brought in by the ice. Elevation, 2125 feet (see map, figure 1).

That these notches were spillways serving as outlets of the various lakes in which the terraces were built is shown by the fact that the upstream end of a notch almost invariably ends in a broad terrace which occupies the valley above (figure 11). In some cases, however, the upstream end of a ridge notch does not emerge on a terrace top, but hangs high above the valley floor. In these examples, a terrace lying at accordant elevation is almost invariably found farther upstream in the valley that the notch heads in. In some cases, as in the spillway illustrated in Figure 12, a line of erratic boulders marks the side of the tributary valley from the front of the terrace to the spillway, showing that the terrace was built against an ice mass that extended farther up the tributary valley than the site of the spillway, and that the drainage from the lake entered the spillway by means of channels across the surface of the ice, or through englacial and subglacial tubes.

A notable feature of the notches and coulees is that they cross divides, usually following the site of a previous saddle. Lateral notches that head and mouth within the same valley are found but are rare, and no examples were seen of curving trenches contouring the end of a spur, such as Rich [14] noted in analagous positions in the Finger Lake district.

In most notches, downcutting has not deepened the original saddle more than 50 or 60 feet although in a few (for example, the notch crossing the Indian Dan-Swamp Creek divide east of Bald Knob) the floor of the notch has been cut more than 200 feet below the surface of the original divide. Large notches of this character are transitional into the "coulees" which are characteristic of the district. Some of the coulees are miles in length and have been eroded to depths of several hundred feet, necessitating the removal of vast quantities of rock.

ALTA COULEE

Alta Coulee,[15] which pursues a course parallel with the Columbia, across a divide that separates the Methow River from Antwine Creek, is typical of these large coulees. It is a narrow slot, five miles in length, varying from a little over 100 yards to half a mile in width and walled throughout almost its entire length by precipitous, unscalable sides. Its head opens upon the Methow Valley in an immense gravel fill, locally called Poverty Flat, which chokes the lower part of the Methow River and the adjacent part of the Columbia Valley, forming one of the largest undissected units of the so-called "Great Terrace" of the Columbia (figures 13 and 15). From the debouchure of the coulee in Antwine Creek a deep channel, cut through the terraces that fill this part of Antwine Valley,

[14] J. L. Rich: Marginal glacial drainage features in the Finger Lake Region. Jour. Geol., vol. 16, 1908, pp. 527-548.

[15] In Russell's and in Dawson's reports Alta Coulee is called Antwine Coulee, but local usage and the U. S. Forest Service restrict the name Antwine Coulee to another coulee to the south which connects the lower part of the Washington-Antwine Creek drainage system with the Columbia River valley at a point a few miles north of the mouth of Chelan River (see map, figure 1). In some of the early reports Antwine Creek is called Peters Creek, but this name does not appear upon modern maps, and is not used by the inhabitants of the district.

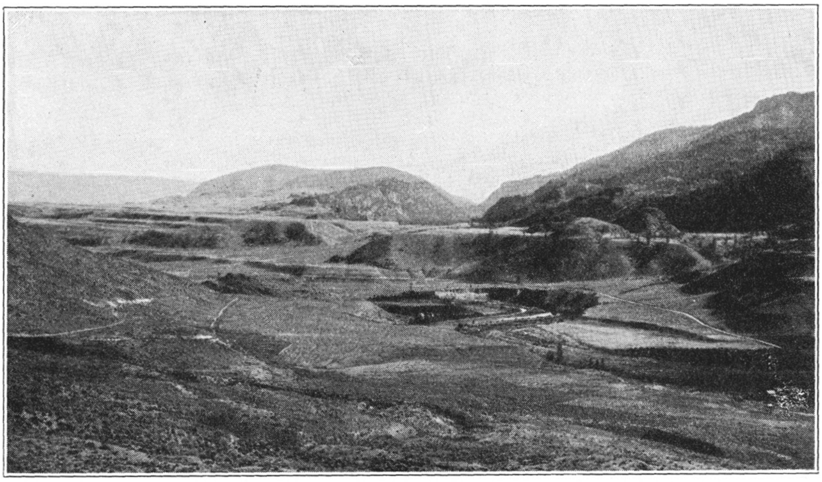

FIGURE 13.—*Head of Alta Coulee*

Looking south, Methow River in the foreground. The large, flat-topped terrace across the Methow is the Poverty Flat expansion of the "Great Terrace" of the Columbia (see map, figure 1).

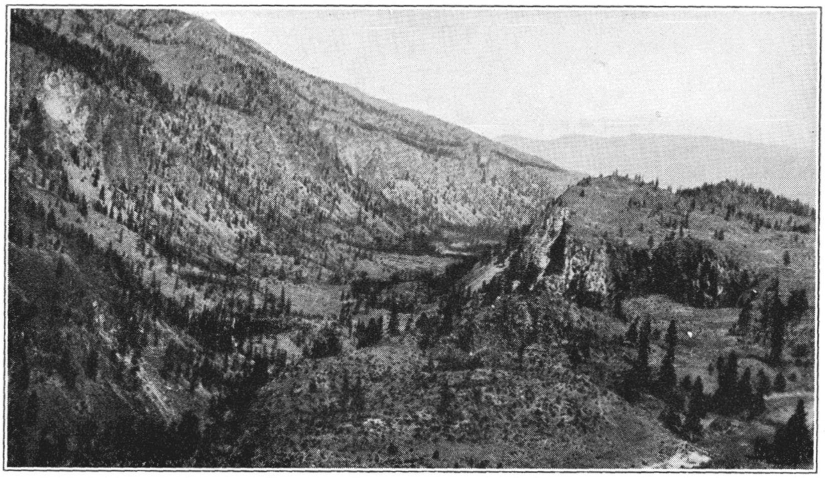

FIGURE 14.—*Northern End of Alta Coulee*

Note how the coulee is cut across the sloping surface of Goat Mountain. View looking north.

