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PLEISTOCENE GEOLOGY

OF THE

LEADVILLE QUADRANGLE, COLORADO

BY

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CONTENTS.

ILLUSTRATIONS.

PLEISTOCENE GEOLOGY OF THE LEADVILLE QUADRANGLE, COLORADO.

By STEPHEN R. CAPPS, JR.

INTRODUCTION.

The field work on which this report is based was begun by the writer, in company with Mr. E. D. K. Leffingwell, in the summer of 1904. The work was undertaken privately, in connection with studies at the University of Chicago. During the following summer the writer, assisted by Messrs. C. A. Kirtley and J. M. Hill, continued the work, to which some support was given by the United States Geological Survey. The investigation was carried on under the advice and direct supervision of Prof. R. D. Salisbury, to whom acknowledgments are due for many valuable suggestions and criticisms.

This region was chosen for the study of glaciation because it was believed to be a type for the mountains of Colorado. In the reports of the Hayden Survey [a] some of the morainic areas west of Arkansas River were mapped, and in his Leadville monograph Mr. S. F. Emmons [b] mentioned briefly the effects of glaciation in this area. Prof. L. G. Westgate [c] and W. M. Davis [d] also recently published articles on the glaciation in a part of the Lake Creek valley, but aside from these publications very little attention appears to have been given to the Pleistocene geology of this region.

[a] Ann. Rept. U. S. Geog. and Geol. Surv. Terr. for 1873, pp. 51–53; idem for 1874, pp. 48–50.

[b] Mon. U. S. Geol. Survey, vol. 12, 1886, pp. 41–42.

[c] Jour. Geol., vol. 13, 1905, pp. 285–312.

[d] Bull. Mus. Comp. Zool., vol. 49 (Geol. series, vol. 8, No. 1), 1905, pp. 1–11; Appalachia, vol. 10 (No. 4), 1904, pp. 392–404.

PART I.

GENERAL CONSIDERATION OF THE REGION.

TOPOGRAPHY.

The chief topographic features of this region are the two great parallel north-south mountain ranges, the Sawatch on the west and the Park on the east. The peaks of both rise to heights of more than 14,000 feet. In the trough between these ranges lie Arkansas and Eagle rivers, the former flowing south and the latter north from Tennessee Pass. East Fork Arkansas River heads in the Park Range to the northeast, southeast of Fremont Pass, and from this pass Tenmile Creek flows north. East of the crest of the Park Range Blue River drains the area north of the Continental Divide, and the South Platte the remainder of the slope.

GLACIATION.

EVIDENCES OF GLACIATION.

Within this quadrangle, which has an area of 945 square miles, more than 350 square miles show definitely the effects of glaciation, and it is certain that at its maximum extent the ice covered a somewhat larger area. The former domination by glaciers of all the important mountain valleys of the region is indicated by a number of characteristic and unmistakable phenomena: (1) Many valleys have U-shaped cross sections, truncated lateral rock spurs, and more or less cliff-like head and side walls. (2) The bed rock in these valleys is often polished and striated, and many of the lakes occupy rock basins. (3) The valleys usually contain definite lateral and terminal moraines, with characteristic topography and constitution. (4) There are numerous departures from the normal relations of stream-developed valleys, as shown by (1) the topographic unconformities of the tributaries, (2) the incomplete drainage control, both of the upper parts of the valleys and of the moraine deposits, and (3) the freedom of the upper parts of the valleys from the products of weathering.

AREA GLACIATED.

Although little more than two-fifths of the area of this quadrangle shows the effects of glaciation, the ice of the last epoch covered by far the greater part of the surface of the mountains in the higher parts of both great ranges. Here only the narrow crests of the ridges projected above the ice. From this collecting field of snow and ice, which was essentially continuous along the crests of the ranges, the glacial ice moved down the mountains. The ice was deepest and most vigorous in the important mountain valleys, each of which was occupied by a glacier, and ice tongues extended far down the mountain slopes, many of them out onto the piedmont plain below. Some of the glaciers consisted of a single lobe, without lateral feeders; others, more favorably situated, were fed by numerous heads, and it was these many-headed glaciers which reached the greatest size and which most profoundly altered the shape of their valleys. Within this quadrangle there were 26 glaciers, or systems of glaciers, of some importance, besides 11 glaciers of smaller size, making 37 in all (Pl. I). These glaciers were distributed as follows:

Glaciers that formerly occupied the Leadville quadrangle.

	Length in miles.	Area in square miles.	Range of elevation in feet.
In valley of Roche Moutonnée Creek	12	7	13,000 to 9,000
In valley of Rock Creek	7	6	13,000 to 9,500
In valley of Homestake Creek	17	46	13,000 to 8,800
East of Mitchell	2	2	11,000 to 9,500
West of Mitchell	4	5	12,000 to 10,000
West of Crane Park	6	20	13,000 to 10,000
In valley of Lake Fork	10	23	12,500 to 9,700
In valleys northeast of Mount Massive	6	15	13,600 to 9,700
In valley of Half Moon Creek	9	18	13,500 to 9,600
In valley of Lake Creek	20	56	13,300 to 9,100
In valley of Clear Creek	18	12	13,000 to 8,900
Between Half Moon Creek and Evergreen Lakes systems	2	3	12,500 to 10,400
Three small cliff glaciers in Sawatch Range		1½	
In Weston Gulch	4	4	13,100 to 9,900
In Empire Gulch	4	3	13,200 to 10,100
In Iowa Gulch	7	6	13,300 to 9,900
In Evans Gulch	6	6	13,000 to 10,300
In valley of East Fork of the Arkansas	15	20	13,000 to 9,900
In valley of Tenmile Creek	10	12	13,000 to 9,800
In valley of West Fork of Tenmile Creek	6	5	12,000 to 9,700
In valley No. 1, northwest of Breckenridge	2	1	12,000 to 9,700
In valley No. 3, southwest of Breckenridge	3	1	12,000 to 9,700
In valley of Blue River	12	14	13,000 to 9,700
In valley of South Platte River	16	49	13,700 to 9,900
In valley of Fourmile Creek	9	11	13,000 to 9,900
In valley of Twelvemile Creek	7	6	13,000 to 9,800
In valley of South Fork of South Platte River	5	3	12,000 to 10,300
Five small cliff glaciers in Park Range		2½	
Total area glaciated		358	

ELEVATION NECESSARY TO START GLACIATION.

On the east slope of the Sawatch Range the minimum elevation at which glaciers started was about 12,000 feet. A few valleys which headed at elevations of 13,000 feet or more were unglaciated, but in most places an elevation of 12,000 feet was sufficient for the formation of glacial ice, and the heads of the glaciers range from this elevation to 13,600 feet. The west slope of the Sawatch Range is beyond the limits of the Leadville quadrangle and was not studied in detail.

Although the west slope shows the effects of glaciation of the same order of intensity as that on the east slope, the data at hand are so few that it is impossible to make accurate comparisons with the east slope in respect to the area which the ice covered or the elevation which was necessary to start glaciation.

In the higher parts of the Park Range many of the peaks reach elevations of nearly 14,000 feet, and below these peaks on both the east and the west slopes of the range all the larger valleys were occupied by glaciers that headed at elevations of 13,000 feet or more. Those on the east slope, however, were larger and more vigorous and occupied three-fifths of the total glaciated area of this range. On this slope, too, the height necessary to start glaciation was in some places only 12,000 feet, while in most valleys on the west slope a height of considerably more than 12,000 feet was necessary. It is probable that the greater size of the glaciers on the east side of the range was due to the superior size of the preglacial valleys here, rather than to any advantage of exposure or precipitation.

The area and length of any glacier depended on the following factors: (1) The height of the mountain ridges surrounding it, (2) the shape and area of the catchment basins, (3) the number and size of the lateral valleys which contributed ice to it, (4) the slope and shape of the valley floor, (5) the exposure, and (6) the precipitation. In the Sawatch Range the Lake Creek and Homestake glaciers were most favored in these particulars, while in the Park Range the South Platte Glacier had the most advantageous position.

Hayden [a] suggested that there was once a great glacier in the valley of the Arkansas, fed by the tributary valleys from both ranges, but evidence of such a glacier is altogether lacking.

GLACIAL EROSION.

A comparison of the topography of a mountain region which has been subjected to severe glaciation with that of a similar region which has not been glaciated shows readily that valleys which have contained glaciers of any considerable size have developed certain distinct features that are lacking in unglaciated regions.

Cirques.—The most striking of these features are the glacial cirques, illustrated in this quadrangle by the head of almost every valley that reaches back to the higher parts of either great mountain range. Normally these cirques have steep walls at the head and sides of the upper valley and present in cross section a marked **U** shape, in contrast to the **V** shape common to most unglaciated valleys in the high mountains. This **U** shape is the result of the widening and deepening of the valley by glacial erosion, and in many places the cutting back

[a] Ann. Rept. U. S. Geog. and Geol. Surv. Terr. for 1873, p. 48.

of the head walls and dividing ridges has left only a row of serrate peaks between adjoining cirques. The glacial deepening of the valley is perhaps greatest near its head, and this increases the gradient of the stream at its upper end and reduces it below.

The abrasive action of the ice is shown in many places by the smoothing and striations of the valley walls and floors, and it is certain that most of the cirques, as left by the ice, contained very little loose material. As soon as the glaciers retreated, however, these steep, bare cliffs were attacked by the agencies of weathering, and great heaps of postglacial talus now lie at the base of many of the steep slopes. The bottoms of many of the cirques show bare bed rock, and some of the hollows gouged in this rock by the ice contain lakes.

Many of the valleys in this quadrangle, although showing definite evidences of glaciation, have failed to develop the typical steep-walled cirque. This may be due to the feebleness of the glaciers in them, for many of the valleys contained only small glaciers, or to the original shapes of the valleys. Thus the two small glaciers between Lake and Clear creeks failed to excavate their valleys sufficiently to form cirques because their erosive action was necessarily weak. The two heads of Mosquito Gulch and the head of Sacramento Gulch, all of the South Platte system, although they lie in the highest part of the Park Range and contained strong glaciers, were not deeply eroded by the ice and developed no cliffs at their heads. Here, however, the lack of cirque development was due to the broad, flat character of the valley heads; the ice was spread out in a comparatively thin lobe and the glacial deepening was slight.

Erosion of main valleys.—Each of the larger systems of glaciers was formed by the junction of a number of cirques, creating a single large lobe which extended down the main valley. In most of these trunk valleys there is an area, below the head of the cirque and above the morainic deposits, in which the ice has widened and deepened the valley. This widening and deepening commonly results in the development of a U-shaped cross section.

In the normal development of a stream-cut valley and its tributaries the constant tendency of each tributary is to keep its bed cut down to topographic conformity with the main valley. The bed of a glacier is filled to a considerable depth by the ice, and while the floor of the main valley is sustaining glacial erosion the ice in the tributary valley, if the tributary has a glacier, is prevented by the great depth of the ice in the trunk valley from lowering its bottom correspondingly. When the ice retreats the topographic unconformity thus produced is revealed. Some idea of the amount of the glacial deepening of the main valley may be gained by noting the amount of this topographic unconformity. Estimates based on the height of the mouth of a hanging tributary were made for a number of gulches. The estimated deepening at some of these places is less than the maximum deepening in other parts of the same valley. Such estimates are subject to error because (*a*) it is impossible to reconstruct accurately the preglacial profile of the tributary stream; (*b*) it is possible that the preglacial tributary did not join the main stream with topographic conformity; (*c*) the preglacial valley may have been U-shaped and not V-shaped (this would make the estimates too small); (*d*) the calculations are based on field sketches and aneroid measurements, both of which are subject to error. Estimates were made of the following valleys:

Estimates of glacial deepening of trunk valleys at junctions of tributary valleys.

	Feet.
Homestake Valley	400
Lake Creek valley	800
Empire Gulch valley	400
Tenmile Valley	200
South Platte Valley	300

Besides this glacial deepening, the widening of the valley by the erosion of the ice is important, so that in many valleys the material removed by the ice was very great.

Methods of glacial erosion.—In considering the removal by the glaciers of this great mass of material two distinct methods of erosion are worthy of attention—plucking and rasping. These methods vary in importance in different regions, according to the characteristics of the bed rock. In an area where the rock is broken by numerous joints, plucking is by far the more important method. Under the enormous pressure of the ice above, that part of the glacier which rests upon the bed rock closes around any inequality of the rock surface and plucks out blocks from the down-valley side of any irregularity of its bed. In this way many of the projections of rock in a glaciated valley have been smoothed on the stoss side and made angular or subangular on the lee side.

In regions where the bed rock is compact and little jointed the ice accomplishes most of its erosion by rasping. The action of the glacier, shod on its underside with fragments of rock, has been likened to that of a huge flexible file, exactly fitting every projection and depression of its bed. By the constant rasping of the rock by the bottom of the glacier, irregularities of the rock surface are removed, and the tendency is toward the development of a perfectly smooth U-shaped trough.

MORAINES.

In the widening and deepening of the glaciated valleys great quantities of fragmental material were taken up by the ice and later deposited toward the lower ends of the glaciers as moraines. The glacial drift of which these moraines are formed is characteristic in that it is composed of an unassorted mixture of fine and coarse materials. Bowlders many feet in diameter lie embedded in fine clay. Some of the bowlders are rounded, but many are angular or subangular, and some of them bear striæ. The bowlders were derived from a great variety of rocks; in fact, every kind of rock over which a glacier passed is represented in the bowlders of its moraines.

The moraines form conspicuous topographic features in many of the valleys of this quadrangle. Some of the glaciers, such as those in the valleys of Homestake, Tenmile, and Weston creeks, ended in narrow, steep-walled gulches, and in these places the materials dropped by the ice were carried away by streams, perhaps as rapidly as they were deposited. Other glaciers, such as those of the Lake Fork and Lake Creek valleys, advanced beyond the foot of the mountains onto the plain beyond, and here the conditions for the building of moraines were most favorable.

The moraine deposits may be divided into three classes, which have characteristic forms but which grade into one another. These are (1) lateral moraines, (2) terminal moraines, and (3) ground moraines.

(1) Lateral moraines occur as benches of drift lying against the rock valley wall or as great ridges composed wholly of drift, one on either side of the lower end of the glaciated area. Some of these ridges extend for several miles below the base of the mountains, and slope with even, gradually descending crests toward the terminal moraine. In the Clear Creek valley the crests of the lateral moraines are, at their maximum heights, 700 feet above the valley bottom. Toward their lower ends the lateral moraines usually converge and merge into the terminal-moraine deposits.

(2) At the lower end of an area that was occupied by a glacier there is generally a body of drift which has extremely irregular topography. This is the terminal moraine. Its surface is characteristically composed of an irregular succession of hummocks and hollows, many of the hollows being occupied by ponds or lakes. Bowlders, large and small, lie scattered over the surface, which may show no signs of drainage control. Terminal moraines are composed largely of unassorted drift, but some sections show a rude tendency toward stratification, with irregular lenses of sand or gravel. The best examples of terminal moraines in this quadrangle occur at the lower ends of the Crane Park, Lake Fork, and Blue River systems.

(3) In almost every glaciated valley, above the terminal moraine, there is an area in which a considerable amount of drift material occurs in the valley bottom. Wherever this drift is sufficiently thick to conceal the topography of the underlying rock it is mapped as

"heavy drift." Some of this was doubtless deposited by the ice during its retreat, but much of it was deposited beneath the body of the ice as ground moraine. It is at many places impossible to distinguish this ground moraine from the drift deposited as ground moraine by the retreating ice, and no distinction between these has been made on the accompanying map (Pl. I).

STRIÆ.

The results of the rasping of their beds by the glaciers are still to be seen in places, as polished surfaces of rock, striæ, and groovings. These polished surfaces and striæ have commonly been obliterated by postglacial weathering, but occasionally they have been preserved, and those that remain point down valley in the direction of the ice movement.

OLDER DRIFT.

At a number of places in this quadrangle there are areas of scattered bowlders, or bodies of unstratified drift, which are certainly of glacial origin, but which are noticeably different from the deposits of the last glaciers. That they are of glacial origin is evinced by their lack of stratification, by the angular or subangular shape of many of the bowlders, a few of which bear striæ, and by their constitution, which shows that they were not assembled by the agency of water. Bowlders many feet in diameter are intermingled with finer bits of rock and with sands and clays.

Wherever found this older drift lies just outside of the moraines of the last epoch, at many places in direct contact with them. That it is much older than the deposits of the last glaciers is shown by the decayed condition of the bowlders. Many of these are so rotten that they crumble readily under the hammer. Others have so weathered that the more resistant crystals stand out roughly from the surface. Only the more resistant quartzite bowlders remain fresh and firm. This drift shows the effects of long oxidation. In cuts it is seen to be oxidized and yellow to a depth of many feet, while the last drift is at many places blue and unoxidized to the surface.

The topographic position of this older drift and its evidently great age indicate that there was an epoch of glaciation in this region considerably earlier than the last. In this earlier epoch the ice occupied approximately the same area as did the ice of the last epoch. Where the glaciers extended farther down valley than those of the last epoch, there are in places remnants of the older moraines. Doubtless, in many other valleys the last ice advanced over these older moraines and either removed them or covered them with newer drift. The meager traces of older drift which still remain occur only where the older glaciers had a greater extent than their successors and where erosion has not removed the deposits of the early ice. A further conclusive bit of evidence as to the relations of the two drift bodies came to light during the summer of 1906, when the placer diggings in the Snowstorm mine, in the moraines of the Platte system, southeast of London Junction, showed a body of older, decayed drift overlain by younger, fresh drift.

POSSIBILITY OF A STILL EARLIER GLACIATION.

Two miles above Granite, on the east side of Arkansas River (fig. 1), bowlders that came from the Sawatch Mountains were found 200 feet above the river. These bowlders are few and are much weathered, though composed of resistant rock—a distinctive porphyritic granite characteristic of the range west of the Twin Lakes and the Clear Creek region. Their position beyond the limits of the ice of both well-determined epochs of glaciation points to a possible glacial epoch older than either, the drift of which has been entirely removed.

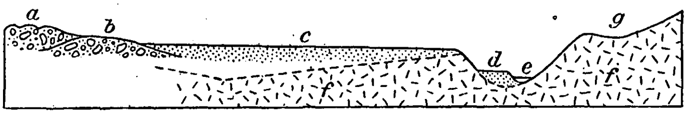

FIGURE 1.—Generalized section across the valley of the Arkansas, to illustrate the conditions in the vicinity of Granite. *a*, Terminal moraine of last epoch from a side valley; *b*, moraine of older drift; *c*, high terrace lying against older drift; *d*, low terrace corresponding in age to *a*; *e*, Arkansas River; *f*, granite in which river cut a channel after older glacial epoch; *g*, bowlders from mountains on opposite side of old valley, which appear to be older than *b*. Broken line indicates the probable preglacial valley of Arkansas River. Horizontal and vertical scale, 1 inch=one-fourth mile.

Another hypothesis might account for the position of these bowlders. During the excavation of the Arkansas Valley the axis of the two slopes might at some time have been farther east than it is now, and the bowlders might have been deposited at that time. This hypothesis seems far less probable, however, than that of the glacial origin of these bowlders, for in the great interval of time which would be necessary for the river to develop a valley 200 feet below these bowlders they would probably have had time to decompose.

HIGH TERRACES.

GENERAL DESCRIPTION.

A striking topographic feature of this region is the great number of high terraces in the Arkansas Valley. These are seen at their best on the east side of the river, between East Fork, Arkansas River, and Weston Gulch (fig. 2), but they extend both north and south of these limits, as well as to the base of the Sawatch Mountains.

Considered as a unit, it appears that these terraces, although now cut into by Arkansas River and its tributaries, are the remnants of two great, gently inclined piedmont plains, which extend continuously along the base of the two great mountain ranges and sloped down to join at the valley bottom. Arkansas River had its course at the junction of the two slopes.

Between the gulches in the terraces there are uneroded, flat-topped ridges, or mesas, which show the original slope of the plain away from the mountains. This slope ranges from 3½° at the mountain base to 1½° at the river edge. Along Arkansas River the flat tops of the terraces slope down the valley toward the south, parallel to the base of the mountains, at a rate of a little more than 1°. There are local variations in this slope, however, which are seen best at the mouths of the gulches from which the gravels came. Here the slope is not that of an inclined plain, but of a flat fan, the apex being at the mouth of the gulch, from which the surface declines toward the periphery of the fan.

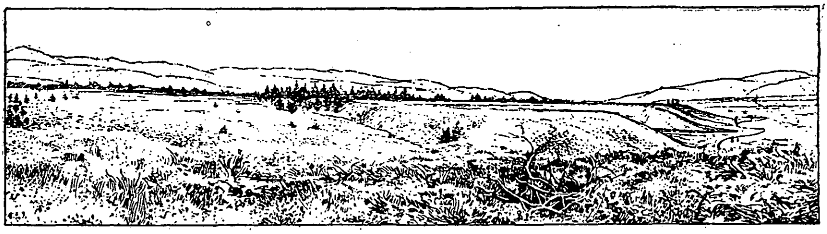

FIGURE 2.—High terraces south of Leadville.

The materials that form the high terraces can be seen in numerous cuts and prospect holes, and they have a characteristic appearance wherever exposed. They consist of imperfectly stratified gravels, with an occasional lens of sand. The gravels are uniformly coarser toward the mountains and finer toward the river; but even in the axis of the valley the pebbles composing them average several inches in diameter, and the deposits include no laminated clays such as are laid down in bodies of standing water. In Little Union Gulch, near Arkansas River, the gravels have been cemented into a loose conglomerate by calcium carbonate.

The surface configuration, the topographic relations, and the structure of the terraces seem to show conclusively that their materials were laid down as alluvial-fan and alluvial-plain deposits,[a] and that these separate alluvial fans laid down by Arkansas River and its tributaries grew until a great compound alluvial fan was formed along the base of each of the great mountain ranges. The lack of

[a] So far as is known to the writer the reference of these gravels to fluvio-glacial deposition was first made in an article published in 1904. Capps, S. R., and Leffingwell, E. D. K., Jour. Geology, vol. 12, 1904, pp. 702–705.

distinct, continuous beds of stratification is characteristic of the deposits of fan-building streams, with their frequent changes of channel, as is also the gradation from coarse materials at the mountain base to finer toward the valley axis, though by no means fine even at the lower edges of the terraces.

AGE AND ORIGIN OF HIGH TERRACES.

The physical condition and the topography of the gravels show them to be of considerable age. Cuts and shafts 60 to 80 feet deep show that the terrace materials are completely oxidized to the bottom. Bowlders of rather resistant rock, which must have been hard and firm when they were shaped and deposited, are now deeply decayed. Only the quartzite bowlders are still fresh and firm. The gravels also show age by the erosion which they have suffered. Great gulches have been cut into them. Iowa Gulch, the deepest of these, cuts 500 feet into these gravels without reaching bed rock. In almost every place where moraines of the older epoch of glaciation occur the high-terrace gravels appear just beyond them. In many places there is only a slight topographic break between the two, and in the amount of oxidization, in the decayed condition of the materials, and in the stage of erosion of the surface, these gravels agree well with the older glacial drift. The upper part of them, at least, was probably deposited during the older glacial period.

But there is positive proof, aside from the topographic relations and the condition of decay, that the older drift and the high terraces belong to about the same period. One mile north of Leadville a shaft through the gravels showed new drift overlying the high-terrace gravels. Two miles west of Leadville a prospect hole showed glacial drift of the older epoch overlain by high-terrace gravels. Thus we see that the high-terrace gravels were deposited before the last glacial epoch, and some of them after the maximum advance of the ice of the older epoch of glaciation. It is probable that these gravels which overlie the older drift were laid down during or soon after the retreat of the older glaciers, for the cutting of the interglacial gorges in the terraces would have soon made impossible the deposition by streams of any considerable amount of materials on their tops.

In addition to the typical development of these gravels in the Arkansas Valley, there are similar gravels on the east side of the Park Range. These lie beyond the moraines of the Platte system of glaciers, and bear the same topographic and structural relations to the older drift of this system as do the Arkansas terraces to the older moraines with which they are associated. The gravels in the Platte Valley, however, did not suffer so much interglacial erosion and do not show the striking terraced appearance exhibited by those in the valley of the Arkansas. The gravels in the Platte Valley were doubtless deposited at the same time and under the same conditions as those in the Arkansas Valley.

The physical and topographic relations of the high-terrace gravels indicate that the conditions of their deposition were as follows: The older glaciers advanced down the stream-developed valleys, where the rock was deeply weathered and there was abundant talus. Under these conditions the ice was heavily loaded with débris. To the extra-glacial streams, swollen by the melting snow and ice, abundant material was supplied by the glaciers and by accelerated stream cutting in the unglaciated valleys. These streams were normally retarded by the lessened gradient at the mouths of the gorges, and consequently dropped their excess load in the order of the size of the material. This tendency of the streams to deposit their loads was stimulated by the partial obstruction of the Arkansas Valley by the glaciers from the Sawatch Mountains. Possibly lakes were formed, but if formed they were shallow and only temporary, for they would have been rapidly filled by the influx of materials from the loaded streams. They could not have been deep enough for the deposition of the terraces because the glaciers from the Lake and Clear Creek valleys never obstructed the Arkansas Valley to any great height. This aggradation of the Arkansas Valley by the alluvial deposits of the river and its tributaries continued until the end of the older glacial epoch.

The high-terrace deposits of the Arkansas Valley have been described by Hayden,[a] Emmons,[b] and others as lacustrine deposits, laid down in a glacial period during which the ice from the valleys of Lake Creek, Clear Creek, and other tributaries blocked the valley of the Arkansas, thus forming a lake above these ice obstructions. The present slopes of the terrace surface are referred to tilting subsequent to the deposition of the gravels.

There are a number of objections to this hypothesis:

(1) The elevation to which the ice from its tributary valleys dammed Arkansas River, as shown by the moraines, is nowhere above 9,400 feet, while above Leadville the high-terrace gravels reach an elevation of more than 11,000 feet. Thus the glacial obstruction of the Arkansas was entirely inadequate to form a lake large enough to permit the deposition of these gravels.

(2) If such a lake had existed there would probably have been beach lines, shore terraces, deltas, and other shore features which would still be recognizable, but no trace of any of these features was observed. If these were lake beds the outer edge of the gravels would

[a] Ann. Rept. U. S. Geog. and Geol. Surv. Terr. for 1873, p. 53; idem for 1874, p. 52.
[b] Mon. U. S. Geol. Survey, vol. 12, 1886, pp. 41, 71, 72.

naturally be the shore line of the lake, yet the upper edge of the gravel ranges in elevation from 9,100 to 11,000 feet, and rises at the mouth of the tributary valleys.

(3) As appears from their structure seen in many surface exposures these gravels differ essentially from lake deposits: (*a*) They include no continuous stratified beds, and in places coarse gravels and sand are intermingled. (*b*) All delta structures are wanting. (*c*) There are coarse gravels at points that would have been near the center of the hypothetical lake, and fine laminated clays, such as would have been deposited in the offshore portions of such a lake, are absent.

(4) Emmons[a] argues that the present slopes of the terraces are due to tilting subsequent to their deposition. There is evidence that the upper edges of the terrace gravels have in places been faulted upward to some extent since their deposition, and such uplifts doubtless account for some isolated patches of the terrace material that occur well up on the slopes of the mountain range. Such an uplift, however, could scarcely account for the slopes of the terrace below the base of the mountains. It seems improbable (*a*) that tilting should have occurred in the gravels on both sides of the valley, with the axis of tilting at the valley axis and the tilting essentially equal on both sides; (*b*) that all of the terraces should have had the normal river valley slope of about 1° to the south; and (*c*) that the component parts of the terraces should have the slopes of a normal alluvial fan.

(5) It is an open question whether the advance of the glaciers from the tributary valleys across the Arkansas Valley would not have been so slow that the débris-loaded Arkansas River would have had time to keep its floor graded up to the level of the outlet beyond the end of the glacier. If this advance was slow enough no lake would have been formed.[b]

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[a] Op. cit.

[b] Since the above was written Emmons and Irving have published, in Bulletin 320 of the Geological Survey (The Downtown district of Leadville), more details concerning the material of these terraces. It appears that, although not insisting that a permanent lake filled this part of the Arkansas Valley, Emmons contends that the evidence disclosed by many shafts sunk on the high terraces near Leadville points to the temporary ponding back of considerable bodies of water by the damming up of the Arkansas Valley near Granite during the earlier glacial epoch These shafts, after traversing 100 feet or more of coarse gravel or bowlder wash, pass into fine-grained marly silts, clays, and sands, which the miners call "lake beds" on account of their stratified appearance. They carry sporadically large angular rock masses which would appear to have been dropped from floating ice. Many of the sand beds, alternating with clays, yield strong flows of water when pierced. These characteristics, and the fact that within large areas these fine-grained materials have been found whenever the overlying gravel or wash has been passed through, indicate, Emmons argues, deposition in still rather than in running water.

He states that mine workings disclose movement or fault planes traversing these so-called lake beds, which afford definite proof of considerable elevation of the Mosquito Range back of Leadville since glacial time.

Although the topography and the oxidation and decay of the high-terrace gravels correspond closely with those of the older drift, it is possible that the enormous amount of material included in these terraces is too great to be referred to a single glacial epoch. Numerous mining shafts show that the gravels have a thickness of 300 to 600 feet over most of the area in which they occur. As far as was observed, the gravels are completely oxidized to their base. This suggests that the materials were deposited slowly and were oxidized as deposited rather than that they were deposited rapidly in a cool climate. If they were laid down during a glacial epoch rapid deposition would have been necessary for the accumulation of beds 500 feet thick.

An uplift of the two mountain ranges in preglacial times might have rejuvenated the streams and given them a transporting power in their upper courses which they did not have below the base of the mountains. This uplift might have marked the beginning of a period of alluvial fan and plain building which culminated at the time of the older glacial epoch. The present relations of the older drift and the high terraces would have been the same in either course of events. If the glacial deepening of the valleys during the older epoch lowered them to any great extent, the gradient of the streams might have been reduced to that which they had before their rejuvenation, and on the retreat of the ice they would have been able to cut their interglacial gorges into their former plain of aggradation. If the terraces are the result of deposition in both preglacial and early glacial times, both mountain ranges must have been uplifted at about the same time, and in both the fan building ended soon after the older epoch.

INTERGLACIAL EPOCH.

As the ice of the earlier epoch retreated the glaciated valleys were subjected to a very different set of conditions. The uncovered rock surfaces were subjected to the agencies of weathering. Stream erosion played an important part, and the irregular topography of the moraine-covered areas was gradually brought under erosional control. The streams, which in glacial times were loaded to their full capacity, were no longer supplied with such an abundance of materials, and were able to intrench themselves in their own alluvial deposits. Below Leadville these interglacial gorges are cut more than 500 feet into the older glacial valley trains. South of Granite Gulch, Arkansas River, which was forced by the older glaciers onto the rock slope of its east valley wall, was continually cutting its gorge deeper, and by the end of interglacial times had cut a gorge 400 feet deep into the crystalline rock.

All the evidence at hand leads to the conclusion that the time which elapsed between the two epochs of glaciation was very long—much longer than the time which has elapsed since the last epoch. A comparison of the materials of the last moraines strengthens this impression. The materials of the older drift are invariably deeply oxidized, and all but the more resistant bowlders are falling to pieces. The drift of the last glaciers, on the contrary, are rarely oxidized more than a few inches below the surface, and the bowlders appear as fresh and sound as though they had been deposited yesterday. Many times the present amount of weathering will be necessary before the last moraines are as old in appearance as the older moraines now are.

LOW TERRACES.

As compared with the high terraces the low terraces are very inconspicuous topographic features. They exist only in the bottoms of the gorges or flats which were eroded in the high-terrace gravels in interglacial times. Most of them occur just below the imposing high terraces, many of which rise 200 to 300 feet above the low-terrace level. Few of the low-terrace tops are more than 30 feet above the stream. The relations of these gravels to the moraines of the last glaciers are the same as those of the high terraces to the older drift (p. 17). Like the new drift, the gravels are unoxidized and undecayed, and the erosion which they have suffered is due to cutting by large streams rather than to the gradual growth of gullies back into the terrace plain.

These terraces are composed of unstratified or partly stratified gravels, which include here and there lenses of sand and show no continuous bedding planes. The gravels are in general coarser nearer their source and finer downstream. They consist of a great variety of materials, most of which can be traced to the mountains upstream. The terrace plain has a slope which ranges from 3½° to 1½°, depending on the distance from the source of the materials. In structure, in materials, and in slope the low-terrace gravels are very similar to the high-terrace gravels; they differ only in age and in topographic development; yet, because of their evident position in bottoms of the gulches and in the valley flats, no one has thought of calling them lake-bed deposits, as the high-terrace gravels have been called.

The conditions for the deposition of the low-terrace gravels were as follows: In interglacial times the great gorges and valley flats were cut into the high-terrace gravels. Down these gulches the last glaciers advanced, bringing to their ends large amounts of débris and there supplying it to the streams, swollen by the melting ice. These overloaded streams began to deposit and built up valley trains for many miles downstream. This deposition continued for some time after the retreat of the ice began, as is evinced by the low-terrace gravels within the glaciated area of the East Fork of the Arkansas.

Comparing the low terraces with the high terraces, we observe a close similarity in lithological contents, but a great difference in age. Most notable, however, is the vast difference in the amount of material, the low terraces containing, even at their maximum extension, a comparatively small amount. The difference is even more striking when we consider that the extent of the glaciation in the periods when the two sets of terraces were formed was approximately the same.

The failure of the last glacial streams to build great terraces is referable to two sets of facts: First, the ice of the older epoch of glaciation advanced down valleys which were stream cut and had the V shape of such valleys. The walls of these valleys were doubtless deeply weathered, so that the ice had great quantities of loose material to handle. Although there was a considerable period of weathering between the two glacial epochs, the fresh rock surfaces left by the older ice do not seem to have been weathered to a great depth, and therefore the last ice had comparatively little loose material at hand. Secondly, the streams from the older ice flowed from their glaciers into a broad flat, in which the gradient of the stream was decreased by the Clear Creek and Lake Creek glaciers damming up the valley, so that conditions were ideal for the streams to drop their load. On the other hand, the streams from the last glaciers flowed into the deep, canyon-like gulches cut into the high terraces. In these narrow valleys the glacial waters were concentrated and held much of their load, while the glaciers below failed to dam Arkansas River effectually, so the materials were carried away by the streams almost as fast as the glaciers supplied them.

In the narrow valleys in which the low terraces were deposited the active streams have been cutting steadily since the end of the last ice advance, and a great part of the low-terrace gravels have been removed.

FLATS.

Along Arkansas and Eagle rivers there are a number of flats of considerable area which owe their existence to the effect that glaciation had upon the drainage.

In the valley of the Eagle there is a flat extending from Pando upstream for about 3 miles. This flat, as represented on the topographic map, appears to have a considerable slope, but a rather accurate level shows that its slope is not more than 20 or 30 feet in the 3 miles. This flat was formed by the damming of Eagle River by the ice from the Homestake Creek Glacier. It is not evident that any considerable lake ever occupied this flat, as no shore lines were observed above Pando, but the lessening of the gradient of the river, by decreasing its carrying capacity, would have been sufficient to cause the building up of the flat. On the south side of the main moraine ridge, north of Pando, there are what appear to be shore lines, indicating that a small lake existed between this moraine ridge and the smaller one south of Pando.