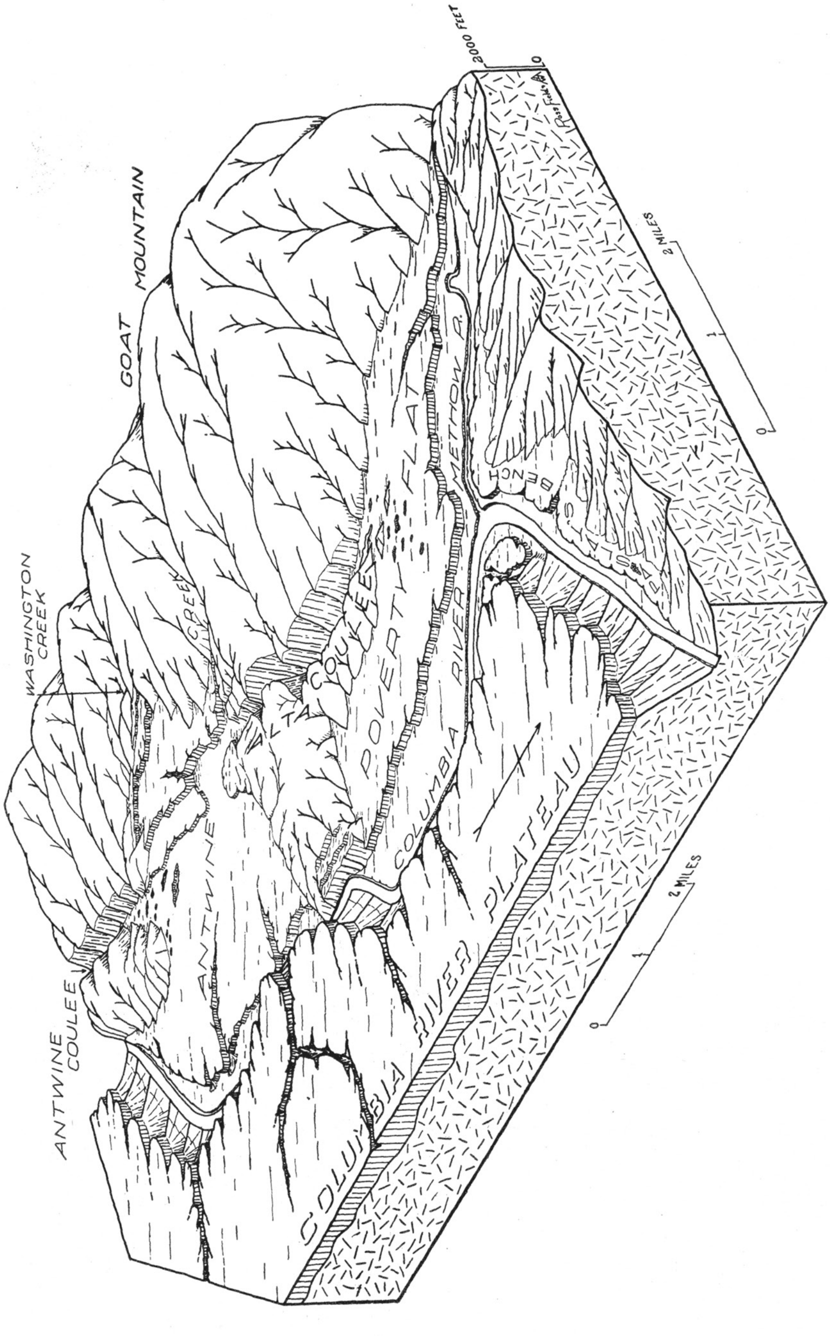

FIGURE 15.—*Block diagram of Alta Coulee*

leads away in a southeasterly direction until it disappears upon the surface of a lower terrace near the head of Antwine Coulee.

Alta Coulee may be divided into three sections. Near its head in the Alta Lake region it is cut straight across the smooth, uniform eastern slope of Goat Mountain. In this part of its course the coulee has an anomalous position, as it is built on the side of the mountain and extends at right angles to the drainage that courses down the mountain slope (figures 14, 15, and 10). A number of gullies on the mountain side have been beheaded by the coulee, and drainage from the mountain slopes west of the coulee now finds its way down to the coulee floor by high waterfalls, at the bases of which alluvial fans have been built. These extend completely across the coulee, segmenting it into a series of undrained depressions, one of which is occupied by Alta Lake. The coulee slot is deep and narrow.

Immediately south of this portion lies the deepest and most precipitous part of the coulee. Prior to the cutting of the coulee, a long spur extended southeastward from the southern end of Goat Mountain and terminated on the banks of the Columbia, north of Azwell. About two and one-half miles south of Alta Lake this spur was crossed by a saddle which, however, was not much lower than the broad top of the spur. Several drainage lines headed at or near the saddle. The most important one was a southward flowing tributary of Antwine Creek. Its site is now occupied by the southern end of Alta Coulee. A second gulley drained westward into Spray Canyon, and a third, which subdivided into two short forks in this vicinity, led the drainage from the southern end of Goat Mountain northeastward into the Columbia, along the north side of the spur terminating near Azwell. Across this saddle the glacial flood poured, beheading the northeastward flowing stream, appropriating and deepening the tributary of Antwine Creek, and probably spilling over for a short time into the tributary of Spray Canyon. Rapid downcutting of the Antwine tributary caused the abandonment of the Spray Canyon spillway before extensive excavation resulted. At the point where the saddle formerly existed, Alta Coulee forms a low col, whose cliffed walls, over 500 feet high, give a measure of the amount of lowering of the former divide (figure 15). Little drainage enters the coulee from the adjacent mountains along this part of its course, and as a result its walls and floor have remained essentially unmodified since the withdrawal of the ice. Although throughout most of its course Alta Coulee trends approximately north-south, in this central portion it follows a rather tortuous path due to the fact that it appropriated the crooked and irregular drainage courses that headed at the saddle.

The southern part of the coulee is merely the overdeepened former tributary of Antwine Creek. Many details of the modification of this tributary by the glacial water that carved the coulee are shown in Figure 16.

Dawson [16] believed Alta Coulee, as well as Knapp Coulee, Antwine Coulee, and the majority of the small ridge notches previously described, to be narrow slots cut by lateral ice tongues from the main Okanogan and Chelan glaciers. In the case of Alta Coulee, called Antwine Coulee in his report, Dawson cites the fact that the coulee floor "is so obstructed by local and foreign boulders that its passage is with difficulty effected with a horse" as evidence of glacial excavation of the coulee. As will be shown in a subsequent section, these deposits are readily explained without the necessity of the coulee being occupied by ice. Russell [17] offered valid evidence for rejecting Dawson's interpretation, and proposed the idea that the coulee is a landslide rent.[18] Smith and Calkins [19] appear to have been the first to ascribe the coulees' excavation to a marginal glacial stream. Their view is adopted in this paper.

That the coulee has not been cut by a tongue of ice is indicated by the following observations:

1. As previously mentioned the northern end of Alta Coulee cuts directly across the eastern slope of Goat Mountain, the trend of the coulee being parallel with the strike of the slope (figures 10 and 14). It seems quite impossible that an ice stream could intrench itself in this position on a steep mountain side.

2. Although the slopes of Goat Mountain above the brink of Alta Coulee show abundant evidence of glacial abrasion, the walls of the coulee are lined with jagged, irregular joint blocks of hornfels and granodiorite, and show no evidence of glacial smoothing.

3. A narrow spur, extending out from the west, causes an abrupt divergence of the coulee around this obstruction at a point about midway in its course. An ice tongue occupying the coulee could not have rounded these sharp corners without leaving marked evidence of cutting at the bends, if, indeed, it could have flowed through such a tortuous passage at all.

4. A short distance from the debouchure of the coulee in Antwine Creek a sharp pinnacle of rock rises abruptly more than 100 feet above the coulee

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[16] W. L. Dawson: Op. cit., pp. 203-217.

[17] I. C. Russell: The Great Terrace of the Columbia and other topographic features in the neighborhood of Lake Chelan, Washington. Am. Geologist, vol. 22, 1898, pp. 362-369.

[18] I. C. Russell: A preliminary paper on the geology of the Cascade Mountains in northern Washington. U. S. Geol. Survey, Ann. Rept. 20, pt. 2, 1898-1899, pp. 201, 202.

[19] G. O. Smith and F. C. Calkins: A geological reconnaissance across the Cascade Range near the Forty-ninth Parallel. U. S. Geol. Survey Bull. 235, 1904, p. 93.

floor (figure 16). This pinnacle has been left in the middle of the coulee by retreat of twin waterfalls. No explanation of this feature is available if we assume that the coulee is an ice-carved chasm; if the pinnacle had existed prior to occupation by ice, the ice tongue would have plucked an obstruction of this character from its path.

5. The Washington-Antwine Creek drainage system into which Alta Coulee debouches is choked by many flat-topped terraces (figure 17). The last drainage through the coulee has cut a deep gash through some of these

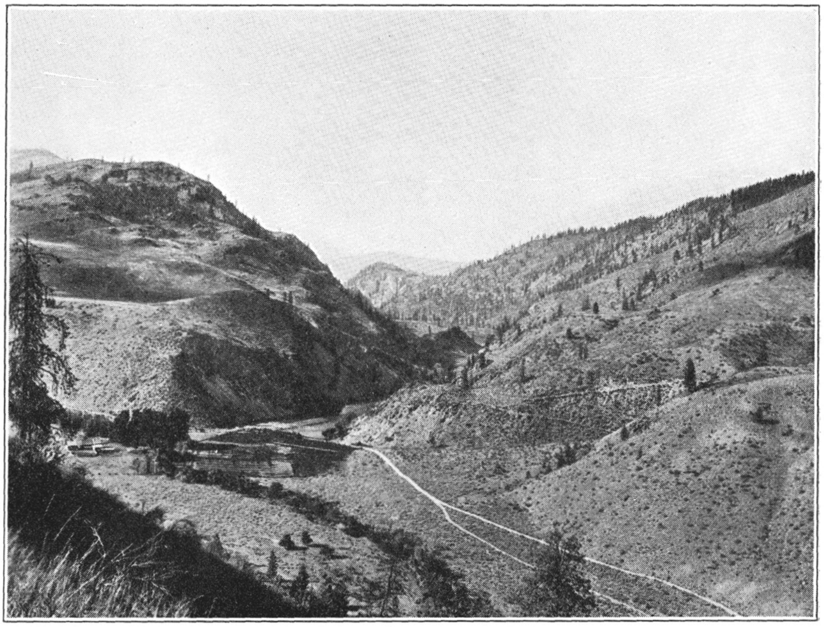

FIGURE 16.—*Mouth of Alta Coulee*

Looking north from the surface of a terrace in Antwine Creek. The rock pinnacle that caused the ice jam is clearly visible at the bend in the coulee walls. Note the steep scars formed through widening of the walls of the former tributary of Antwine Creek by the glacial melt water.

terraces. This gash follows the former course of Antwine Creek, nearly at right angles to Alta Coulee. If an ice tongue emerged in this terrace-filled valley, it would expand into a bulblike mass and thrust back the loose, unconsolidated terrace fillings instead of turning at right angles and cutting through them in a narrow, straight channel.

Smith and Calkins [20] cite good evidence for rejecting Russell's hypothesis

[20] G. O. Smith and F. C. Calkins: Op. cit., p. 93.

that Alta Coulee is a landslide fissure. In addition to their evidence, it may be mentioned that although the floor of Alta Coulee is covered with débris, and consequently the presence or absence of the supposed fissure cannot be proven, there occur in this region many ridge notches and coulees, attributed by Russell to the same origin, which have bare rock floors upon which no trace of the supposed rent can be seen. The landslide origin [21] of the notches at the northeast end of Chelan Butte has been definitely disproved by a tunnel bored beneath them.

Glacial meltwater appears to be the only agent that could have accomplished the excavation of Alta Coulee. As can be seen by reference to the map (figure 1), the northern end of the coulee lies opposite a sharp bend in the Columbia River. This would cause the ice tongue advancing down the river to pile up against the northern end of Goat Mountain, and the thrust of the ice would quickly close any subglacial or englacial tubes that opened up in the main ice mass. The development of a vigorous marginal stream along the site of Alta Coulee would, therefore, be favored. Undoubtedly, a large quantity of water was available for the work, for practically the entire drainage from the melting ice sheet west of Grand Coulee would have been concentrated along the western margin of the Okanogan lobe, thus being available for the cutting of the coulee. In addition, all the meltwater from the Methow glacier and other valley glaciers in this portion of the Cascades crossed the divide on which Alta Coulee is located. At the beginning of the cutting the glacial torrent, highly charged with cutting tools from the melting ice, cascaded on a gradient of approximately 300 feet per mile. A large part of the total length of time of the Wisconsin advance may have been utilized. The ice never passed over the summit of Goat Mountain, and therefore the marginal streams may have been in operation across the face of the mountain throughout the entire time of ice occupancy. It is also possible that a part of the coulee cutting was done by meltwater from older ice advances, but no visible evidence of this was found.

ANTWINE COULEE

Antwine Coulee is similar to Alta Coulee. A narrow, cliff-walled slot, locally 400 feet in depth, it forms a striking defile across a lofty spur separating Washington-Antwine Creek from the Columbia River valley in the vicinity of the mouth of the Chelan River (figure 17). Both its head in Antwine Creek and its mouth on the Columbia lie on the surface of por-

[21] I. C. Russell: A geological reconnaissance in central Washington. U. S. Geol. Survey Bull. 108, 1893, p. 80.

tions of the "Great Terrace," but at the Antwine Creek end the entrance of the coulee is choked by a sheet of kettle-pocked stratified drift that rises about 150 feet above the level of the "Great Terrace."