Crane Park was formed because the ice of the Crane Park Glacier pushed out and retarded Tennessee Fork above its moraines. Another considerable flat occurs above the point where the moraines of the Lake Fork Glacier pushed across to the terraces on the east side of the river. No definite shore lines occur here to show whether or not a lake ever occupied this flat, but if there ever was a lake here it could never have stood much higher than the present flat level, for the ice advanced scarcely far enough to dam the valley at all.

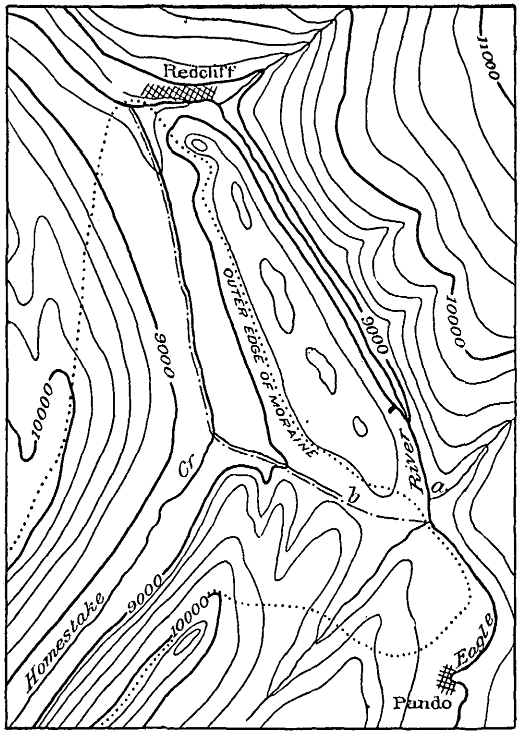


FIGURE 3.—Sketch map to illustrate a glacial change of drainage in Eagle River valley. The map comprises an area of about 17 square miles near Pando; *a* represents the head of the postglacial rock gorge entered by Eagle River a mile below Pando; *b* indicates the position of the probable preglacial course of Eagle River. The dotted line represents the position of the moraine of the glacier which came down Homestake Creek.

From the edge of the Lake Fork moraine down to the mouth of Little Union Gulch, Arkansas River has a flat from half a mile to a mile wide. This flat has been cut by the river into the valley deposits.

GLACIAL CHANGES IN DRAINAGE.

Two clear cases of changes in drainage due to glaciation were worked out in this region.

EAGLE RIVER VALLEY.

Eagle River, 1½ miles below Pando (fig. 3), enters a narrow rock gorge about 3 miles long. In this gorge the stream, although of considerable size, has cut itself only a shallow valley, which is clearly very young. Just west of the point where the stream leaves its broad valley for the narrow gorge there is a low, broad col (fig. 3, *b*), filled with drift, beyond which lies Homestake Creek, which has from this point down a much larger valley than its size would require.

The history of the change seems to be as follows: As the ice of the last glacial epoch came down the valley of Homestake Creek it pushed across the gorge then occupied by the Eagle (fig. 3, *b*), and by obstructing the stream ponded it and caused it to find a new outlet to the north. On the retreat of the ice a drift dam was left across the old valley, and the Eagle continued to occupy its new channel as far as Redcliff, where it reenters its old valley.

GLACIAL CHANGE IN DRAINAGE IN ARKANSAS VALLEY.[a]

In preglacial times Arkansas River must have flowed at the foot of the rock slopes of mountain ranges on either side, and had a well-developed valley. With the advance of the ice of the older epoch of glaciation, the normal course of the stream was disturbed. From the valleys of Lake and Clear creeks the glaciers of that epoch pushed eastward until they reached the river. Advancing still farther, the ice forced the stream eastward, and the river, abandoning its old course, was compelled to find a way of escape to the east of the ice lobe which blocked its valley. This blocking forced the stream up onto the rock slope of the east valley wall, and here it intrenched itself (fig. 1, *e*). It is possible, even probable, that shallow lakes were formed above these dams, but the rapid débris-charged streams would have quickly filled these lakes, so that there is little probability that any considerable lake ever existed here.

Between Lake and Clear creeks Arkansas River was not pushed eastward by the ice, though it now flows against the rocky east valley wall. Borings in the terraces in this area show that the rock surface below the gravels declines to the west for a considerable distance from the present stream, to what is doubtless the preglacial axis of the Arkansas Valley. The preglacial Arkansas must therefore have cut across the area now occupied by these terraces and by the moraines of the Lake Creek and Clear Creek systems, joining its present channel somewhere south of Clear Creek.

The river, pushed over to the east by the ice from Lake and Clear creeks, may have had at first a great loop to the west between these points. If so, the bend may have been cut off by piracy or it may have been crowded over between these ice lobes by fluvio-glacial deposition.

POSSIBLE CHANGE IN DRAINAGE IN EAST FORK OF ARKANSAS VALLEY.

Since the field work of this report was finished, evidence of the existence of a deep channel in the rock surface northwest of Lead-

[a] Prof. L. G. Westgate, of Ohio Wesleyan University, was studying this problem when the writer reached this portion of the field, and had already worked out its essential features. With his general conclusions the writer agrees. (See Jour. Geology, vol. 13, 1905, p. 294.)

ville has come into the hands of S. F. Emmons, of this Survey. He suggests that this channel is an old valley of East Fork of Arkansas River. The hypothesis is offered that the ice of the older glacial period, advancing from Evans Gulch, pushed westward beyond the base of the mountains and forced East Fork of the Arkansas northwest to the base of the rock spur. Here the stream established itself and the old valley was filled by outwash during the ice retreat. The mouth of the present valley of the stream has never been cut to depths equal to those of the gulches to the south, as is shown by the rock outcrops in its bottom, into which only a shallow channel has been cut. This cut is doubtless the work of the stream in postglacial times. The old stream may have joined the main stream of the Arkansas at about the position of Malta, but this can not be determined without knowledge of the rock surface in this vicinity.

POSTGLACIAL EROSION.

In the rock valleys, left bare of loose material by the last glaciers, we may see how trivial has been the rock cutting by the streams since the glaciers retreated. Occasionally a stream with a very steep gradient or with favorable rock conditions has cut a postglacial gorge 20 to 30 feet into the rock, but usually there is only a shallow channel.

The amount of material removed by stream cutting is very small as compared with the amount loosened by weathering and moved by gravity. Wherever there are steep cliffs there are talus heaps, and in some places the amount of this talus is enormous. In Willis Gulch, of the Lake Creek system, the whole east wall of the cirque head is deeply buried beneath talus which shows the crescentic ridge forms of "talus glaciers."

Beyond the limits of the glaciated areas postglacial stream cutting has accomplished more than in the glaciated regions. The low terraces, built by the extraglacial streams when they were overloaded, have since been vigorously attacked by these same streams. Where the low-terrace gravels occurred in narrow gorges they have all been removed, except occasional patches. Where they were laid down in more extended flats the streams have now intrenched themselves as much as 30 feet into the gravels.

PART II.

SPECIAL CONSIDERATION OF PARTICULAR AREAS.

ROCHE MOUTONNÉE CREEK SYSTEM.

Although most of the system of Roche Moutonnée Creek, locally known as Cross Creek, lies beyond the limits of the Leadville quadrangle, one of its cirques and part of its main valley are contained in the northwest corner of the quadrangle.

The cirque just east of the Mountain of the Holy Cross is one of the most perfectly developed cirques in this region. Broadly U-shaped, the walls at the side and head rise steeply above the valley floor. Very little talus occurs at the base of the slopes, and the whole valley is exceptionally free from loose material. The rock floor has scarcely any covering and is smoothly polished and striated. In a number of basins gouged out of the solid rock by the ice are small lakes.

The main valley of this creek well deserves the name of Roche Moutonnée Creek. For several miles above the terminal moraine the valley bottom is covered with beautifully developed roches moutonnées. These differ in size; some are of considerable height and are so smoothly and symmetrically shaped and have slopes so steep that it is difficult for one to reach their tops.

No heavy-drift deposits occur in this valley within the Leadville quadrangle, but beyond the northern boundary of the quadrangle there are extensive morainic deposits. The southeast wall of the valley, however, shows no distinct lateral-moraine ridge until the terminal moraine is approached. One finds in places on this wall patches of scattered bowlders or a thin layer of drift, but no extensive, continuous moraines.

On the northwest side of the valley, on the contrary, a well-developed lateral moraine runs far up the valley. It is 500 feet above the stream in places, and from the opposite side of the valley presents the appearance of a remarkably smooth, even-crested bench. At one place a cut in this ridge shows it to be merely a layer of drift 50 feet thick, lying against the rock wall, but this is evidently not the case through most of its length.

At the point where the valley enters the Paleozoic terranes the ice lobe curved to the north around the nose of the Paleozoic rocks, and here the lateral moraine loses its distinctive form, although considerable drift rests on this slope. Beyond this nose the lateral moraine resumes its ridge form, swings in a broad curve to the northeast, and merges gradually into the flattened terminal moraine which lies beyond the limits of this quadrangle.

ROCK CREEK SYSTEM.

An ice system lay in the valley of a stream locally known as Rock Creek, between Roche Moutonnée and Homestake creeks. It consisted of a large primary lobe fed by two tributary cirques from the northwest side, one of which does not appear on the map (Pl. I). The main valley shows well the broad U shape so characteristic of severely glaciated valleys. The ice at the head of this system was separated only by a broad, low col from the ice of the Homestake system. At the time the glaciers were active this col was undoubtedly covered with névé and presented a continuous snow field connecting the two systems.

The valley at the upper end was severely eroded by the ice, for the bare unweathered rock appears almost everywhere in the bottom. Little postglacial talus has accumulated anywhere along the valley sides. In the bottom are a number of lakes, the basins of which were gouged out of the solid rock by the ice.

Northwest of the head of this valley there is a deep, well-developed cirque (the Leadville topographic sheet, base of Pl. I, fails to indicate it), which joins this system from the northwest. This cirque is even more severely glaciated than the head of the main valley, and shows bare walls and floor, with lakes in rock basins.

On the southeast side of the Rock Creek trough the ice limit is not well defined for some miles below the head of the valley, the weathering of the rock and the movements of talus having obliterated most of the glacial features. On the northwest side, however, the ice limit is everywhere sharp and is easily located by the shape of the valley, by the presence of smoothed surfaces of rock, and by a beautiful lateral moraine.

A second tributary lobe of ice entered the main valley from the northwest some 3 miles below its head. Here the ice action was not severe and no well-marked cirque resulted. The ice limit is not sharply defined and the valley was never very well cleaned out. The lower end of this valley has considerable heavy drift.

Just above the junction of this tributary with the main valley, a fine lateral moraine appears in the latter. It runs directly across the lower end of this tributary and shows that the ice was still very vigorous in the main valley after ice had ceased to come out from the tributary. The ice, in crossing the mouth of the tributary, built up its lateral moraine, and in so doing obstructed the side valley. As a result there is now a considerable flat which was developed behind this lateral-moraine dam. The lateral moraine at this point has a height, on the outside, of 60 to 100 feet, and the material lies at an angle of 35°. The inner slope is here about 25°, and the crest of the ridge is 600 feet above the valley bottom.

This lateral moraine runs for several miles with a uniform slope and an unbroken crest, and is a most striking topographic feature of this system. Bowlders up to 10 feet in diameter occur in considerable abundance over the surface of this ridge.

The lateral moraine on the southeast side of the stream appears farther down, beyond the boundary of the quadrangle, and nowhere reaches the perfect development of the opposite moraine, though it is a well-formed ridge toward its lower end.

There is no well-marked terminal moraine in this system. At the point where the lateral moraines begin to converge the stream has a very steep gradient, and the drift was probably carried away as fast as it was deposited. The stream bed beyond the drift is filled with bowlders which may be of glacial origin, but no distinctive drift of the terminal-moraine type is found.

HOMESTAKE CREEK SYSTEM.

Except one the Homestake Creek system was the largest on the east side of the Sawatch Range. At its maximum the ice covered an area of about 46 square miles, and its maximum length was more than 17 miles.

The main body of ice lay in the valley of Homestake Creek, but 15 well-developed cirques and a number of minor valleys contributed ice to this system. These cirques head near the tops of the ridges which surround the Homestake Creek basin, and in many cases are separated only by low cols from the cirques of the other systems.

SOURCES OF THE ICE.

Source 1 heads northwest of Whitney Peak, and is separated only by a low col from the head of the Rock Creek system. The cirque has a broad **U** shape. The side walls are, in general, not very steep, but the head wall rises abruptly and terminates in a row of serrated peaks, which divide this system from the Roche Moutonnée and Rock Creek systems. There is little talus at the base of the slopes; yet the topography does not give the impression that the glacial erosion was severe. The shoulders and knobs of the walls are rounded, but not intensely so, and few polished and striated surfaces occur. The valley bottom consists of a number of smoothed rock knobs, and is not at all level and floorlike. Three small lakes occur near the upper end of the valley, with basins apparently in the solid rock.

Source 2 is a hanging cirque, its junction with source 1 being several hundred feet above the floor of the latter. It has flaring side walls, but a rather steep head wall, which, like that of source 1, terminates above in a row of sharp needles. The walls do not appear to have been severely glaciated. Talus has everywhere accumulated to a considerable extent, and the rock floor where it is exposed is not well polished or smoothed. It was merely a collecting basin which was somewhat eroded.

Source 3, like 2, is a hanging cirque, and its lower end does not reach below 11,900 feet. It contains little talus, and its head and side walls are well shaped, although few smoothed and polished surfaces remain. It ends rather abruptly at its junction with the main valley.

Between cirques 2 and 3 there is a "talus glacier" about 100 yards wide and 50 feet high, extending in a long tongue out into the valley. The front and sides of this tongue are very steep, and the blocks are large and angular.

Source 4 has a broadly U-shaped trough with steep head walls. Below an elevation of 11,300 feet the valley is free from drift and talus, and many smoothed and polished rock surfaces outcrop. The cirque is not cut down to the same level as the valley which it joins, but has a very steep gradient at the point where its floor joins that of the main trough.

At the 11,300-foot level in this cirque there is a recessional moraine of bowlders and angular blocks. Above this moraine the cirque floor contains considerable drift and talus. On the northeast wall there is an even-crested ridge of bowlders sloping back from the terminal moraine, which is the lateral moraine of this recessional stage, contemporaneous with the terminal recessional just mentioned.

Source 5 is not a well-developed cirque, although the head has a good U shape. The side and head walls have occasional marks of glaciation, but are not conspicuously smoothed or polished. Considerable postglacial talus has accumulated, and this tends to lessen the impression of great intensity of ice action. The bottom of the valley contains a considerable lake, which has its basin in the solid rock. The valley floor is not well smoothed, but contains numerous rounded rock hummocks, which are often polished and striated. To one at any particular place the floor seems much more severely glaciated when looking downstream than it seems when looking upstream, for plucking has left many sharp points of rock on the lee side of the rock knobs, while the stoss sides have all been smoothed.

Sources 1, 2, 3, 4, and 5 all sent their ice into a single valley, tributary to Homestake Creek. Below the junction of these cirques this tributary valley is strongly glaciated. No areas of heavy drift occur in the valley bottom. In many places the stream flows on rock, though more often the channel is filled with bowlders. For some distance above Gold Park the stream falls very rapidly, and the water power was here used to a considerable extent when Gold Park was a flourishing mining camp.

Between the ice in this valley and that of West Fork there was deposited a considerable body of heavy drift. In the area where the edges of the two lobes came together the ice action was naturally weak, and over the flat top of the dividing rock ridge the ice must have been spread out in a rather thin sheet. Its transporting power was thus lessened, and the glacier deposited here a large quantity of drift, which has the form of a sharply defined interlobate ridge for some distance below the point where the ice lobes joined. This ridge flattens out below, and grades into a thin sheet of drift which caps the whole of this flat ridge. Bowlders up to 10 feet in diameter are thickly scattered over this drift.

Source 6 is broadly U-shaped and has three minor heads. These heads, though small, are all U-shaped and show evidence of somewhat intense ice action. The side and head walls are all steep, and little postglacial talus has accumulated at the base of the slopes.

Below the junction of these heads the valley is broad and troughlike. The side walls, although well rounded, do not now show striated or polished surfaces, but this may be due to the gneissic character of the country rock, which in general has failed to retain its glaciated surface.

All loose material was removed by the ice from the bottom of the valley, and it now contains few bowlders and little talus. In several places the stream flows through postglacial cuts in the bed rock, one of which is 30 feet deep in the fractured gneissic rock. Beginning at the 10,600-foot level, there is a low backbone of rock which extends between the two branches of the creek, and this ridge has been more or less moutonné.

In the valley bottom, along the north side, between the elevations of 10,000 and 9,300 feet, there is a long, narrow deposit of drift, parallel to the stream. This drift has not the characteristic moraine topography, and is probably only a thin sheet.

Sources 7, *8*, and *9* have much the same characteristics. All show the effects of vigorous glaciation, are U-shaped, and are comparatively free from accumulations of postglacial talus. Numerous bare surfaces of rock appear, which often show smoothed and striated surfaces.

The lower portions of these cirques are heavily timbered, and all but the general features are obscured.

Source 10 includes the valley of Middle Fork of Homestake Creek. At the head of this cirque, above the lake, the walls rise precipitously, with little talus. The rock walls of granitic gneiss do not take polishing or striæ well, but the slopes are well rounded and no angular outcrops appear below the well-defined upper limit of glaciation. The lake in the cirque seems to have its basin in bed rock which everywhere presents well-cleaned-off, rounded surfaces. The valley is broadly U-shaped, and the ice limit along the sides is well marked where it crosses spurs running down to the valley.