INVASION OF THE LAKE CHELAN BASIN BY THE OKANOGAN LOBE

That a tongue from the Okanogan lobe entered and extended up the lower end of the Chelan drainage basin seems to have been first noted by

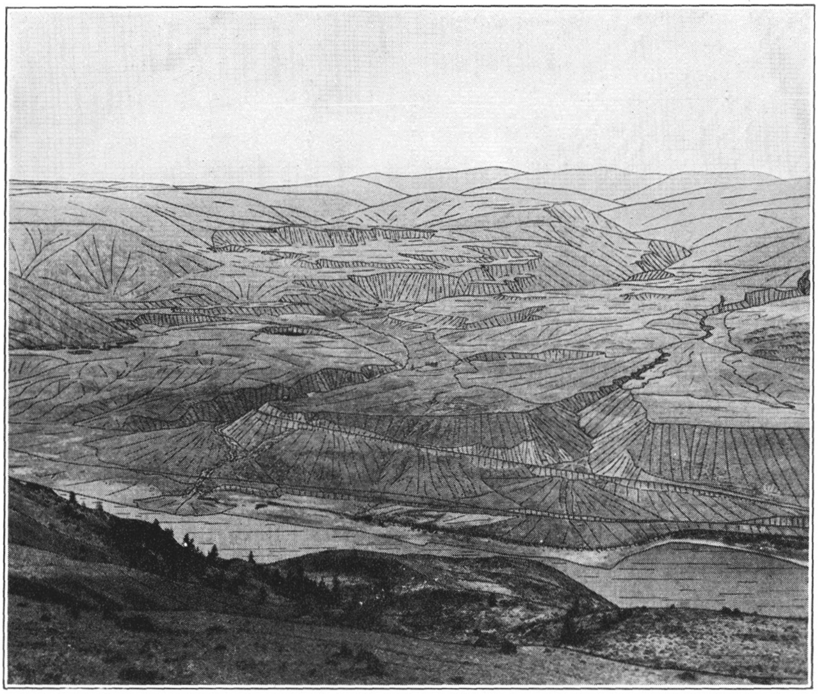

FIGURE 17.—*Retouched Photograph of Terraces blocking the Washington-Antwine Drainage System*

Washington Creek at left, Antwine at right, Columbia River in foreground. The ridge in the background rises 4500 feet above the surface of the river. Note the kettles on the surface of the lowest terrace at the left.

Dawson [22] who notes the occurrence of an erratic boulder of basalt, weighing many tons, on the north shore of the lake. Similar relations were noted by Runner.[23] "Haystack Rocks" of this nature, whose source cannot pos-

[22] W. L. Dawson: Op. cit., p. 214.

[23] J. J. Runner: Origin and history of Lake Chelan. Bull. Geol. Soc. Am., vol. 32, 1921, pp. 87, 88.

sibly lie in the Chelan Basin drainage territory but must be in the basaltic plateau to the north and east, were found by the writer at a number of places. Perhaps the most significant occurrence is a large, well-jointed block of basalt perched on the summit of a lateral moraine, at an elevation of 1795 feet, immediately south of the town of Lakeside. This moraine can be traced continuously along the northern side of Chelan Butte. It contains many basaltic blocks, showing that the moraine was built by ice that advanced from the Columbia Valley up Lake Chelan and not by a glacier moving down the lake.

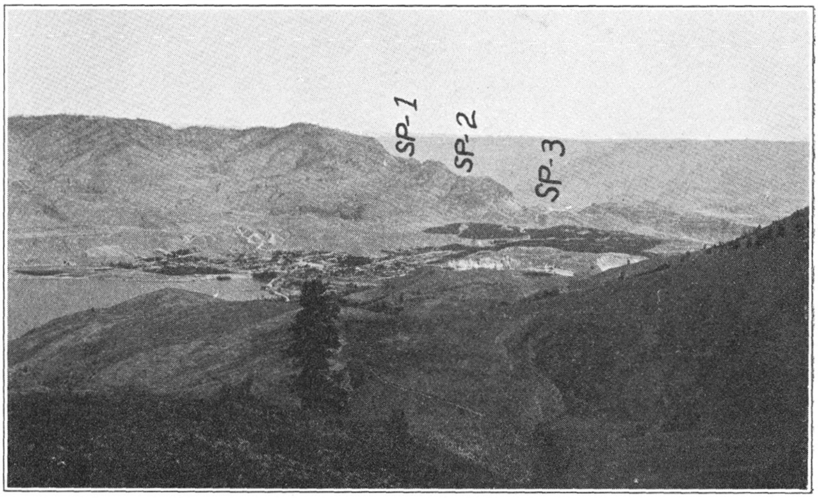

FIGURE 18.—*Ridge separating the lower Chelan Basin from the upper Columbia Valley*
Three ridge notches (SP-1, SP-2, SP-3) by which marginal glacial drainage entered the lake basin from the Columbia valley are shown.

Additional evidence of the invasion of Chelan Valley by the Okanogan lobe is furnished by the fact that the end of the spur forming the southeastern termination of the Methow Mountains, which separate Lake Chelan from the Columbia River above the mouth of the lake, is sharply transected by three deep notches (figure 18) that are in all ways similar to the ridge spillways previously described. They served to lead marginal drainage into the Chelan Basin from the ice mass occupying the Columbia Valley. Similar ridge notches transect the divides between the short canyons on the north side of lower Lake Chelan, and show by their relation to associated terraces that they were cut by water that flowed up the lake. Some terraces on the north shore of the lake decline in elevation when traced up the lake, and cuts in the terraces commonly reveal long delta foresets dipping up the lake. Part of the fill in the old, abandoned channel [24] of the Chelan River is composed of stratified drift which shows lakeward dipping delta foresets.

How far up the lake the Okanogan ice advanced was not ascertained because the writer's work was confined to the region near the outlet of the lake and no opportunity was presented to make a detailed examination of the shores beyond the entrance of Knapp Coulee. It is unlikely that the ice from the Columbia extended farther than the shallow portion of the lake that terminates at Wapato Point. Beyond this point the floor of the lake drops abruptly into the narrow trough scoured by the glacier that came down the Chelan Valley. The bottom of this trough is locally below sea-level. A study of the region in the vicinity of Wapato Point would probably reveal whether the tongue from the Okanogan lobe coalesced with the Chelan glacier. A vast quantity of meltwater was discharged by these two glaciers into the lower part of the Chelan Basin and was carried from there into the Columbia by means of the two spillways described below.

KNAPP AND NAVARRE COULEES

Transecting the high divide that separates Lake Chelan from the Columbia River west of Chelan Butte are two narrow coulees that served as spillways to carry the ponded water of the Chelan Basin into the Columbia Valley. Of the two, Knapp Coulee is the smaller and more winding. Navarre Coulee, locally called Wells Coulee, which lies farther to the west (figure 1), has a broad, flat-floored valley, locally a mile wide. Its head, near the south shore of Lake Chelan, ends in a great amphitheater which was formerly the site of a high waterfall.

Knapp and Navarre coulees are similar to Alta Coulee in that they transect a high divide along the site of a previous saddle. However, the walls of Knapp and of Navarre, though steep and abrupt, rarely tower in great precipices like the walls of Alta. In each coulee the coulee walls near the site of the former divide commonly slope at angles of 20° to 50°. The floors of the coulees are heavily choked with alluvial fans that have been washed down from the side canyons. All these features indicate that Knapp and Navarre coulees are of pre-Wisconsin age, and this hypothesis is confirmed by the fact that a small tongue of Wisconsin ice entered the upper end of Navarre Coulee for a distance of at least a third of a mile. It seems probable that Knapp and Navarre coulees were cut in the same

[24] W. L. Dawson: Op. cit., p. 216.

manner as Alta and Antwine but by glacial water from an ice sheet, or ice sheets, older than the Wisconsin.[25]

In the district to the north and west of Wapato Lake, numerous ridge notches are found which have gently sloping sides and flat floors mantled with Wisconsin drift. They are probably analogous to Knapp and Navarre coulees in origin and in age. Although the coulees served as spillways for Wisconsin meltwater, this discharge has modified them only slightly. Some of the spurs on the side of Knapp coulee have been cliffed to a height of about 30 feet by the Wisconsin flood.

Continued melting lowered the surface of the Wisconsin ice in Chelan Basin until Knapp and Navarre spillways were eventually abandoned and meltwater escaped into the Columbia along the margin of the ice tongue that still occupied the river valley east of Chelan Butte. In rounding the northern and eastern corner of Chelan Butte, the marginal stream cut a plexus of channels with precipitous walls. One of these channels is followed by Chelan River for a short distance, the river then tumbling over its side into the Columbia Valley. Another wide channel forms a striking terrace-like shelf across the eastern end of Chelan Butte, about 600 feet above the level of the Columbia, and there are several narrow notches on the northeastern corner of the Butte.

THE "GREAT TERRACE" OF THE COLUMBIA

Although the majority of the terraces that hang from the walls of the Columbia Canyon are confined within the short tributary valleys, there occurs, throughout the region between Chelan Butte and the mouth of the Okanogan, an almost continuous sheet of terrace-fill covering a wide area. This fill, which at most places lies between 550 and 650 feet above the river, has notable expansions in certain parts of the Columbia Valley, particularly at the mouths of the larger tributary rivers. Discontinuous fragments of a terrace are also widespread in the Columbia Valley below Chelan Butte but do not occupy such broad areas as in the region between the butte and the Okanogan River. To the broad, flat-topped remnants of the terrace above Chelan Butte, Russell [26] gave the name, "Great Terrace of the Columbia," and he assumed that the terrace repre-

[25] Willis (U. S. Geol. Survey Prof. Pap. 19, 1903, pp. 56-58) and Dawson (Am. Geologist, vol. 22, 1898, p. 211) have proposed two other suggestions as to the origin of Knapp and Navarre coulees. Willis has recently revisited the area and now agrees with the writer's interpretation. Dawson's hypothesis has been effectively disproved by Russell (Am. Geologist, vol. 22, 1898, pp. 368, 369).

[26] I. C. Russell: A geological reconnaissance in central Washington. U. S. Geol. Survey Bull. 108, 1893.

sented a great delta fill, deposited in an enormous lake, called Lake Lewis, which is supposed to have filled the Columbia Valley in eastern Washington immediately after the recession of the ice. The front of the delta was believed to be a short distance downstream from Chelan Butte. Dawson,[27] on the other hand, believed the terrace to be a stream terrace with a definitely graded upper surface which decreased in elevation when traced downstream.

Much additional testimony can be marshaled in support of each of these hypotheses, but the writer holds, with Russell, that most of the fill above Chelan Butte is lacustrine. Thus, as Russell states, delta structure is well exposed in the terrace south of Chelan Butte, where it has been trenched by recent stream gullies. Long delta foresets are also well shown in road-cuts in the terrace south of Azwell, on the road between Chelan Station and Chelan, on Brewster Flat, and on the road to Indian Dan Canyon, as well as at numerous other places. In addition, fine sands and silts, showing the remarkable lamination characteristic of lacustrine deposits, are seen in the "Great Terrace" near the mouth of Antwine Creek, along road-cuts in the margin of Paslays Bench, and in gullies that trench the slopes of the terrace on the east side of the Columbia River opposite Pateros.

At several localities, however, and notably near the top of the terrace at the northern end of Poverty Flat, cuts reveal the short, irregularly dipping crossbeds and the cut-and-fill structure characteristic of fluviatile deposits. These deposits, though sometimes found at low elevations, appear most commonly in the upper parts of the terrace fill. At still other points, usually near the junction of the terrace with the valley wall, excavations reveal a puzzling assemblage of glacial till, lacustrine silts and sands, and stream-bedded gravels Although the field observations of both Russell and Dawson are absolutely correct, the accumulation of much additional data, not available to these early observers at the time when their work was done, indicate that the simple hypothesis of a lake-built delta or of a continuous graded stream terrace will not explain all the complexities of these deposits. Nor is it necessary to invoke the presence of a hypothetical Lake Lewis in the lower Columbia Valley.

Much of the controversy between Russell and Dawson centered about the figures for the height of the "Great Terrace" above the Columbia. Russell believed the terrace to lie about 550 to 600 feet above the river. Dawson states that its surface is only approximately 300 feet above river-level. The writer has determined the elevations at many points on

[27] W. L. Dawson: Op. cit.