The southernmost tributary cirque on the west side of this valley is a small hanging cirque, which joins the main trough about 500 feet above the bottom of the latter.

In the valley, just above its junction with East Fork, there is a lake almost a mile long. This lake is shallow, and the upper end has been filled in for several hundred yards by the silt from above, making a low, marshy flat through which the stream meanders. For about 2 miles below this lake the valley contains numerous moutonné hills of rock, some 20 feet in height.

Above the junction of Middle and East forks the east wall of the valley is of bare rock, smoothed and moutonné, and bears scarcely any talus. This wall is almost unbroken by draws, and the rock is generally smooth and polished. The west wall also is practically free from talus, but is broken by two tributary cirques. The lower of these is a hanging cirque and is not deeply eroded, but is divided into two or three heads by minor spurs. The inaccuracy of detail in the topographic map at this place makes close mapping of the ice limit impossible.

Source 11 comprises the trough of East Fork. At its upper end this valley forms a beautifully developed cirque. This is broadly U-shaped, with the head and side walls rising almost perpendicularly for more than 1,000 feet above the valley floor. Very little talus has accumulated, and the moutonné bed rock appears in many places. Three lakes occur in this cirque, apparently in rock basins. One of these has been almost completely filled up with silt, forming a marshy flat at its upper end.

Source 12 was placed on the map geographically, without reference to the contours as given. This cirque heads back in an almost southerly direction and is deeply eroded, with little loose material in the bottom. The head and side walls rise abruptly on all sides, and in many places the ice limit has been obscured by the weathering of the rock walls and by the talus from above. The cirque bottom contains one lake, the basin of which is carved out of the bed rock. Around the outlet of this lake the surface of the rock is talus covered, but the lake has some depth, and numerous rock outcrops below show the talus covering to be thin.

In the main valley, below the junction of sources 11 and 12, the ice moved with great vigor, cleaning out and excavating the bottom and sides of the trough, and leaving the hard, unweathered surface of the granite everywhere exposed. On the west side of the stream the ice reached almost to the divide on both sides of the ridge, and left only a sharp, narrow backbone untouched. At about 10,900 feet the ice from opposite sides of this ridge joined, covering the ridge below this point.

Source 13 lies just west of Homestake Peak and contained a small glacier tributary to the main ice lobe. This cirque, U-shaped at its head, is a hanging cirque, and loses itself in the main valley at an elevation of about 10,600 feet. The impression of severe glaciation is marred by the considerable accumulations of postglacial talus. Northeast of this cirque the topographic mapping is inaccurate, and the limits of the ice were dotted in without regard to the topography as mapped.

The main valley of the Homestake, from the junction of Middle and East forks down to Gold Park, is strongly glaciated. Numerous roches moutonnées appear in the valley bottom, and the sides are cleaned off and rounded. Although locally patches of bowlders occur, numerous outcrops of rock and numerous bosses of glaciated rock make this area one of light drift.

Source 14 lies north of Gold Park and southeast of Whitney Peak. Although some ice movement took place in this area, it is not a well-developed cirque, but was a broad collecting field divided into two shallow heads which have been shaped, but not deeply excavated, by the ice. Many scattered bowlders lie over the valley floor, but owing to the absence of steep walls there have been slight accumulations of talus.

About a mile below the head of this cirque there is a lake in the gulch bottom, which was formed by the ponding of the stream behind accumulations of drift in the valley.

Source 15 lies about 3 miles northeast of 14 and joins the main trough from the west. It heads at an elevation of 12,000 feet and is shallow, and the ice from it was therefore less effective than in the cirques which head much higher. Only a small area just at the head of the cirque shows severe glaciation.

DRIFT AREAS AND MORAINES.

In the lower ends of sources 14 and 15, and along the upper edge of the glaciated portion of the northwest wall of the Homestake Creek gorge, there is a body of heavy drift which extends from a point above Gold Park down to the point where the ice limit reached the 10,200-foot level. Although rock outcrops occur here, almost the whole of this area is covered by drift of sufficient thickness to mask the topography of the rock wall. Large bowlders are scattered over the surface, one 40 feet in diameter being found. This heavy-drift area does not reach down to the valley bottom, but lies along the upper edge of the glaciated area, the lower edge being from 400 to 500 feet above the stream.

On the southeast valley wall is a body of heavy drift occupying much the same relative position and having much the same characteristics as that on the northwest side. It extends from the upper side of source 13 down to the point where the ice limit reaches the 10,000-foot level. Bowlders, large and small, are everywhere scattered over the surface, and numerous kettles, forming ponds or marshes, dot the area. Some rock outcrops occur, but they occupy only a small part of the whole area.

The upper limit of glaciation along this side of Homestake Creek is not everywhere sharply defined. In some places it can be traced only by the presence of scattered bowlders.

About 2½ miles southeast of Gold Park is a cirque-shaped valley which does not seem to have been affected by the ice of the last epoch. It will be referred to again later (p. 36). Below this cirque the upper limit of the ice is marked by a definite lateral-moraine ridge for more than a mile. This ridge has an outer slope 50 feet high in places, although 15 to 30 feet is a more common height. Its surface contains many bowlders, and numerous kettles occur both in the lateral moraine itself and just outside of it, where the drift has dammed up small streams. At the point where the ice limit reaches an elevation of 10,800 feet this ridge form of the moraine disappears and the ice limit is marked only by scattered bowlders and occasional glaciated outcrops.

The upper limit of the ice continued northward in this way to the point where it crossed the 9,800-foot contour, at which place it curved sharply to the east around the nose of the ridge and pushed up the Eagle Valley as far as Pando. East of this nose the drift again develops a ridge form at a point where it crosses a draw. This ridge is 30 to 50 feet high and has bowlders up to 6 feet in diameter. There is only a shallow post-glacial cut through this ridge. Beyond this draw the ridge form of the drift disappears and the drift lies against the slope of the cliff and is often mingled with talus from the steep slopes above. The limit of the ice becomes lower and lower and finally swings to the southeast just beyond the deposits of terminal moraine.

On the northwest wall of the Homestake Valley, below the patch of heavy drift, the upper edge of the ice lay along the rock valley wall. There is no lateral-moraine ridge of any kind, and the height to which the ice reached is shown only by the rounded appearance of the rock wall. The wall shows no smoothed or striated surfaces, but all projecting points and angles have been subdued. This bare rock wall continues northward to the limit of the Leadville quadrangle. Beyond this the ice limit swings somewhat to the northwest, following the course of the Homestake Valley. Some heavy drift occurs against the rock on the west, but this has no typical drift topography and is mingled with talus from the cliff above. Beyond the Leadville quadrangle the ice edge descended rapidly on both sides of the valley, and all evidences of glaciation end where the Homestake joins Eagle River, just west of Redcliff. The ice, ending in the narrow valley, left no terminal moraine, for the swift stream carried the drift away as fast as it was dropped by the ice. Some heavy drift occurs on the east side of the valley beyond the quadrangle limit, but it consists mainly of large bowlders lying in a col on the valley side and has no drift topography.

MAIN VALLEY.

The main valley of the Homestake, below Gold Park, has the features one would expect to find in a valley formerly occupied by a glacier of this size. The bottom is broad and broken only by occasional roches moutonnées, some of which rise 150 to 200 feet above the stream. Some mounds of what appears to be heavy drift occur, but sections in many of these show them to be bosses of rock with a thin veneer of drift. One patch of heavy drift about one-half mile long and one-fourth mile wide lies just below the point where the 9,000-foot contour crosses the valley. Below this there is an alluvial flat, which was probably built by the stream while it was removing some obstruction below.

At the bend of Homestake Creek, 2 miles south of the edge of the quadrangle, there are remnants of terraces on either side of the present river flat. These terraces stand from 12 to 15 feet above the stream, and are composed of gravel, the constituents of which are less than 6 inches in diameter. Occasionally larger pieces of rock occur, but these may be talus from the cliff above. These terraces seem to be remnants of a valley train which was built from the edge of the ice during its retreat and which has since been almost completely removed. The stream is a vigorous one and is now cutting into these terraces.

Along the west and southwest side of the ridge between Homestake Creek and Eagle River the limit of glaciation is hardly traceable. Doubtless the ice from the Homestake Valley, meeting this ridge almost at right angles, became stagnated along the side and had little effect on it. No definite line to which the ice reached could be drawn, and only scattered bowlders show that the ice once covered the lower slopes.

This ridge, opposing the ice in the Homestake Valley, sent most of it down the gorge to the north, but a lobe was pushed to the south, to a point one-fourth mile above Pando. Here a thin terminal moraine was deposited across the valley of Eagle River. This terminal moraine is of very slight relief, and although it has hummocks and kettles they are of no great size. After the deposition of this drift the ice retreated to a point one-fourth mile north of Pando, where it deposited a very considerable terminal moraine across the valley of the Eagle. This terminal moraine is 80 feet high at the west side of the valley, but becomes lower toward the east. The drift is composed of bowlders which correspond to the rocks in the valley of Homestake Creek, and the topography has a modified hummock-kettle character. The outer face of this ridge shows roughly a benchlike arrangement, three benches appearing, one above the other, as though the ice had built one bench and then retreated a little way to build others above the first. Beyond the terminal moraine the waters of Eagle River were ponded between the two distinct moraine deposits, and a flat was built up. Outside of the later moraine, in this flat, there is a considerable body of gravels, probably deposited as an outwash apron.

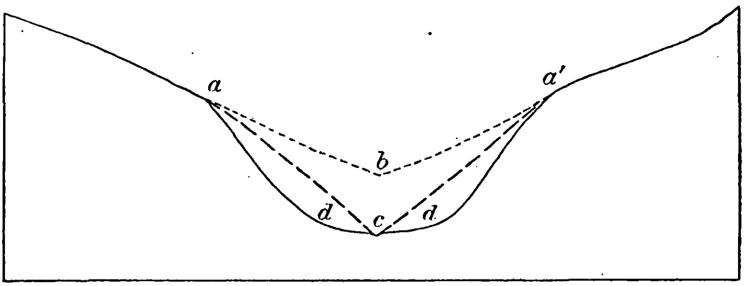


FIGURE 4.—Diagrammatic cross section of Homestake Creek valley. *a*, *b*, *a'*, Probable preglacial shape of valley; *a*, *c*, *a'*, preglacial shape of valley if it was not deepened by glacial erosion; *a*, *d*, *c*, *d*, *a'*, present shape of valley; *b*, *c*, probable glacial deepening of valley; *a*, *d*, *c*, material removed by glacial erosion if valley was not deepened by the ice; *a*, *b*, *a'*, *d*, *d*, material removed by glacial erosion if valley was deepened from *b* to *c*. Horizontal scale, 1 inch=one-half mile. Vertical scale, 1 inch=one-fourth mile.

Within the inner ridge the valley bottom contains heavy drift for about a mile to the northwest. This drift is remarkably free from bowlders and has little of the drift topography.

The valley of Homestake Creek, viewed at a point about 5 miles below Gold Park, is broadly U-shaped and shows the effect of glaciation on the walls for about 1,000 feet above the stream. All spurs have been truncated and the walls and floors of the valley have been smoothed and rounded. This broad U shape does not accord with the cross section of the normal stream-cut valleys of these mountains, and the amount of material removed by the ice in changing the valley section from a V shape characteristic of the unglaciated valleys of this region, to a U shape was great, even if there was no deepening of the valley. It is certain, however, that this valley was considerably deepened by glacial erosion, as is evidenced by the smoothed and montonné condition of the floor rock in numerous places, and that as shown in the diagram (fig. 4, *d*, *d*) the amount of erosion was considerably greater, perhaps several times greater, than it would have been if there had been no deepening.

The amount of postglacial weathering in this valley is small. Only at the base of the steepest slopes are there accumulations of talus, and the smoothed rock surfaces appear hard and fresh. The stream has here and there cut its channel 10 to 15 feet into a rock obstruction in its bed, but its course is usually in a bowlder-strewn channel in the flat valley bottom.

OLDER GLACIATION.

From observations made in various parts of the Leadville quadrangle it is certain that many of the valleys were occupied by glaciers during two distinct epochs, one much earlier than the last. This was the case with the valley of Homestake Creek. East of the area occupied by the last glacier, at a point 2 miles west of Pando, there is an area covered with bowlders left by the older glaciers. This area is beyond the crest of the ridge which limited the ice of the last epoch, but if the last glacier had been 100 feet thicker, it would have overspread the valley wall at this place and would have left drift in about the position where these bowlders now occur. The older drift here consists merely of scattered bowlders lying upon the rock wall or on the very thin soil of this slope. They are composed of rocks which occur far up the valley of Homestake Creek and not of the rocks of this ridge. No sections were found which showed any body of drift at this place. The bowlders are deeply weathered and many of them are falling to pieces, and their surfaces long ago lost any distinct glacial markings which they may have had, but their lithological character and topographic position indicate their glacial origin.

Five miles farther up the valley of the Homestake, southeast of Gold Park, there is a cirque opening into the main valley which shows a decided glacial shape, but does not seem to have been occupied by ice during the last epoch. The walls and bottom are covered with talus to a greater extent than are the other cirques of this system, and the moraines of the last ice epoch lie across the mouth of this valley. A possible explanation of the formation of this cirque is that the ice of an older epoch excavated it and gave it its shape, but that the ice of the last epoch did not accumulate here in sufficient quantity to renew glaciation.

MITCHELL SYSTEM.

The Mitchell system lay in the valley of the creek that joins the Eagle one-fourth mile north of Mitchell. It headed in a single broadly U-shaped cirque from which the ice went down a narrow valley at its lower end. For the upper end of this valley the topography of the map (Pl. I) is so imperfect that only approximate mapping of the glaciated area was practicable. The cirque has two principal heads, one reaching back to the northwest and the other to the southwest. Nowhere in this cirque was the glaciation intense. The valley lacks the gouged-out appearance presented by the troughs of the larger glaciers, and its bottom and sides have quantities of postglacial talus. In the floor are numerous hillocks of rock 50 to 100 feet high, which, although shaped somewhat by the ice, are not strongly moutonné. The upper lift of glaciation around the head of the cirque is difficult to locate on account of the abundant talus. Only an occasional rounded shoulder of rock gives a clue to the height to which the ice reached.

Along the north wall of the valley the line to which the upper edge of the ice reached is in general indefinite, and can for the most part be located only by scattered bowlders. At about the point where the upper limit of glaciation as shown on the map crosses the 10,700-foot contour a draw runs back from the main trough. Across this draw a lateral-moraine ridge 30 feet high was built by the ice. Behind this ridge a small stream was ponded and a marshy flat developed. The moraine on this side of the stream locally takes the form of a broad bench of drift, about 75 yards wide. The upper edge of the glaciated area on the south wall is nowhere more than 200 feet below the crest of the ridge, except near the head of the cirque. The supply of ice seems to have been sufficient to fill the valley brimful on this side. For about 2 miles from the cirque head the ice developed no lateral moraines along the south side of the valley. Its upper limit is marked by scattered bowlders only, and these are often difficult to distinguish, lying as they do among the talus blocks. Where the upper edge of the ice reached the 11,500-foot level, however, there is a slight sag in the crest of the ridge, and the ice crowded over at this place and sent a short tongue down into the valley to the south, making a terminal moraine on the slope. This moraine is of considerable thickness and consists mostly of large bowlders. It has numerous kettles and the topography characteristic of terminal moraines.

Beyond this sag in the ridge the upper border of the glacier followed rather closely the top of the ridge—sometimes pushing a little way over it—to Mitchell. This system, ending in the narrow gorge, has no typical terminal moraine, although the valley bottom at the lower end is covered with drift, which has little of the irregular moraine topography and is apparently of no great depth.

Just beyond the edge of the glacier a very considerable alluvial fan was built out into the valley of Eagle River. It may have been built as an outwash apron from the edge of the Mitchell glacier and have been considerably more extensive formerly than it is at present. The Eagle has now made a cut of about 20 feet into this deposit of gravel, which corresponds in age to the low-terraced gravels observed below the moraines of many of the glacier systems.

GLACIER EAST OF MITCHELL.

Two miles east of Mitchell there is a north-south valley which joins the East Fork of Eagle River. This valley was occupied for 2 miles of its length by a feeble glacier. Its head had an altitude of only 11,700 feet, and the existence of a glacier here was due more to the protected north slope of the valley than to its elevation. The valley is broadly U-shaped, but does not give the impression of very severe glaciation, for the slopes are covered with talus and little bare rock shows. The greater part of the glacial excavation of this area was probably accomplished during the earlier epoch of glaciation, while the glaciers of the last epoch were feeble.

The terminal moraine of this system lies on the slope southeast of Eagle Park and consists of an area of drift with a rough kettle-hollow topography. The deep weathering of some of the morainal material at this place suggests the possibility that some of it may be of older glacial age, although it has not been mapped as such.

CRANE PARK SYSTEM.

The main lobe of this system lay west of Crane Park, although the system was peculiar in having three distinct termini and in occupying the valleys of four separate streams.

SOURCES OF THE ICE.

Source 1.—The northernmost head of the system lay east of Homestake Peak and sent its ice due east. The head of the glacier was double, but the dividing ridge was almost wholly covered by the ice. This double cirque is not well developed. At the head the rock walls are covered with talus and few smooth surfaces of rock appear. There is little bare rock about the lake in the southernmost of the two heads, and the lake basin may or may not have been hollowed out of the rock.

The ice limit on the north side of the valley is often difficult to locate, as it is indicated only by scattered bowlders. In a few of the more favorable topographic locations feeble lateral-moraine ridges appear for short distances. At the lower end of this lobe the topographic map (Pl. I) lacks detail and has been disregarded to some extent in mapping the position of the moraines.