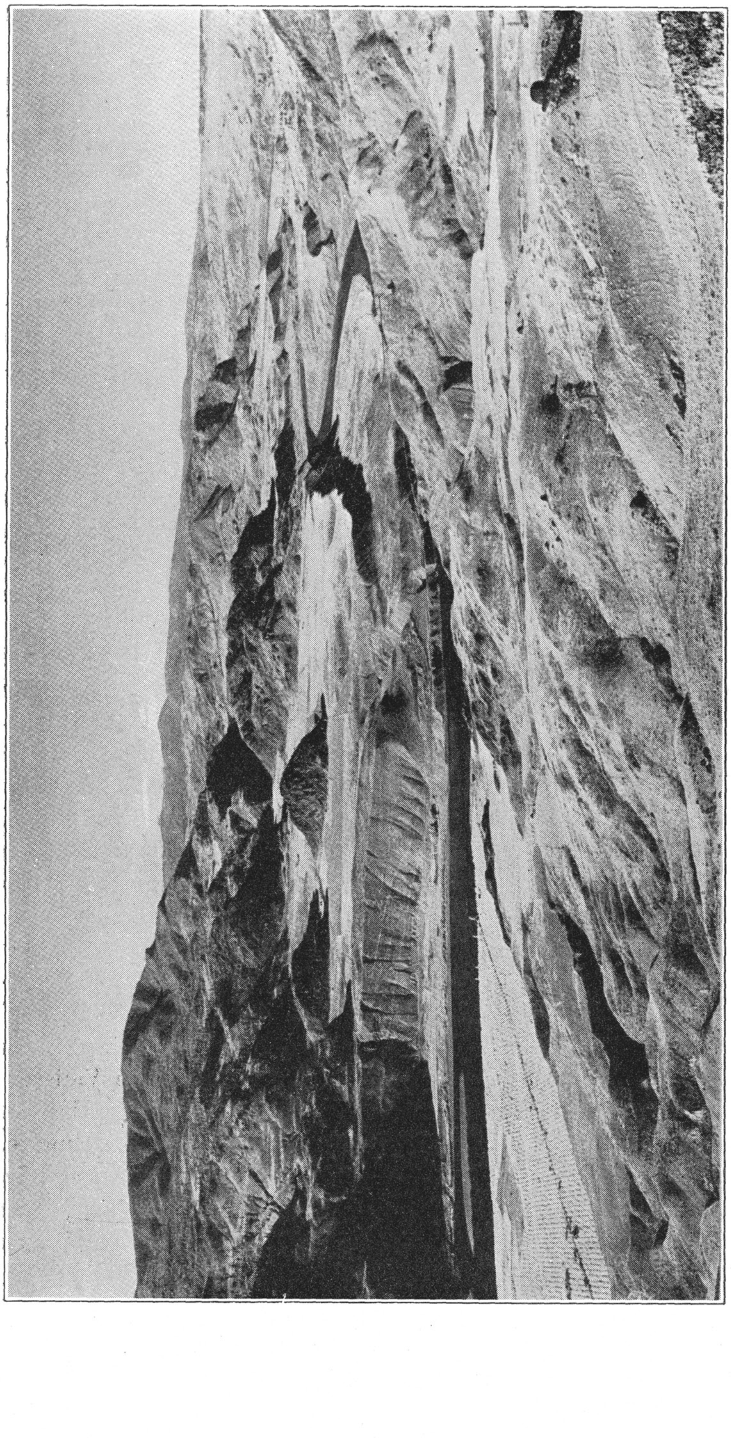

FIGURE 19.—*Expansion of the Great Terrace*

Looking north across the Columbia River, two miles north of the mouth of the Chelan River. Note the black, pyramidal-shaped rock island rising out of the terrace. The steep-walled, shadow-filled gap across the ridge immediately behind this island is Antwine Coulee. Photograph by Eliot Blackwelder.

the "Great Terrace" between the mouth of the Okanogan and Chelan Butte. Although the writer's measurements agree, in a general way, with those given by Russell, there is considerable difference in elevation at different points, and these differences vary in no systematic manner. Therefore, the deposit is not a single terrace but a series of terraces closely linked together in elevation and origin. The elevation of the terrace top, in feet above mean sea-level, is indicated for several different localities on the map (figure 1). In this part of its course the surface of the Columbia is about 675 feet above tide.

A discussion of the elevation of this terrace-fill can best be entered upon by treating separately the notable enlargements that the terrace shows in various parts of the Columbia Canyon. At the mouth of the Okanogan a great expansion of the terrace forms Brewster Flat (figure 10). The surface of Brewster Flat is lightly engraved by old channels and pitted by kettles, but between the lower troughs the surface of the terrace has a fairly uniform elevation varying between 1230 and 1260 feet. Below Brewster the Columbia enters a narrow gorge and is bordered by granodiorite bluffs against which no terraces cling. The next terrace remnant is a small one which blocks the mouth of Indian Dan Canyon, its surface lying 1295 feet above tide, considerably higher than the surface of Brewster Flat. Continuing downstream, the terrace disappears against the narrowed walls of the valley only to form a large expansion at the mouth of the Methow in Poverty Flat, Paslays Bench, and an analogous, unnamed flat on the east side of the river (figure 10). The elevation of this part of the terrace, neglecting the numerous kettles that dot its surface and the alluvial fans that have been built upon it, is approximately 1245 feet. One can walk for miles on this extensive flat (figures 13 and 15) and not change elevation more than 10 feet.

Farther downstream the terrace is lost in a rock-walled gorge near Azwell only to expand again in the mouth of the Washington-Antwine drainage system. At this point the terrace top has an elevation of 1210 feet. This remnant is separated from another expansion (figure 19) with an elevation of approximately 1260 feet, by the spur across which Antwine Coulee is cut. Still farther downstream a large terrace remnant blocks the mouth of Gillespie Canyon and extends southwestward to form the prominent bench (figures 20 and 4) on the south bank of the Columbia opposite Chelan Butte. Towards the west it subdivides into two terraces having elevations of 1265 and 1150 feet respectively.

Dawson and Russell assumed that the "Great Terrace" ends at this point, but there are remnants of terraces that block the mouth of the

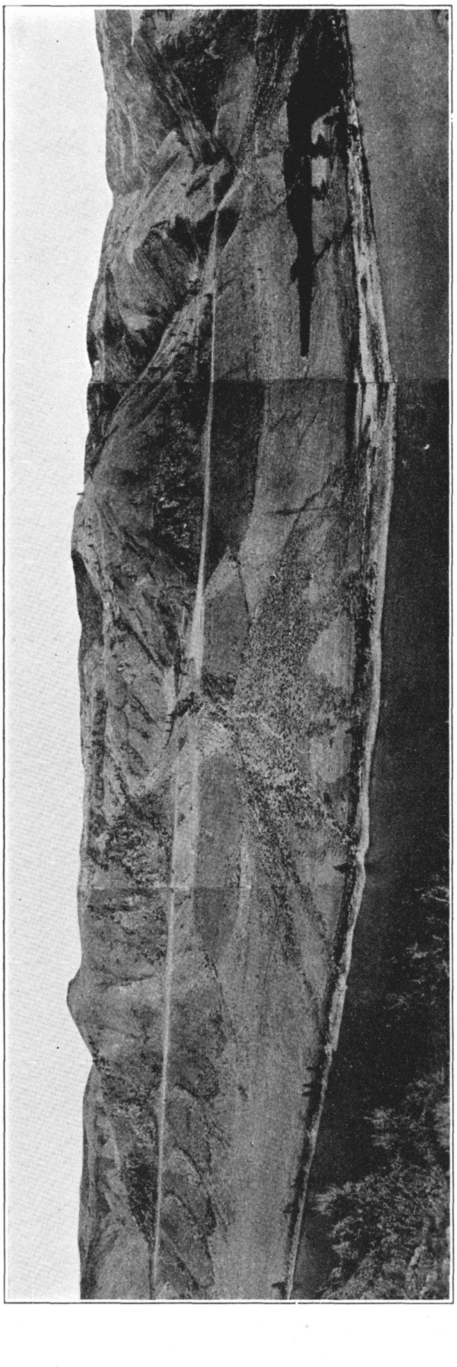

FIGURE 20.—*Terraces on the South Wall of the Columbia Canyon opposite Chelan Butte*

The higher terrace rises over 650 feet above the level of the river.

tributary canyons for miles downstream, and a large expansion occurs in Brays Flat on the east side of the Columbia opposite Navarre Coulee. In contrast to the terrace remnants upstream from Chelan Butte, cut-and-fill structure is much more common than lacustrine bedding, and the top of the terrace lies at a lower elevation than the dominantly lacustrine terraces upstream. It also declines in a regular manner when traced down the river, suggesting that the terrace is stream built. Starting at an elevation of 1020 feet at the north end of Brays Flat opposite the mouth of Knapp Coulee, the terrace gradually declines to 925 feet at the mouth of Swakane Canyon, and the extensive flats blocking the mouth of Moses Coulee at an elevation of 850-900 feet, shown on the Malaga topographic map, may possibly represent its continuation downstream.

According to the writer's interpretation, the terrace remnants south of Chelan Butte are stream-built and represent the valley train of the Wisconsin glacier. The terraces upstream from Chelan Butte, though locally stream-built, are mainly lacustrine and were deposited in lakes dammed by melting ice and morainal débris held in the constricted portions of the valley. These lakes did not form a continuous sheet of water throughout the Columbia Valley, and consequently the top of the "Great Terrace" does not have the same level in all its expansions. However, the actual surface of the terrace in the region above Chelan Butte owes much of its general accordance in elevation and many of its unique surface features to a great flood of water, that poured through the valley near the end of the period of ice occupancy as a result of the breaking of the Okanogan ice barrier across the Columbia Valley and the sudden resumption of its former channel by the Columbia River which, during the time of the ice invasion, had been forced to flow through Grand Coulee.[28]

Kettles on the "Great Terrace"

One of the most characteristic things about the "Great Terrace" is its kettle-dotted surface (figure 21). Over areas several square miles in extent the surface of the terrace is in places an intricate maze of depressions. Most of the kettles range from 50 to 200 feet in length. They are not distributed evenly over the surface of the terrace but are concentrated in certain localities and entirely absent in others. The areas of concentration are invariably on the outside of sharp bends in the Columbia River, or immediately against the upstream side of spurs that project out into the Columbia Valley. Thus, on the outside of the bend

[28] J. Harlen Bretz: The Grand Coulee. Am. Geogr. Soc., Spec. Publ. no. 15, 1932.

that the Columbia makes at Pateros, the northern end of Poverty Flat is pitted by closely spaced kettles some of which are large enough to be shown by the 100-foot contour interval of the topographic map (figure 10). Remnants of this flat on the east side of the Columbia are entirely free of kettles, however, and kettles are not numerous on Paslays Bench. Another place where kettles are concentrated in great numbers is on the upstream side of the spur that is transected by Antwine Coulee. The edge of the terrace expansion immediately north of this spur is a maze of depressions (figure 17), and even the entrance of Antwine Coulee is blocked by a sheet of kettle-pitted stratified drift that rises above the

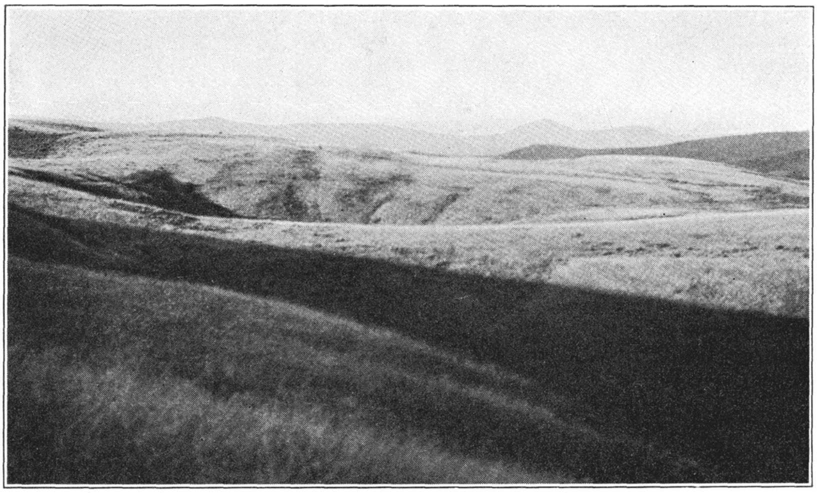

FIGURE 21.—*Kettles on the Surface of the "Great Terrace"*

level of the terrace. On the surface of the terrace expansion, just north of the mouth of the Chelan River, numerous kettles are found on the upstream side of a pyramidal islandlike mass of rock (figure 19) that projects through the surface of the terrace.[29]

That the kettles have been produced by the melting of ice blocks partially buried in the débris that forms the upper surface of the terrace is shown by the common occurrence of a rim of glacial boulders around the margin of the kettle, which have sloughed off the edge of the ice upon the terrace surface as melting progressed. Nests of boulders are also found on the floor of the kettles.

[29] For a different explanation of these pits see I. C. Russell: U. S. Geol. Survey, Ann. Rept. 20, 1898, 1899, p. 179.

The origin and distribution of the kettles is admittedly difficult to explain, but their concentration on the outside of bends and behind spurs and projections in the valley appears to indicate that they have been formed by the melting of river-rafted icebergs, lodged against obstructions by a greatly swollen Columbia. Had the kettles been formed by stagnant blocks of ice left in situ by the wasting away of the ice sheet, there is no apparent reason why they should be concentrated on the outside of the bends or behind projecting spurs. In addition, kettles formed by ice in situ would, as a rule, show much variation in size. In the Okanogan Highlands of northern Washington there are many examples of kettles formed by stagnant masses of ice melting in place. These kettles range from small pits up to great depressions several miles in extent. (See, for example, the large depressions in Wagonroad and Toats coulees, shown on the Chopaka topographic map.)