As seen from below, the terminal moraine of this lobe appears as a great dam or plug across the valley. The outer border is crenate and consists of three lobes, as though the ice edge had reentrant angles. The terminal moraine is of the extreme hummock-kettle variety. Bowlders up to 15 feet in diameter abound on the surface. Within the terminal moraine proper the heavy-drift area extends up the valley for some distance, and though lacking the very irregular topography of the terminal moraine the material is the same. Some undrained depressions occur, but in general the relief is mild.

Source 2 is a much more pronounced cirque. Its side and head walls are steep and fairly free from talus, and in many places the bed rock shows smoothed and striated surfaces. Two spurs running down into the valley from the northwest head wall divide the cirque into three lobes, but the ice was continuous over these spurs, which were worn by it. The cirque bed is free from talus and drift, and the rock floor is smoothed and moutonné. The lakes mapped have rock basins.

Between sources 1 and 2 there is a well-defined interlobate moraine ridge, 30 to 50 feet high, which marks the line of junction of the ice lobes from the two cirques. Below the end of this ridge there is nothing to indicate whether or not ice from source 2 went down to help make the terminus below source 1, but no large percentage of the ice from source 2 got into the other cirque, as its own outlet is lower. The ridge west of Tennessee Pass served as a wedge to keep the ice of the two lobes separate. On this ridge the ice rose almost to the top, but was not quite able to cover it.[a] The ice south of this dividing ridge swung down to the valley and formed a perfect lateral-moraine ridge, 30 to 60 feet high, having an almost unbroken crest down to the point where it merges into the terminal moraine.

The terminal moraine is strongly developed. As seen from below, it rises from the flat in a steep wall, 100 to 150 feet high, with the crest still higher. The sky line is not like that of a lateral moraine, being much more broken. Within this outer wall is a broad area of the most typical terminal moraine. The topography is very irregular, hillocks and kettles occurring in great confusion. Many of the depressions still contain ponds, while others have been silted up to form marshes. The moraine surface is covered with bowlders, most of them less than 6 feet in diameter.

On the south side of this lobe the moraine ends in much the same way as on the east, the drift having more of the characteristics of a terminal than of a lateral moraine. It has an outer crest which presents not the unbroken lines of a lateral moraine but rather the topography of a terminal moraine. The south edge of this lobe in the light-drift area lies along the ridge which separates it from source 4 and reaches almost to the top of this ridge. The wall is not free from talus, and the limit reached by the ice can be determined principally from the rounded cross section of the valley below this line.

Source 3 has a fan-shaped head, and falls short of symmetrical development as a cirque in that the head is divided into five subdivisions by spurs which run down from the west wall to the valley

[a] The topographic map is inaccurate at this place.

bottom. The valley contains considerable talus and drift, and the gneissic rock has failed to hold striæ or polishing. Scattered blocks, 15 feet in diameter, occur. The upper limit of the heavy-drift area is fairly well defined here. The heavy drift appears as a mound in the center of the trough, and from the head of this mound the heavy-drift line swings down to the valley sides to the north and south.

Source 4 is intimately connected with source 3, in that it receives part of its ice from the head of 3. The col at the head of source 4 is much lower than the map shows, and ice came down both valleys from 3. The symmetry of this valley is destroyed by a spur which runs down into the cirque from the northwest side. The slopes have a good deal of talus and little bed rock appears on the floor, except at the very head.

The lower half of this cirque shows the characteristics of a typical glaciated valley much better than the upper half. The lateral-moraine ridges on either side of the valley are well formed and in places rise 400 feet above the valley between. The north lateral moraine has a rather broad crest and not much of an outer slope, and lies as a great bench of drift against the rock wall. The south lateral moraine has a better defined crest.

At the lower end of the system the lateral moraines flatten out into a feeble terminal moraine. This lobe, unlike the one just to the north, deposited no great amount of material as terminal moraine.

OLDER DRIFT.

That the area of this system was occupied by ice of the older epoch of glaciation is shown by an occurrence of older drift 2 miles southwest of Mitchell, between the two forks of the stream. (The north fork is not shown on the map, Pl. I.) This older drift area extends for three-fourths of a mile below the edge of the new terminal moraine. There is evidently a considerable body of drift here, although no sections were found to show its depth. Bowlders up to 6 feet in diameter are scattered over the surface. The materials are much oxidized and more deeply decayed than those of the last drift, and many of the bowlders are falling to pieces. Although many bowlders show subangular forms, no certain striæ were found. The surface here has an erosion topography, and all signs of kettles or of a ridge form have been removed. The new drift comes down to, and probably overlies, the older drift, and may cover a considerable part of the whole area of older drift.

LAKE FORK SYSTEM.

This system of glaciers extended from the crest of the range to Arkansas River. Ice gathered in eleven cirques and united to form a single lobe in the valley of Lake Fork.

A. ROCK SURFACE IN CIRQUE 1.

Although glaciated, the loose material was not all removed, and the preglacial decay was probably very deep.

B. BOWLDERS IN HEAVY-DRIFT AREA ABOVE BUSK.

SOURCES OF THE ICE.

Source 1 is a well-developed cirque with head walls rising almost perpendicular 1,000 feet above the cirque floor. Much talus and some drift bowlders occur in the valley, but in many places the walls are so steep as to be free from loose material. The rock walls are striated and polished in numerous places, and all projections are rounded. At the base of the head wall a rather large lake lies in a rock basin.

Sources 1 and 2 are separated from each other for only a short distance at their heads. At an elevation of about 12,300 feet the ice covered the dividing ridge, and a little lower the cirques join. This ridge was severely worn and shows striæ pointing obliquely down into the valley of each of the cirques.

Source 2 is much like 1 in character. It has even steeper walls, which on the northwest side rise almost vertically for 1,200 feet. The cirque as a whole is well cleaned out, though some postglacial talus has collected below the cliff-like walls. The smoothed bed rock shows at many places on the lower rock slopes. At the foot of the spur which divides source 1 from 2 there is a patch of heavy drift (Pl. II, *B*). It occurs just where an interlobate moraine would be likely to form, and may have been deposited in this way, though it does not take the form of a ridge. Bowlders 15 feet in diameter are not uncommon in this area. Along the southeast wall of source 1 the ice limit is definite for only about a mile from the cirque head. Beyond this, to the point where the cirque joins the main valley, the line to which the ice reached is more or less indistinct, and is marked chiefly by scattered bowlders, although the drift is nowhere of any considerable thickness. Shallow cuts along the railroad show repeatedly that the surface of the rock is deeply weathered and that all the loose material was not removed by the ice of the last epoch (Pl. II, *A*.) The glaciation here could not have been very severe, else this rotten material would have been removed.

On the northwest side of the cirque the limit of glaciation is much more distinct. The walls below, however, are much the same in character as those on the opposite side, since cuts show the arkose and rotten rock at the surface. On this rock wall one-half mile above its junction with source 3 there is an isolated patch of heavy drift high on the valley side. This is probably a coating of only moderate thickness over the rock below.

Source 3 was a broad, rather shallow reservoir of ice. Although the steep head wall would indicate glaciation of some intensity at that place, the imperfectly cleaned-out and shallow lower part of the basin does not strengthen this impression. Considerable postglacial talus has accumulated at the base of the cliffs. The lower end of the cirque was not cut down to the level of the main valley, but is hanging with its mouth 300 feet above the floor of the main valley. A small patch of heavy drift occurs at the mouth of this cirque, which was probably deposited as a recessional moraine of the retreating ice.

Sources 4, 5, 6, and *7*, although differing considerably in shape, have the same general characteristics. These cirques, with steep head and side walls, were all strongly glaciated. The gneissic rock, however, weathers readily, and all smooth and polished surfaces have been removed. Large quantities of talus everywhere bury the base of the cliffs and extend out into the cirques, which give the impression of having been severely glaciated a long time ago.

Source 8 is a well-developed cirque. It is U-shaped, and the bottom is free from loose material as far down as the heavy-drift line. The walls at the head and sides show the bed rock everywhere and still bear traces of glacial smoothing, though for the most part the outcrops have been somewhat roughened by postglacial weathering. The ridge between sources 8 and 9 is almost covered with heavy drift and forms an interlobate moraine here. On the side of this ridge toward source 9 the drift has a maximum slope of 35°. An occasional outcrop of rock shows this ridge to be composed largely of rock, with a somewhat heavy veneer of drift.

Source 9 has a steep head wall, which shows glaciation almost to the top, but has been much roughened by postglacial weathering. The cirque is broad and free from drift and talus as far down as the heavy-drift line, and the impression given is of rather severe glaciation.

Source 10 is broad and not especially well developed. The shoulders of rock along the valley sides are not notably worn, and the side walls, although without much talus, are not strongly glaciated. The low slopes of the side and head walls show that the erosion effect of the ice was not intense. Although the ice reached almost to the top of the col, the divide is flat topped, and shows no tendency to take the sharp-toothed form seen at the heads of many deeply cut cirques.

Source 11 consists of two shallow, parallel gulches, which were filled by a single ice lobe. The west wall of this cirque is very steep and has been cut back almost to the top of the peak. The cirque as a whole is broad and shallow, and the ice against the west wall was much higher than on the east side. At their upper ends the two parallel cirques are strongly glaciated, but accumulations of talus have obscured most of the rock surface, and the upper limit of glaciation can not be determined closely.

HEAVY-DRIFT AREA.

The heavy drift in this system occurs in irregular patches. In the trough of North Fork one patch begins just above the junction of the streams from sources 6 and 7, and continues in the valley bottom for

2 miles downstream, beyond which it is continuous with a body of drift lying on the north wall. The west end of this drift area is remarkable for the large number of bowlders on its surface, many of them 20 to 30 feet in diameter. Below sources 10 and 11 the drift lies on the north wall as a sheet of varying thickness. The surface, as a rule, is thickly scattered with bowlders, and occasional undrained depressions occur. Another patch of heavy drift occurs on the south side of Lake Fork, at the junction of the North and South forks of the main stream, and extends up the valley side about 600 feet at the curve of the railroad. The drift is of varying thickness. Along the railroad cuts show it to be thin over the rotten and deeply weathered granite beneath, and this condition seems to hold wherever the drift occurs on the steep rock slopes. Between the curve of the railroad and the main stream the slope of the valley side becomes less, and here the drift is apparently much thicker and has the characteristic drift topography which is independent of that of the underlying rock surface.

MORAINES.

Below the junction of North and South forks the trough bottom has a flat one-fourth to one-half mile wide. The rock walls on either side are unlike the walls of most recently glaciated valleys. All outcrops show the rock to be deeply weathered and rotten, and numerous prospect holes show this to be the condition for a score of feet below the surface. This indicates either that the ice of the last epoch did not severely erode the walls of its gorge at this place or that the decay was very deep, for the ice would have removed any superficial layer of decayed rock. This weathering must have taken much more time than has elapsed since the last glacial epoch. Therefore, either the U shape of the trough must be due to the erosion of ice of an earlier epoch or the preglacial weathering of the rock here must have extended to a greater depth than that to which the ice eroded its valley wall at this place. The latter is probably the proper explanation of the weathered condition of the rock. This condition is confined to a limited area in this system of glaciation, and is probably due to some local cause of decay. Two and one-half miles below the junction of North and South forks there is a kamelike dam, one-fourth to one-half mile wide, which extends across the gulch bottom. The material here consists of gravels 2 inches and less in diameter, which were formed of such granitic rocks as the stream is handling at present. This area has a weak morainic topography, with shallow kettles, and may have been formed, during the retreat of the ice, behind a huge block of ice left across the valley below this area. Behind this kamelike dam there is a lake flat, which was probably formed while the stream was cutting an outlet through this obstruction. At the foot of the mountains the ice was confined by the narrow valley to a width of about a mile. As it escaped the gorge it deployed in a great piedmont lobe more than 3 miles wide. Here the ice built a terminal moraine in the form of a huge crescent. This moraine rises abruptly from the flat, the top being 100 to 200 feet above the plain. The drift here has the characteristic terminal-moraine topography, although the relief for the most part is slight, the hummocks rarely rising more than 15 to 20 feet above the adjacent kettles. In keeping with the weathered and decayed condition of the surface rock in the valleys above, the materials of the terminal moraine are remarkably old in appearance. Only an occasional fresh-looking bowlder appears, and most of the few bowlders on the surface are old and rotten. So far as the materials are concerned, the drift looks like that of the earlier epoch, but the topography is undoubtedly that of the last glacial epoch. On either side of the valley, where the moraines swing away from the rock walls the drift takes the form of a well-defined lateral-moraine ridge with a crest 100 to 200 feet high. These ridges become lower away from the mountains, and gradually flatten out and merge into the terminal moraine.

Lake Fork has its outlet through the terminal moraine to the south. At this place the stream has a cut about 30 feet deep. Above this cut a broad flat formerly extended up the valley about 2 miles and was evidently once a lake. A dam about 30 feet high has now been built across this stream cut and a reservoir formed, which probably occupies about the same area as the former lake. The cut in the drift from which the material for the dam was taken shows the terminal moraine to be composed mostly of fine materials, most of the bowlders being deeply decayed. Lenses of sand occur in the drift, and the disturbed lines of stratification show plainly.

HIGH TERRACES.

There can be little doubt that at the end of the earlier epoch of glaciation there were high-terrace gravels deposited in connection with the older moraines of the Lake Fork system. These gravels, however, were for the most part removed in interglacial time by Arkansas River, although it is possible that the last glacier of this system advanced over some of these old gravels and covered them with newer drift or incorporated them into the new deposits. The old and weathered appearance of the materials of the Lake Fork terminal moraine may be in part due to the presence of much old high-terrace material.

LOW TERRACES.

During the last ice advance Lake Fork flowed south from the ice edge and entered a considerable flat, cut in interglacial times into the high-terrace gravels. In this flat the stream deposited gravels which are related to the last epoch of glaciation and to the latest moraines in the same way that the high-terrace gravels of the Arkansas Valley are related to the older ice epoch and older drift. They are imperfectly stratified and are of fresh, unoxidized appearance, and in erosion are as little touched as the last moraines. Lake Fork has cut a postglacial channel into these gravels, which is only a few feet deep at the southern end of their area, but is 15 to 20 feet deep where the gravels join the Lake Fork moraines. The gravels have the slopes of an alluvial fan, its focus at the stream cut in the moraines, and they slope to the south and southeast with a gradient of 3° at the upper end to 2° at the lower.

CLIFF GLACIER NORTHWEST OF SODA SPRINGS.

About 2 miles northwest of Soda Springs there is evidence of the former existence of a small cliff glacier of the last epoch. This glacier had its origin at about 11,900 feet and sent a narrow tongue of ice three-fourths of a mile down the valley. At its lower end a plug of drift lies across the valley.

EVERGREEN LAKES SYSTEM.

The ice of this system had the characteristics of a small ice cap rather than a valley glacier, for it occupied an area on the mountain side 2 to 4 miles wide, and was not limited to any single valley,[a] but moved down the mountain in a broad sheet, covering ridges and valleys. Nevertheless, it had several distinct sources.

SOURCES OF THE ICE.

Source 1 has very steep walls at its head, but the rock is almost everywhere covered with postglacial talus. Though moutonné outcrops appear, the rock surface is generally concealed by drift. The cirque is broadly U-shaped, and the glaciation must have been strong to give it its present shape. The side walls of the cirque head are steep, and contain little loose material. All shoulders and projections of rock have been well rounded, although few of the glacially smoothed surfaces have withstood the postglacial weathering. The ice limit is not particularly well defined, but can be approximately determined by the absence of rough outcrops and the somewhat steeper slopes of the walls below the upper ice limit.

Source 2 is a broadly U-shaped, shallow valley. The slopes are for the most part covered with talus, and little bare rock appears at the

[a] The topography as shown on the map differs essentially from the actual topography of the region. The stream which the maps shows as running into the Evergreen Lakes from cirque 4 is not in existence, and the stream which drains valley 4 is a tributary of the main stream in the valley of cirque 1. At the point where a steep ridge is shown to separate the valleys of these two cirques there is no ridge.

surface. The glaciation here was comparatively feeble, for the valley is free from heavy drift for only a short distance from the head. Along the ridge which separates this cirque from source 1 the rock wall is very steep. Below this cliff long tongues of talus run out into the valley. The talus blocks are angular and large, blocks 8 to 10 feet in diameter being common. These tongues of talus have probably been carried to their present position by landslides or by avalanches from the steep slopes above. At the point where this cirque joins the main valley there is a considerable plug of heavy drift across its lower end. This has the typical terminal-moraine topography, and the kettles often contain small ponds. Behind the drift dam is a small lake surrounded by a considerable flat. This drift plug was deposited when the ice in this cirque had retreated and severed its connection with the main ice lobe, the drift being dumped just outside the edge of the larger glacier.

Between sources 2 and 3 there is an interlobate-moraine ridge one-half mile long, which lies on the top of the dividing rock ridge. It has a crest about 60 feet high at the upper end, and gradually becomes lower down the valley, where it loses its ridge form.

Source 3 gives the impression of having been only feebly glaciated. The considerable thickness which the ice had here may have been due to the fact that the ice of the main valley stood high across the outlet of this cirque, rather than to any great thickness of moving ice in the cirque itself. The valley is not deeply excavated, and the walls and bottom are not severely eroded. Heaps of talus cover most of the rock surface.