Many of the kettles on the "Great Terrace" are of such great size that it would require a raging flood of water over 100 feet deep to carry the bergs that formed them. The stage was well set for the occurrence of a great flood near the end of the glacial epoch. As the Okanogan lobe advanced, it shoved the Columbia completely out of its course, filling the 2000-foot canyon with a dam of ice in the region between the head of Grand Coulee and Chelan Falls. The Columbia discharge was diverted into Grand Coulee and aided in widening and deepening that chasm. The head of Grand Coulee is over 500 feet above the level of the Columbia River, and as the ice wasted away in the portion of the canyon above the coulee, a large lake must have been impounded behind the ice dam. As the Okanogan lobe slowly melted, this dam holding the lake became more and more unstable until eventually it collapsed, giving rise to a spectacular flood. The impounded water, charged with large blocks of ice from the broken dam, rushed through the Columbia Valley, jamming the bergs in great numbers behind every spur and projection, just as logs are jammed behind obstructions by flood water in a brook. As the flood subsided, it laid down vast quantities of silt and gravel that now form the upper surface of the "Great Terrace." The ice jams were left half buried in this recently deposited débris and upon melting left the characteristic kettles.[30]

[30] The flood here suggested as responsible for the surface features of the Great Terrace is not the same as the Spokane Flood which, according to Bretz, is responsible for the development of the "scablands" and the shaping of numerous coulees on the Columbia Plateau. The Spokane Flood was vastly greater in volume, and it originated from an older ice sheet.

Icejam in Alta Coulee

Perhaps the most spectacular record of the flood is visible in the central part of Alta Coulee. If one starts at the mouth of the coulee in Antwine Creek and proceeds toward its head, he passes for a short distance over a flat floor (figure 16) which has a gentle slope toward the center of the coulee. This is an arm of an alluvial fan built by Antwine Creek since the period of ice occupancy. In less than a mile the fan ends, and a sharp rock pinnacle rises abruptly in the center of the coulee floor. This pinnacle has been previously described as a small spire left upstanding by the retreat of twin waterfalls.

North of the spire there is a depression, about 100 yards wide, the northern border of which is formed by gravelly, boulder-studded fill, which rises in a steep scarp to a height of 80 feet. For the next two miles the traveller passes through wild and chaotic topography. The entire coulee floor is so thickly studdied with steep-walled, locally coalescing depressions, 50 to 200 feet deep, as to make the coulee almost impassable. Neither words nor photographs (figure 22) convey an adequate picture of this unusual stretch of topography. At the northern end of the coulee the depressions have been masked by alluvial fans formed by run-off from Goat Mountain, but in the central part, where there is little tributary drainage from the sides, they are entirely unmodified. This wild jumble of depressions is interpreted by the writer as the record of a great jam of ice brought into the coulee by the bursting of the Okanogan barrier and piled behind the pinnacle of rock near the mouth of the coulee. Much of the débris that now remains to record the ice jam is rudely stratified sand and gravel, but it is intermixed with vast numbers of large boulders rafted in by the ice blocks, and its surface is thickly studded with blocks of rock that have been subsequently rifted from the cliffs forming the walls of the coulee.

Alta Coulee is situated in a logical place for an ice jam (figure 1). The mouth of the coulee lies opposite the sharp bend of the Columbia at Pateros; consequently, the floating bergs in the flood would have been concentrated on the west bank of the river as it rounded this curve, and would have poured into the open coulee slot.

Summary

At the time of the last glaciation in north-central Washington a broad expanse of ice, known as the Okanogan lobe, crossed the Columbia Canyon, diverted the river from its former course, and rode out upon the flat surface of the northwestern part of the Columbia Plateau. In the spurs of the Cascade Range, west of the river, the same ice mass encroached upon an area of serrate topography, burying peaks and ridges that rise 4000 feet above the adjacent streams. The deposits left by the ice in the two regions contrast strikingly. On the plateau there is a huge moraine, dotted by hundreds of erratic basalt boulders, many of which measure 100 feet on a side. Stratified drift is rare. In the region of rough topography, however, moraines are only occasionally found, but numerous terraces composed of stratified glacial drift are conspicuous elements of the topography. Most of the terrace material shows deltaic structures and appears to have been deposited during the period of deglaciation, in temporary

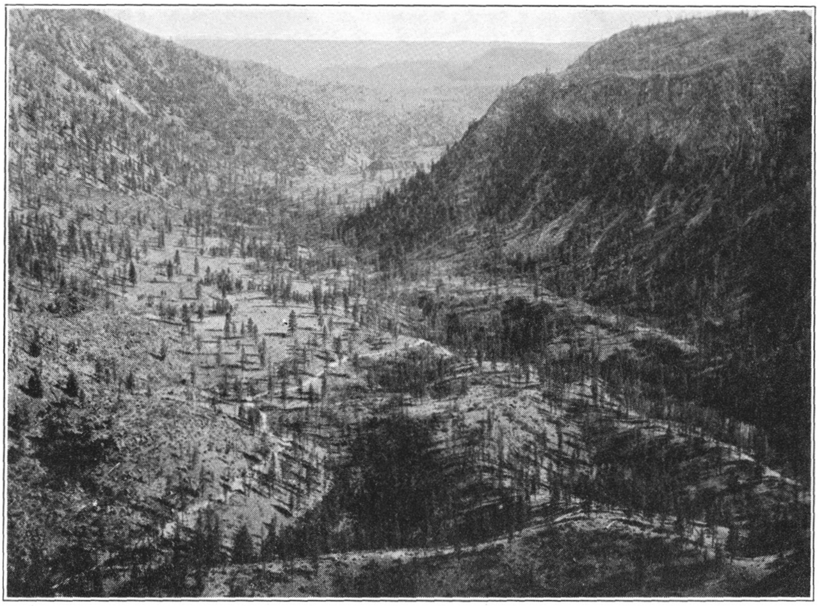

FIGURE 22.—*Alta Coulee*

Looking obliquely downward upon the ice jam in Alta Coulee from the summit of the coulee wall. The top of the rock pinnacle that caused the jam is barely visible just beyond the bend in the coulee. View looking south.

lakes that were dammed by the ice. The lakes in which the terraces formed were drained by streams flowing along the margin of the ice. In places, the marginal streams crossed rock spurs and excavated precipitous-walled spillways, which subsequently were abandoned as a result of continued melting. The majority of the spillway notches are less than 75 feet deep, but in a few cases a prodigious amount of rock excavation was accomplished. The most remarkable is Alta Coulee, a narrow, cliff-walled slot, cut 500 feet into granodiorite by a marginal glacial stream.

With the withdrawal of the Okanogan lobe, the Columbia River resumed its former course. Re-occupation of the old valley took place when the last remnants of the Okanogan ice dam suddenly collapsed. The record of the flood thus released is visible in the surface features of the lowest glacial terrace in the Columbia Canyon.