About a mile below the head of this cirque, on its east side, a lateral-moraine ridge swings out from the rock nose and lies along the valley side. At its upper end it has an outer slope 80 feet high. The material is old in appearance, owing to the fact that the cirque above was not deeply eroded. Bowlders 4 feet in diameter are uncommon. This lateral moraine is composed of a number of minor ridges or benches, all running parallel to the outer edge of the moraine. Near its upper end it crosses and obstructs a large draw in which a considerable flat has since developed. The drift dam stands up above this flat from 5 to 30 feet in a well-defined ridge. Below this flat the lateral moraine lies along the rock valley wall, with only a low ridge crest, for about a mile, and then descends to the valley floor and flattens out to merge into the terminal moraine.

Source 4 is broad, but was not deeply eroded. It slopes with a somewhat continuous gradient almost up to the head, instead of having steep head walls and a low gradient for the valley floor. Here the erosive action of the ice was distributed over a wide floor, and the glacial deepening was consequently much less than it would have been if the ice had been concentrated in a narrow valley bottom. The walls and bottom of this cirque basin are completely covered with talus, which everywhere obscures the rock below.

On the south side, just below the peak of Mount Massive, the topography of the talus is due to avalanches or landslides. The talus lies in curved ridges, the convex side toward the cirque wall. The ice limit on these talus-covered walls can be only approximately mapped, as there is no difference in the appearance of the walls below and above the line to which the ice must have filled the valley. Farther down the valley the ice is spread out on the flank of the mountain and was not confined to any single drainage line. Here the erosive power of the ice was not great and a body of heavy drift lies far up the mountain side.

The south wall of the cirque is steep and no heavy drift lies upon it, but the drift covers the valley floor to within little more than a mile of the mountain peaks. This heavy drift has often a humpty-dumpty topography, and many little ponds are scattered over it. Large fresh bowlders lie scattered everywhere, and the drift has considerable relief, indicating some thickness.

From the point where the ice limit crosses the ridge between sources 1 and 4 a recessional moraine crosses the valley in a great curve to the southeast. This moraine has a low but well-defined ridge and must have been made late in the history of the glacier.

Source 5 heads in the east side of Mount Massive and its top reaches an elevation of 13,700 feet. Notwithstanding the altitude of its head and the absence of close competition from parallel valleys, the glaciation was not at all strong. The cirque is narrow and not conspicuously U-shaped, and the upper limit of glaciation is nowhere more than 300 or 400 feet above the valley bottom. The walls at the very head are steep, but no glacially smoothed outcrops occur. The ice limit in the upper end could be determined only from the shape of the valley. The valley floor is covered with talus and bowlders to its upper end. Hard, fresh bowlders are rather uncommon in this valley, as is often the case where the ice action was of only moderate intensity.

HEAVY-DRIFT AREA.

In the lower part of this valley there is everywhere a considerable quantity of drift, but the topography is largely that of the underlying rock, and few kettles and hummocks appear. Between the Evergreen Lakes and the upper edge of the heavy-drift area there is a great stretch of mountain side which is covered deeply with drift. This drift sometimes occurs as distinct ridges, but over most of the area there is a confused succession of hummocks and kettle ponds. Bowlders, often 15 to 20 feet in diameter, lie scattered over the irregular surface, which shows almost no trace of postglacial erosion.

A cut of a few feet through the loose drift would drain many of these ponds, yet even this much erosion has rarely taken place. Even the surfaces of many of the bowlders are free from lichens and moss. The new appearance of the material of this drift is in striking contrast to the material of the Lake Fork moraines. (See pp. 43–44.)

TERMINAL MORAINE.

The terminal moraine rises sharply from the plain just east of the Evergreen Lakes. It has no uniform crest line, but rises in a series of irregular hummocks. The Evergreen Lakes themselves are kettles filled with water, and the whole area around them is of the strongest terminal-moraine type. South of the Evergreen Lakes the outer edge of the terminal moraine swings back to the southwest as far as the base of the mountains. Here it swings south at a sharp angle, where the ice from source 5 reached just below the base of the mountains. South of source 5 the ice limit can be determined only by the presence of scattered bowlders and the lack of unglaciated outcrops back to the point where it lies along the talus-covered slopes of the valley wall.

SYSTEM NORTH OF HALF MOON CREEK.

Between source 5 of the Evergreen Lakes system and Half Moon Creek there was a small body of glacier ice which occupied the parallel valleys of two small streams. In the northernmost of these valleys the ice movement started at an elevation of 12,000 feet, but in the valley south of this it had an altitude of 12,500 feet. Both of these valleys are broad and not very steep, so the ice action was not strong except at the very heads. Neither cirque is deeply eroded, and drift and talus cover the valley floors throughout their entire length.

On the south side of this system the ice edge lay along the rock wall for most of its length. Toward its lower end a lateral moraine ridge 20 to 30 feet high was formed. This swings away from the valley side in a northeast direction and grades into the terminal moraine. The terminal moraine of the south valley was built on the lower edge of the mountain slope, its lower edge reaching almost to the plain beyond. From this plain the drift rises steeply to a bench which corresponds to the crest, and then slopes up toward the mountains with a more gradual slope. In the northernmost valley the terminal moraine is not so well marked. It crosses a rock ridge in a reentrant loop at about the 11,100-foot level and then runs north with a distinct crest. This crest then curves to the west and the ice limit lay along the side of the rock ridge which separated it from the Evergreen Lakes system. Within, the terminal moraine is of slight relief and not very irregular. In the south valley a recessional moraine ridge 15 to 30 feet high lies within and parallel to the outer ridge, one-fourth mile above it. Although the drift everywhere covers the rock, it is probably rather thin over most of the area, and its topography is due, in its larger features, to the underlying rock.

HALF MOON CREEK SYSTEM.

This system occupied the valley of Half Moon Creek from its head to a point well out upon the piedmont plain. It headed in three fan-shaped cirques which brought ice from the west of the high ridge of which Mounts Massive and Elbert are the peaks, and received no ice at all from the east slopes of these ridges.

SOURCES OF THE ICE.

Source 1 took the ice from the west slope of the Mount Massive ridge and from the east slope of the next ridge to the west. Its fan-shaped valley consists of the valleys of eight minor streams, which join at the apex of the fan. The rock of the walls of this cirque is a banded gneiss. The walls are very steep, and are almost everywhere covered by great accumulations of talus, with slopes of 35° to 40°. The abundance of talus here is due to the easy weathering of the rock. This would also account for the absence of smoothed and rounded outcrops. The talus-covered walls show no distinct marks of glaciation and the ice limit could be determined only approximately. The bottom of the valley is free from loose material, and the signs of glacial action are here well preserved, for the rock is everywhere rounded and smoothed. The ice and snow, lying longest in the cirque bottom, would protect it from weathering for some time after the walls had been exposed. The basins of the three lakes in the north end of this cirque are in rock. From the highest of these lakes the valley floor descends in a series of steps, on which the lakes occur.

Directly north of the uppermost lake is a broad shallow area which is not glaciated but which shows evidences of glaciation. With this exception the head wall of this cirque ends at its upper edge in a series of sharp needles, where the ice from opposite sides of the ridge has excavated the cirque heads back to the divide, lowering the divide an unknown amount.

At the mouth of this fan-shaped cirque, at the point where it joins the main valley, lies a narrow deposit of heavy drift, occupying the valley bottom. This must have been left by the ice during its retreat, for this would naturally be the point of severest glaciation, as the narrow valley here greatly concentrated the ice from a wide head.

Source 2 has many of the characteristics of source 1 and is separated from it only by a narrow ridge. The rock valley wall on the north, however, is comparatively free from talus and shows the effect of ice erosion. The rock of this wall is banded gneiss, and while the bands are much contorted they are somewhat persistent, and the general dip is about 20° to the northwest. The valley at the upper end is free from talus, and all projections of rock are moutonné. This source is divided into five minor subdivisions. Over the four to the west the ice was continuous and the ridges between are rounded and moutonné. The fifth valley, entering from the south, is separated from the others by a high, craggy ridge, over which the ice did not pass. At the lower end of it there is, as in source 1, a plug of heavy drift, which must have been left as a recessional moraine. This plug is about 200 feet high against the south valley wall, and slopes down to the valley floor on the north. It has an irregular surface containing a few shallow depressions and is strewn with bowlders.

Source 3 consists of the basin of Elbert Creek, in which the ice moved almost directly north to the main valley. At the lower end of this cirque the valley walls are glaciated only one-third of the way up the slope, so the valley could never have been nearly full of ice. Below the upper limit of the ice the ends of the spurs from the Mount Elbert ridge have been truncated and the valley is U-shaped. The walls of this valley, even where it has been glaciated, are weathered considerably, so that none of the original glaciated surfaces remains. The rock surface is everywhere covered with talus, and the shape of the valley gives the only clue to the height reached by the ice. Near the head of Elbert Creek the valley is somewhat broader and the head walls rise in a steep, unbroken slope to the crest of the ridge. This head wall is covered with talus, and the upper limit of the ice could be determined at points only.

The west wall of the cirque is broken into a number of minor valleys, and the upper limit of the ice is an irregular line much obscured by talus, but determinable at many points by rounded shoulders or truncated spurs. At the lower end of this cirque, as of heads 1 and 2, there is a drift plug in the valley. It dams up the mouth of the cirque to a considerable height, and the stream has a steep gradient on the outside of this plug.

MAIN VALLEY.

The main valley, below the junction of these three heads, has a broad U shape, but is not altogether free from loose material. Even in the light-drift area there is considerable drift in patches. On the north valley wall the upper limit of glaciation is very indistinct. On the south wall the glaciation was more intense and the ice was higher than on the north side. This may have been caused by the north wall receiving more heat from the sun and thus keeping the ice melted back. A series of truncated rock spurs gives a definite line to which the ice reached. In the main valley, below the junction of the three heads, the ice was from 600 to 800 feet deep, and to this height has widened the valley and given it a U-shaped cross section. For the development of such a trough from the V shape, which the unglaciated valleys of this region have, the removal of a great quantity of material was necessary, and much of this material is now to be found in the moraines and terrace deposits.

MORAINES.

One mile southeast of the junction of Elbert and Half Moon creeks a distinct lateral-moraine ridge leaves the rock wall and runs parallel with the valley for about a mile, but with its crest 200 feet below the upper limit of the ice as it appears on the rock wall above. This is plainly a lateral moraine of a recessional stage of the glacier, and between this ridge and the stream the valley floor has a covering of heavy drift.

Three miles above the terminus of this system, on the north side of the valley, a great lateral-moraine ridge leaves the rock spur which forms the valley wall above it and continues for 3 miles to the northeast with an unbroken, evenly descending crest. The ridge at its highest point is 500 feet above Half Moon Creek, and on the outside is 150 feet above the plain. Bowlders are scattered over it, and upon its very crest are basins. This ridge becomes lower and lower downstream, and is only 20 to 30 feet high where the stream cuts through it.

The south lateral moraine is smaller than the ridge shown on the map. By aneroid its crest is 700 feet high on the stream side, though only 60 to 70 feet above the surface outside. The ridge is even crested and almost unbroken, and in places has an inner slope of 25°. A little below the place where this ridge leaves the valley wall a small stream has made a postglacial cut 15 or 20 feet deep in the side of the ridge and a shallow notch in the crest, which is otherwise unbroken.

At their lower ends these two great lateral moraines flatten out and converge, forming a belt of terminal moraine of slight relief. Some undrained depressions occur, but the glacier has left a smaller deposit of terminal moraine than would have been expected from a glacier of this size. The ice, by building up the great lateral-moraine ridges on either side, confined itself to a narrow valley, and the result was much the same as if the glacier had ended in a narrow canyon. The narrow depositing end of the glacier dumped its material in the narrow valley, and this material was carried away by the abundant glacial waters about as fast as it was deposited.

HEAVY DRIFT AND TERRACES.

The heavy drift, within the moraines, has a somewhat irregular topography. It is unevenly distributed, in some places filling the valley to a considerable depth, while at other places the stream has developed a good flat in the drift.

Locally, patches of stratified gravel make terraces, doubtless deposited in advance of the retreating ice edge as a valley train.

OLDER DRIFT.

Southeast of the south lateral moraine of this system, and bordering it, is an area of glacial drift left by the ice of the earlier epoch of glaciation. This drift has been cut by gullies into a number of spurs which slope from the new moraine ridge down toward the east. The material of these spurs is older than that of the new moraines, and its topography is certainly an erosion topography, valleys of considerable size having been cut into it. On its surface are bowlders up to 3 or 4 feet in diameter, some of which have smoothed, subangular surfaces which look extremely like those of glaciated stones. On some of these there are indefinite markings which look like striæ, but no unequivocal striæ were found. The topographic position of this material and its physical characteristics point strongly to its glacial origin.

HIGH TERRACES.

Below the area of older drift connected with the Half Moon Creek system of glaciation and extending eastward from it to Arkansas River is a fan-shaped area of high-terrace gravels. This fan is about as broad as it is long, and although it has been considerably cut by erosion, the remnants of the old summit lie in a common plane which has a slope upward toward the mountains of about 2° at the valley edge and about 3½° at the mountain edge. Few good sections in these terraces were found. The material, however, is gravel, the stones being sometimes almost a foot in diameter at the upper edge of the terrace, but grading down to cobbles and still smaller gravels at the lower edge. The gravels of this terrace are much older in appearance than the materials of the new drift. Few surface stones have withstood the weathering, and those that remain are often so decayed as to crumble beneath the hammer. So far as is known, these terraces are formed of loose, uncemented material. For the development of the plain of which they are remnants there must have been a great amount of detritus supplied to the streams. In following these terraces to their upper edge we get a clue as to the source of this material, for the terraces appear to be built out from the moraines of the older epoch of glaciation. During this epoch great quantities of material must have been supplied to the extraglacial streams. These streams, depositing their materials on the flat beyond the edges of the moraine, built up a great outwash plain, of which these terraces are the remnants. The terrace materials correspond closely in age and appearance with the older drift. In degree of erosion, in oxidation of materials, and in the decay of the bowlders the two agree closely. Another fact which fits well with the theory of fluvial origin is that the slopes of these terraces are not always in the same direction, but the slope is everywhere toward the periphery of the alluvial fan. This would be very unusual if the deposits were laid down in a lake bed, but is the normal way in which the gravels from a fan-building stream are deposited. At the end of the earlier glacial period, when the streams ceased to build up their channels and began to cut away the deposits which they had already laid down, Half Moon Creek had its course along the northwest edge of its fan. Here it intrenched itself, and before the last ice advance had cut a broad flat into its old alluvial deposits. When the last glacier moved down the Half Moon Valley it was walled in on the east by this great gravel deposit and by the moraines of the older glacier, and was forced to turn to the north along the interglacial gorge which the stream had cut into the older moraines and the outwash plain.

LOW TERRACES.

In the valley of Half Moon Creek, beyond the terminal moraines of the last glacial epoch, are deposits of gravels which bear the same relations to the last moraines that the high terraces bear to the older moraines. These low terraces have their best development in the Half Moon Creek valley because it is here that interglacial erosion had made the greatest inroads into the high-terrace gravels and had developed a considerable flat. In this flat conditions were favorable for the deposition of the low-terrace gravels. These gravels form an alluvial fan of low slope, with the apex at the sag in the terminal moraine through which Half Moon Creek flows. From this cut the gravel deposits slope away from the moraines in a great cone, the average slope being $1\frac{1}{2}°$ to $2°$. The top of this terrace plain is some 200 feet below the level of the high terraces immediately south. In physical condition as well as in topographic position these gravels are related to the ice of the last epoch. The materials are not at all oxidized, and the surface shows little erosion.

The glacier waters of the last epoch, with their burden of sediment, poured from the gap in the moraine onto a comparatively flat plain, where the material was deposited, with the slopes of a low alluvial fan.

Since the retreat of the ice the stream, less heavily loaded than before, has begun to deepen its channel in the steeper portion of its course. It has now cut its bed some 20 feet into these gravels at the top of the slope, but at the lower edge the stream meanders along with its bed only 3 or 4 feet below the surface of the terraces.

CLIFF GLACIER SOUTH OF HALF MOON CREEK.

Between Half Moon and Lake creeks there was a small cliff glacier which headed on the northeast side of Mount Elbert. This glacier was about a mile long and one-third of a mile wide. Its erosion was feeble, as it only slightly modified the upper end of its valley. At its lower end is a terminal moraine of coarse, angular blocks. The ice from this glacier did not descend much below 11,000 feet during the last epoch of glaciation, though there is evidence that it descended considerably farther at some earlier stage.

LAKE CREEK SYSTEM.

This system lay in the valley of Lake Creek and the Twin Lakes. It was the largest and longest system west of Arkansas River, having an area of about 80 square miles and a length of about 20 miles. It was fed by about 20 tributary cirques, of which 10 are in the Leadville quadrangle. The ice supplied to this glacier came not only from the east-west valley of Lake Creek; the glacier head was west of the ridge that limited the Half Moon Glacier, and it received ice from the west side of this ridge. The cirques shown on the Leadville sheet are those which join the main east-west valley from the north and from the south.

SOURCES OF THE ICE.

Source 1 took the ice from the east and south slopes of Mount Elbert, where the ice at the head had an altitude of more than 13,000 feet. This source had two subheads, partly separated by a dividing ridge, but the valleys on either side of this ridge have much the same characteristics. They show much bare rock and have only small accumulations of talus. The rock outcrops, however, do not seem to be severely glaciated, but are often more or less angular. These exposed surfaces are very generally covered with mosses and vegetation, and this tends to weaken perhaps unduly the impression of any great severity of glacial erosion. The head walls rise steeply from the valleys with slopes of 25° to 30°. On the ridge between the two heads is a rock hill, which was glaciated all over, but it stands well up above its surroundings and must have been a nunatak at one stage of the glacier's history. Below the mouth of this cirque, beyond the point where the ice was constricted to a narrow neck, the glacier spread, some of it moving to the southeast and some pushing, in a comparatively thin sheet, eastward. This sheet deposited a thick layer of drift, masking the rock topography, and joined the ice in the main valley to the southeast.

Source 2 is a small cirque in which lay a cliff glacier. The supply of ice from this glacier must have been small, for the valley shows little evidence of glacial erosion. A drift plug fills the valley just above the point where the ice from source 1 crosses the valley mouth.

Source 3, often known as Monitor Gulch, is a fairly well-shaped cirque, but was not severely glaciated.[a] The walls and bottom of the cirque are covered with talus and residual material. No considerable areas of bare rock occur, and postglacial weathering has reduced all the outcrops to roughness. In earlier glacial times this glacier may have joined that in the Lake Creek valley, but during the last glacial epoch this cirque sent ice down only a short distance from the cirque head. Below the cirque valley head the gulch becomes narrow and V-shaped.

Source 4, sometimes called Echo Gulch, has much the same characteristics as source 3. It has a cirque at its head, but is V-shaped toward its mouth, and although its ice may have joined the Lake Creek Glacier in the earlier epoch of glaciation, it did not do so during the last epoch. The gulch is broken up by minor ridges into a number of subordinate valleys, so as to destroy the symmetry of the whole. The cirque floor has considerable loose material, and in places the glacial erosion has been so slight as to make the determination of the ice limit difficult.

Source 5, known as Hayden Gulch, is much like sources 3 and 4 in general features. Its U shape has not been well developed, except at the valley head, and the upper limit of glaciation is therefore often indistinct. All outcrops have been weathered to roughness, and this weathering has produced talus sufficient to cover most of the surface. At the point where this valley joins the main trough the evidence of glaciation is so slight that one might pass along the main valley without suspecting the existence of the cirque, although the ice from this valley joined the Lake Creek Glacier. The valley mouth is hanging.

Source 6, or La Plata Gulch, is much more perfectly developed than any of those on the north side of Lake Creek. It has a peculiar, spatulate shape, being very narrow and deep along its lower course, but having a wide head, with a rather flat floor. The head walls are steep and high, and the valley floor at the head has little loose material. Where the ice was restricted to a narrow neck between the cirque walls the glacial erosion was pronounced and the walls were severely glaciated. The rock at the sides and head weathers easily, and there are now considerable accumulations of talus. The ice from this cirque crossed the ridge to join that of source 7 at an elevation of about 12,000 feet.

Source 7, known as La Plata Basin, is a hanging cirque. It has not the typical cirque shape, for it lacks the characteristic flat bottom and steep head and side walls. The ice action here was relatively

[a] Monitor Gulch is the gulch next east of Echo Gulch. The Leadville sheet (base of Pl. 1) shows this area so inaccurately that source 3 on the map occupies only approximately the actual position of Monitor Gulch.

weak and did not excavate the valley to so great an extent as it did in the cirques to the east and west. The cirque contains considerable talus, which covers most of the rock of the walls.

Source 8, or Crystal Lake Gulch, is one of the most perfectly developed cirques of the whole area. Its broad, flat valley and steep head and side walls are typical of intensely glaciated valleys. These walls rise almost perpendicularly for 1,500 feet above the valley floor. Everywhere they are smoothed and rounded, although the polished and striated surfaces have rarely been preserved. The valley is almost free from talus, although some has accumulated at the base of the cliffs. In the upper end of this cirque the rock floor is often bare, and its surface is everywhere rounded and smoothed. In basins scooped out of the solid bed rock are several small lakes.

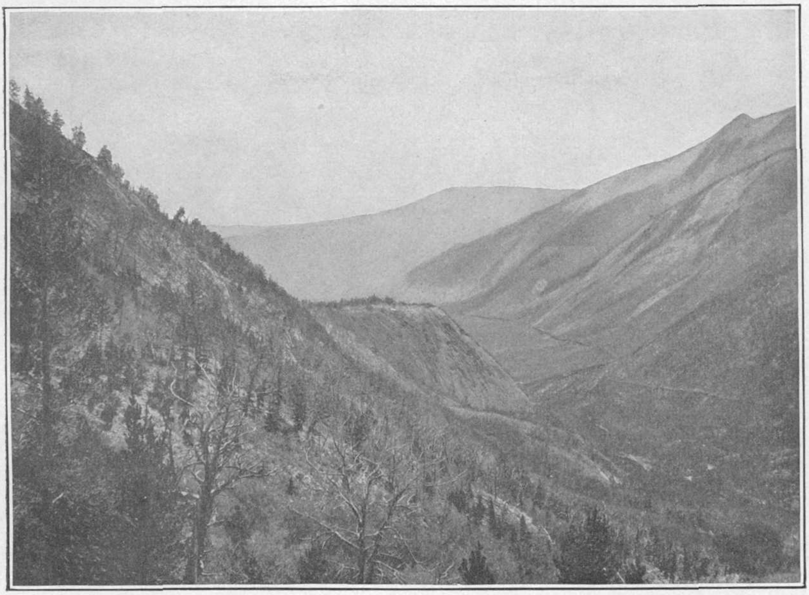
Source 9, or Willis Gulch, has a wide, well-developed upper end, but narrows noticeably toward its junction with cirque 10. This narrowing is probably due to the increased gradient of the valley at this place, the ice moving more rapidly, and consequently failing to fill the valley to so great a depth as in the upper, more sluggish portion.

The upper limit of ice in this cirque could not be determined definitely. Everywhere the valley walls are covered with great quantities of talus, which obscure the rock in situ. This is especially true of the southeast side, where the talus, sliding down into the valley from the cliff above, has accumulated in enormous heaps, which sometimes show a crescentic, landslide ridge form.

Very few outcrops of rock occur in the valley, which is everywhere covered by talus. This talus has sometimes formed into huge "talus glaciers," which have advanced out into the valley from the walls on either side. There is now no lake at the place where one is shown on the map, but about a mile above this place there are two shallow lakes where the stream has been dammed up by rock slides. In the valley bottom at the lower end of the cirque is a body of heavy drift, covering the floor and extending up almost a mile beyond the point where source 10 joins it. This heavy drift varies in thickness and its surface has many bowlders.

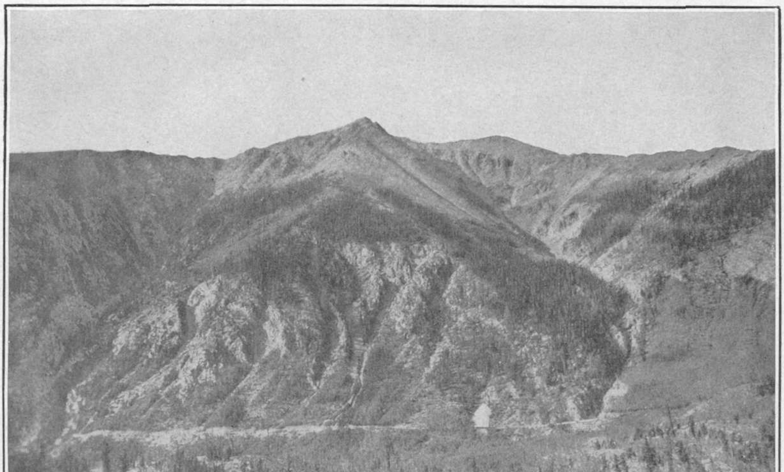
Source 10, or Little Willis Gulch, is narrow and has not been greatly deepened by the erosion of the ice. It is shallow and not well U-shaped, and could not have been subjected to very vigorous glaciation. The walls and bottom are everywhere talus covered, and the upper limit of the ice could be determined only approximately.

Source 11, or Boswell Gulch, is a wide, shallow basin from which some ice moved to join the main glacier, but it is not at all a characteristic cirque. The walls on the west and south are fairly steep, but not very high, while on the east the valley was deepened but little by the ice. The head of the valley is only a little above the altitude



A. LAKE CREEK GORGE AND MONITOR ROCK.

Photograph by Westgate.



B. TRUNCATED SPUR, SHOWING TRIANGULAR FACET, BETWEEN CRYSTAL LAKE AND WILLIS GULCHES.

Photograph by Westgate.

which was necessary for the formation of a glacier, so that the ice action was naturally feeble. Few rock outcrops occur in the valley bottom, and the impression given is of very mild glaciation. Heavy drift extends some distance up this area on its eastern edge, where the drift takes on the form of a low topographic ridge for about three-quarters of a mile.

MAIN VALLEY.

The main valley of Lake Creek, above the mouth of the rock gorge, is typical of a severely glaciated mountain valley. In this great gorge the ice was about 2,000 feet deep. The movement of this enormous body of ice, shod with an abundance of rock fragments, altered fundamentally the preglacial shape of this gorge. The valley cross section was changed from a **V** to a broad **U** shape. All projecting spurs from the valley walls to the north and south were truncated, and the triangular facets which these truncated ridges now present afford an indication of the extent of the glacial erosion (Pl. III, *B*). At the mouth of Monitor Gulch, or source 3, there is a great projection of rock from the valley wall which stands out prominently into the valley (Pl. III, *A*). This projection is known as Monitor Rock. Although it stood up nearly to the upper surface of the glacier, it shows polished surfaces and striæ to its top. This rock is one of the few notable breaks in the otherwise perfectly developed **U** shape of the valley, and owes its preservation to its hardness and its freedom from joints. From the mouth of the Lake Creek Gorge to the edge of the Leadville quadrangle the valley bottom is free from drift, and the rock outcropping in the valley bottom is rounded and moutonné.

HEAVY-DRIFT AREA.

The upper limit of the heavy-drift area of this system runs from the mouth of cirque 1 in a southerly direction and includes all of this system to the east of this line except the upper part of sources 10 and 11. In the western part of this area the heavy drift lies as a thin mask over the rock ridge, and the large features of the topography are doubtless due to the underlying rock. Occasional kettles occur, and everywhere over the surface are scattered numerous bowlders. Of these bowlders the most conspicuous are granites composed of great crystals of feldspar in a gray matrix. The bowlders came from the Sawatch Range, and the parent rock occurs in this range only in the valleys of Lake and Clear creeks. In the eastern part of the area of heavy drift the drift takes on a huge ridge form which rises in places 400 feet above the lakes, and this ridge seems to consist wholly of drift. It has a well-defined, sharp crest for most of its length, the crest being near the outer limit of the new drift, which is built up against older drift. On the outside this crest stands 60 to 80 feet above the old drift and the high terraces. North of the lower lake the inner slope of the lateral moraine shows benches, one above the other, which probably mark halts in the ice during its retreat. In one place four distinct levels are shown.

The lateral-moraine ridge swings in a broad curve to the southeast with a descending crest, which ends rather abruptly. The ice at its maximum extension reached beyond the end of this great lateral moraine and pushed east to Arkansas River, leaving a terminal moraine of slight relief.

On the south side of the valley the heavy drift lies against the valley wall without ridge forms down to the point where the ice edge left the rock wall. Below this point the moraine is a ridge 300 feet above the lake. This ridge swings to the northeast, gradually becoming lower and lower toward the river. It has a rather notched, uneven crest and on the outside stands about 75 to 100 feet above the terraces. Outside of the main ridge are low ridges parallel with it, showing that at some time the ice of the last epoch extended farther south than it did when the larger ridge was built.

The character of the drift on the south side of the valley is much the same as it is throughout the whole heavy-drift area. The surface is everywhere strewn with bowlders ranging up to 15 feet in diameter.

TWIN LAKES.

The glaciation of the last epoch is directly responsible for the formation of the basins which are now occupied by the Twin Lakes. At the time of the farthest advance of the ice in this valley the glacier reached down to Arkansas River and built up the great lateral moraines on either side of its valley. When conditions changed and the ice began to recede its edge did not move backward at a steady, uniform rate, but the retreat consisted of an alternation of recessions and halts. At the halting places the ice edge remained long enough to build crescentic terminal-moraine ridges across its valley. The most conspicuous of these ridges is that which lies to the east of the lower lake, and it is this ridge which has dammed up the basin now occupied by this lake. A second noticeable recessional-moraine ridge is that which separates the two lakes at Interlaken. This was formed in the same way as the ridge below the lower lake, but at a later stage in the retreat of the ice. The lower lake existed while the site of the upper was still covered by the glacier. The upper lake had formerly almost as great an area as the lower, but subsequent silting has reduced its area by more than half and formed an extensive meadow above it.

GLACIAL EROSION.

The valley and tributaries of Lake Creek offer excellent opportunities for the study of glacial erosion and the relations of glaciated tributary valleys to the main valley. The exceptional development of these features has been recognized. L. G. Westgate[a] has given a valuable contribution to the study of glacial erosion in mountain valleys, based upon his studies of this valley and its tributaries, and W. M. Davis[b] has contributed two papers on his observations in this region.

As stated on page 11 the amount of topographic unconformity which a tributary valley has with its main valley is a fair estimate of the amount of glacial deepening which the latter has suffered. This process of deepening of the main valley and leaving the tributaries in unconformity with it is beautifully illustrated by the Lake Creek trough and its tributaries. These features are embodied diagrammatically in figure 5. The trough of Lake Creek above the Twin Lakes is

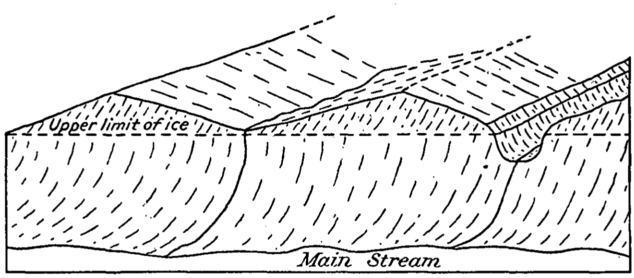


FIGURE 5.—Diagram showing glaciated valley and its relations to a glaciated and an unglaciated tributary. (After Westgate.)

a type of a severely glaciated valley. In cross section it is broadly U-shaped, the walls rising steeply to the line that the ice reached, which is as much as 1,600 feet above the stream. The erosion of the ice in this valley has in most instances entirely truncated the ends of the rock spurs between the tributary gulches (fig. 5). On the north side, on the lower slopes of the Mount Elbert ridge, there are a number of spurs which although rounded and much reduced still project somewhat into the troughlike valley. The fact that they were not entirely removed may be attributed to the superior resisting powers of the rock at these places, perhaps because of the absence of pronounced joints, without which glacial plucking is reduced to a minimum. That glacial plucking was important in the deepening and widening of this valley is shown by the characteristic shape of the rock knobs and moutonnées. The stoss, or upstream, side has usually a gentle

[a] Jour. Geology, vol. 13, 1905, pp. 285–312.
[b] Bull. Mus. Comp. Zool., vol. 49 (Geol. series, vol. 8, No. 1), 1905, pp. 1–11; Appalachia, vol. 10 (No. 4), 1904, pp. 392–404.

slope, while the lee, or downstream, side commonly shows a steplike form where the angular joint blocks have been plucked out (p. 12).

Of all the tributary valleys of this system Crystal Lake Gulch, or source 8, shows best the relations of a glaciated hanging valley to the main gulch. The collecting field for this tributary comprised the slopes of high north-south ridges, of which the highest point, La Plata Peak, reaches an altitude of more than 14,300 feet. With their altitude and favorable north exposure these ridges supplied ice for a strong glacier in this gulch, which now shows a marked **U**-trough development. At its junction with the Lake Creek valley the mouth of this gulch hangs 800 feet above Lake Creek. The postglacial erosion of Crystal Lake Creek has cut only a shallow notch in the bottom of the hanging **U**. On either side of the mouth of Crystal Lake Gulch the ends of the rock ridges have been sharply truncated, and above the upper limit of the ice they show triangular facets, due to glacial undercutting (fig. 5). A diagrammatic cross section of the trough of Lake Creek shows in characteristically developed localities (see fig. 6)

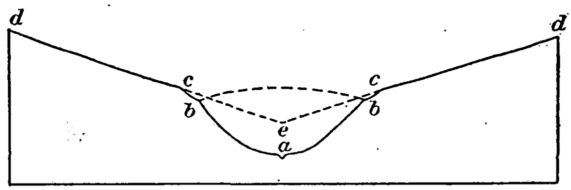


FIGURE 6.—Diagrammatic cross section of trough of Lake Creek. *d, e, d*, Preglacial profile of valley; *b, a, b*, area which suffered from direct glacial erosion; *b, c*, area of indirect glacial erosion by glacial undercutting; *c, b, a, b, c, e*, cross section of material removed, directly and indirectly, by glacial erosion. Horizontal and vertical scale, 1 inch=1 mile.

a **U**-shaped trough, with steep wall to the upper limit of glaciation (*b*, *a*, *b*). Above this the rock slopes are still steep, owing to glacial sapping, but less steep than below (*b*, *c*). Above the slope steepened by undercutting is the still more gentle slope of the unglaciated, normally developed mountain ridge (*c*, *d*). *b*, *b* shows the probable shape of the ice surface at its maximum. *e* is the preglacial position of Lake Creek, and *e a* shows the glacial deepening of the valley. *c*, *e*, *c*, *a*, *c* is the cross section of the mass of rock removed by glacial erosion.

It is not possible to reconstruct accurately the shape of the preglacial valley of Lake Creek from the unglaciated slopes above. However, estimates[a] of the amount of glacial deepening that are well within the limits of probability may be made from the relation of the hanging valleys to the main stream. Figure 7 shows a profile of Crystal Lake Gulch (source 8) and a cross section of the Lake Creek valley, taken from field sketches, photographs, and aneroid

[a] The reasons why such calculations are subject to error have been given on page 12.

measurements. The mouth of this tributary hangs 800 feet above Lake Creek. If we assume that the glacial erosion in the tributary gulch did not lower its valley floor at all, then by continuing the profile *a*, *b* to *c* we have the point at which the preglacial tributary

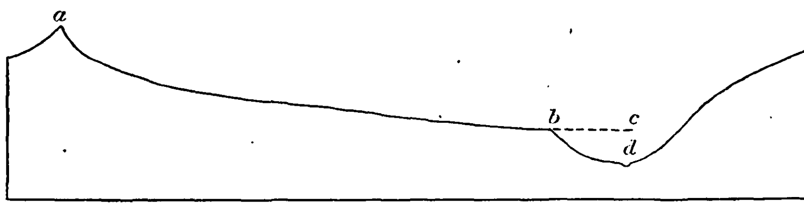


FIGURE 7.—Longitudinal section of Crystal Lake Gulch and cross section of Lake Creek valley. *b*, *c*, Extension of profile *a*, *b* to center of valley; *c*, *d*, glacial deepening of Lake Creek valley if mouth of tributary at *b* was not lowered any by glacial erosion.

would have joined Lake Creek with topographic conformity. *c*, *d* gives the amount of glacial deepening of the Lake Creek valley.

If we assume that the glacial erosion in gulch *a*, *b* lowered the valley bottom 100 feet, we need to add 100 feet to the glacial deepening of the main trough. (See fig. 8.) This estimate is probably conservative, for the smoothed, rounded floor of the tributary valley

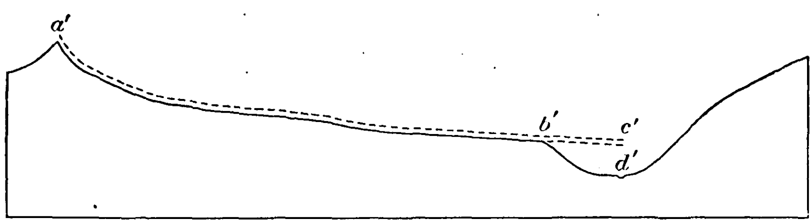


FIGURE 8.—Same section as figure 7. *a′*, *b′*, *c′*, Preglacial valley of tributary stream. Assuming that glacial erosion in tributary valley has lowered valley floor 100 feet, the preglacial mouth of the tributary would have been at *c′*, and *c′*, *d′* would be the glacial deepening in the main valley. Horizontal scale, 1 inch=one-half mile. Vertical scale, 1 inch=one-fourth mile.

shows that the glacial erosion of the rock at this place was a considerable factor.

OLDER DRIFT.

North of the north lateral moraine of this system there is an area of drift of the earlier epoch of glaciation. It is a narrow belt just beyond the outer edge of the new moraine ridge, its length being about 3 miles and its width nowhere more than a few hundred yards. Its topography gives no indications of undrained hollows or hummocks, although at one place it has the form of a low ridge parallel with the outer edge of the new moraine ridge. At the surface are occasional bowlders up to 4 feet in diameter, all deeply weathered and partly buried in the soil. Few sections were available, but one 30 feet deep showed a bowlder clay in which the bowlders were all so decayed as to be readily cut by pick and shovel. The materials were the same as those in the new drift, only more weathered and rotten.

HIGH TERRACES.

Northeast and east of the Twin Lakes moraines there is a set of high terraces which bear the same relations to the older drift of this system of glaciation as the terraces below the Half Moon Creek system bear to the older moraines at that place. These terraces, although much more restricted in area, appear even at first glance to correspond to the terraces a few miles north. On closer inspection the similarity is even more striking. The two groups are obviously in the same stage of erosion. In the size and the weathered and oxidized condition of the gravels they are alike, and the pebbles differ in lithological characters only as would be expected, coming as they do in part from different localities. But the most striking fact bearing on the origin of these terraces is that they, too, occur just outside of older drift, as if built out from it, with only a slight topographic break between. This would seem to be strong evidence that the terraces were built at the same time as the moraines, and as outwash from them.

Between the south lateral moraine of the Twin Lakes system and Cache Creek there is an area—about 4 square miles—of terrace gravels not so high or so striking as those farther north, but probably of about the same age, as is shown by their topography and by the condition of their materials. An excellent section is offered at the placer mines along Cache Creek. About one-half mile west of Granite is a 60-foot section of gravels lying on a granite base. These gravels are mostly under cobble size, though some have a diameter of 4 feet. These materials are not everywhere distinctly stratified, but they are fairly well rounded. Lenses of sand are interstratified with the imperfectly assorted gravels. The materials have not been much oxidized, but most of the pebbles are much decayed, and porphyries of the sort which in the new drift hold striæ are here falling to pieces. The rock surface upon which these gravels lie is deeply decayed and can often be scraped up with a shovel and washed with the other materials. The rock surface dips to the west, suggesting that the main stream of the valley was once considerably west of its present position (fig. 1).

These terraces were built in much the same way as those farther north. The valleys in the mountains to the west were unglaciated, but their streams were probably stimulated to greater cutting and transporting by the abundant waters from the melting snows, and so aided the extra-glacial streams in aggrading this flat. These streams are still building up their alluvial fans on top of the terraces, and the process of fan building may have been somewhat continuous since the earlier glacial epoch (fig. 9).

The plain of this set of terraces is considerably below the level of the high terraces to the north and south. At its eastern edge the plain is broken by a number of gullies which have worked back from Arkansas River and cut deep gulches into the gravel plain. Toward the mountains this plain is unbroken, and the flat-topped ridges between the gulches on the east edge of the area correspond in height so perfectly with one another that there can be little doubt as to the former flat, unbroken character of this area from the Twin Lakes moraine to Cache Creek. Westgate[a] states that these terraces are the erosive remnants of a set of high terraces which were originally in the same plane as the other high terraces to the north and south. If such were the case, it seems improbable that we should get such flat-topped ridges corresponding exactly with one another in level, unless the whole area had been peneplaned in interglacial times, and this seems almost impossible with gravels of such recent origin. The gravels which Westgate mentions, above the level of these terraces, might have come from the slopes east of the Arkansas Valley before the river cut its postglacial channel into the gravel deposits.

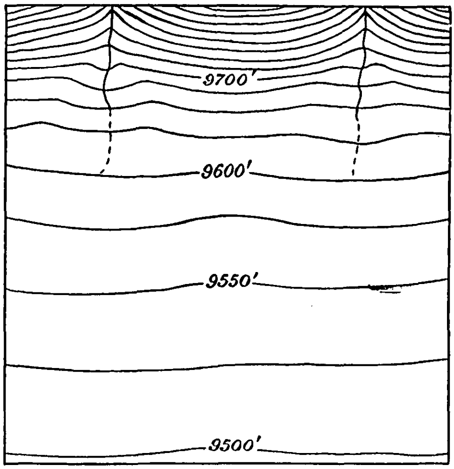


FIGURE 9.—Sketch map of an area, one-half mile square, showing relations of terraces between Lake and Cache creeks to mountain slope and to drainage lines.

LOW TERRACES.

Along the valley of the Arkansas below the Twin Lakes moraines there are a number of low-terrace remnants, all having about the same height above the river and occurring on both sides of it for 4 or 5 miles below the outlet of Lake Creek. These terraces all stand 10 to 30 feet above the river and 100 to 200 feet below the high-terrace level, and are composed of fresh, unoxidized gravels of apparently the same age as the late drift. Although the river has removed all but small patches of these terraces, they are evidently young, for gullies have not begun to work back into them. They were deposited during the last glacial epoch as a valley train, and later, when the river was not overloaded, it cut into the valley train it had built.

[a] Jour. Geology, vol. 13, 1905, p. 298.

CLEAR CREEK SYSTEM.

The basin of Clear Creek lies for the most part outside of the Leadville quadrangle, but the lower moraines of the system are within its boundaries. The total area covered by the ice is not known, but the system would certainly be classed with the larger ones of this range. The three sources belonging to this system that are in the Leadville quadrangle are not of the same type as the cirques farther southwest, but are only moderately glaciated, owing, perhaps, to their limited area and to southern exposure. The valleys are not deeply eroded by glaciation, and accumulations of talus have entirely obscured any signs of glaciation on the wall rocks. Their form gives some clue to the height which the ice reached. Beyond the limits of this quadrangle there are in this system several beautifully developed cirques, where the glacial erosion was more effective.

The main valley down to the point where the heavy-drift area begins is strongly glaciated. It had a well-developed U shape and all projecting spurs have been truncated. The easily weathered rock does not retain striæ on exposed surfaces.

Beyond the rock walls of the valley the glacier built up a pair of very perfect lateral moraines. These moraines are almost parallel and have even, unbroken crests which stand 700 feet above the stream at their upper ends. The inner slopes are often as steep as the material will lie, and slumping has notched the north lateral moraine in one place.

Between the two lateral moraines the valley is broad and is occupied for more than 2 miles by a flat, probably an old lake bed formed behind the terminal-moraine dam. At their lower ends these two lateral moraines flatten out and merge into a broad, low terminal moraine which reaches to and crosses the present bed of the Arkansas. Here the river occupies a new channel, and was pushed out to its present channel by the edge of the ice advancing from the valley of Clear Creek.

North of the Clear Creek north lateral moraine is a considerable patch of older drift, as shown on the map. This area is, for the most part, heavily timbered, but certainly patches of older drift occur in it. This drift has in general the same characteristics it shows in the other areas already mentioned. Weathered bowlders lie scattered about over a surface from which erosion has removed all traces of kettles or hummocks. The materials are all oxidized, and many of the bowlders are deeply decayed and falling to pieces. At one place in this area the older drift shows to some extent a lateral-moraine ridge form just outside of the new lateral moraine. This ridge is only about 30 feet high, and the slopes have an angle of 10° to 12°.

Between it and the ridge of the new lateral moraine there is a kettle, but no kettles occur in the older drift itself.

One mile west of Granite, on the south side of Cache Creek, there is a patch of terrace material, sloping north and northeast, which is notably higher than the terraces just north of Cache Creek. The materials in this area are about the same as those north of Cache Creek. Bowlders 2½ feet in diameter were seen at one section, but all were so rotten that they could be cut with pick and spade. Its topography is comparable with that of the other high terraces. At its upper end this area grades into a deposit of older drift and therefore can be definitely classed with the other terraces which are built outside of patches of older drift.

SYSTEM OF EAST FORK OF THE ARKANSAS.

East Fork of Arkansas River was occupied by a glacier for the upper 15 miles of its course. This glacier had an area of 20 square miles and was a typical mountain glacier, the ice body in the main valley being fed by the ice from 10 tributary valleys.

SOURCES OF THE ICE.

Buckeye Gulch.—In ascending the valley of East Fork the first of these tributary cirques that one reaches is Buckeye Gulch. The valley running south from Buckeye Peak has a cirque development, its head walls rising steeply for 500 feet above the valley floor. The valley floor is covered with loose material into which the stream has cut a gorge about 30 feet deep. At its head the valley is U-shaped, but farther down it becomes V-shaped, and the side walls are covered with heavy drift for 500 feet above the stream. The hill a mile south-southwest of Buckeye Peak was slightly cut into by the ice, but in the west fork of Buckeye Gulch the excavation was insignificant and the valley form was but little changed by the glacier.

The little cirque on the north side of Prospect Mountain is small and not deeply excavated. The head is U-shaped, but lower down the valley narrows and becomes V-shaped. There is little bare rock in this cirque, and the walls are everywhere covered with talus.

The little cirque east-northeast of Prospect Mountain is somewhat further developed than the cirque just mentioned. The head was more severely glaciated and the lower half is broader and shallower, but the walls and floor are covered with talus, so that little of the bed rock can be seen.

Birdseye Gulch.—This is a broad basin which was occupied by glacial ice. It is nowhere very deep, although the mountains to the east rise to elevations of more than 13,000 feet. The valley floor is completely covered with loose material, into which the stream has cut a sharp though not very deep gorge. The upper limit of glaciation coincides rather closely with the timber line on the east wall, and the ice reached almost to the col on the south. In the whole of this valley the glacial erosion was slight, for in the wide, flat-floored valley the ice was not concentrated and was comparatively thin, so that the glacial gouging was correspondingly mild.

Valley southwest of Mount Arkansas.—This valley is short and steep and was rather strongly glaciated. It lacks the precipitous head walls so often seen in these cirques, but has a good U shape. In the head, above timber line, there is considerable postglacial talus, but below timber line the floor is covered with heavy drift.

Cirques east of Buckeye Peak.—The four small cirques on the east side of the Buckeye Peak ridge have much the same characteristics. The southernmost one is much the smallest and is the least perfectly developed. The three to the north all have rather steep head walls and broad, spatulate heads, though the ice never stood very deep in them. Toward the main valley these tributaries show more of a V-shaped cross section—a change due to the increased gradient of the valleys toward their junction with the main glacial trough. The increased slope of the floor caused the ice above it to move more rapidly and thus lessened the area of ice in a cross section at this point. This process, once initiated, would tend to augment itself, the more rapidly moving ice bringing about increased erosion of the valley bottom, and this, increasing the slope, would give increased velocity to the ice movement. The amount of deepening of the lower ends of these tributary valleys was limited by the height at which the ice stood in the main valley below.

Valley west of Chalk Mountain.—No ice originated in the valley of the stream which flows south along the west base of Chalk Mountain. The lake at the head of this stream was formed by the damming of the valley by talus blocks which came down from Chalk Mountain. At the point where this stream enters the main valley of East Fork of the Arkansas it flows over a cliff about 35 feet high, forming a beautiful waterfall.

Head of valley.—The head of the Arkansas Valley north of Mount Buckskin is a beautiful cirque, the east wall showing especially well the effects of glacial erosion. The whole cirque is excavated in the pre-Cambrian gneiss, and the amount of material removed by the ice was enormous (fig. 10). The upper $2\frac{1}{2}$ miles of the valley are almost entirely free from drift, and although there is considerable postglacial talus at the base of the steep walls, it is insignificant in the wide valley. The ice limit along the mountains to the east is distinctly shown by the perpendicular outcrops of gneiss, above which the unglaciated slopes rise more gently to the peaks. Toward the head of the cirque the east and south walls rise steeply to a row of serrate peaks, all of them well above 13,000 feet in height.

The west wall of the cirque is not so strongly eroded as the east wall, but is broken by minor valleys and spurs, and the talus accumulations are conspicuous. Throughout the head of this cirque the topography of the original stream-developed valleys has completely disappeared. Not only is there now no evidence of overlapping spurs and of tributary valleys, but these spurs, particularly on the east valley wall, have been so far truncated that the courses of the former tributary streams can not be located. At its deepest the ice in this valley was more than 1,000 feet thick, so that the extensive gouging and shaping of the valley is easily accounted for.

Fremont Pass.—Ice stood in East Fork of the Arkansas about 100 feet above the crest of the divide at Fremont Pass, so that some ice may have gone over into the Tenmile Valley. It is probable, however, that the ice from the cirque south of Bartlett Mountain stood almost

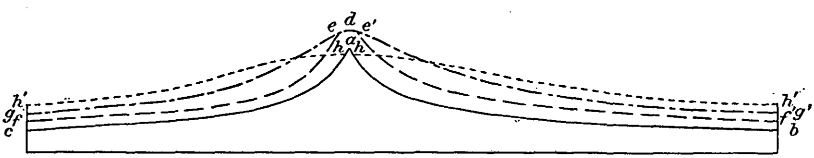


FIGURE 10.—Diagrammatic cross section of divide between head of East Fork of the Arkansas and Mosquito Gulch. *c, a, b,* The divide at the present time. On either side of *a* peaks rise to 13,700 feet, or to point *d*. *d, a,* Probable amount which this divide was lowered by glacial erosion; *g, d, g',* probable preglacial cross section of this divide; *f, e, e', f',* an intermediate stage in the glacial lowering of the divide; *h', h, h, h',* height to which the last glacier filled the present valleys. Horizontal scale, 1 inch=1 mile; vertical scale, 1 inch=one-half mile.

as high on the north side of the pass as the Arkansas ice did on the south side, so that the movement of ice over the pass was slight.

MAIN VALLEY.

From a point one-half mile above the loop in the upper railroad south of Fremont Pass to the lower edge of the terminal moraine the main valley floor has enough heavy drift to mask the topography of the underlying rock. With the exception of a few rock outcrops, the drift sheet in this area is continuous.

Along the river valley south of Chalk Mountain the stream has a cut 60 to 100 feet deep, and this cut exposes the Chalk Mountain rhyolite. A long ridge of this same rhyolite outcrops in a north-south direction near the union of East Fork of the Arkansas and the tributary from the west side of Chalk Mountain. On either side of the mouth of the glaciated valley southwest of Mount Arkansas there are knoblike outcrops of porphyry, and on the west side of the main valley are similar knobs. Between these the ice was somewhat constricted, but the valley widens both above and below them.

At many places in the main valley below Buckeye Gulch determination of the upper limit of the ice is difficult, but it can be located by an occasional bench or plug of drift across the mouth of some small side valley. Below this limit the easily weathered rock outcrops have in many places been reduced to roughness, though the general outlines of these outcrops are more rounded than those of the outcrops above the ice limit.

MORAINES.

No lateral moraines occur until the stream emerges from its rocky gorge. On the west slope of Prospect Mountain a good lateral moraine appears. This swings away from the mountain slope with a good ridge form, the outer slope being 50 to 75 feet high. This ridge curves to the west, and has an east-west course at the point where it is broken by a cut through which Evans Creek flows. West of this cut the moraine ridge continues to the west, and stands 50 feet higher than the lateral moraine on the north side of the Arkansas. One section afforded by a prospect hole showed the new drift to be more than 30 feet thick, overlying high-terrace gravels, so that this

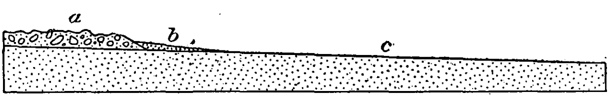
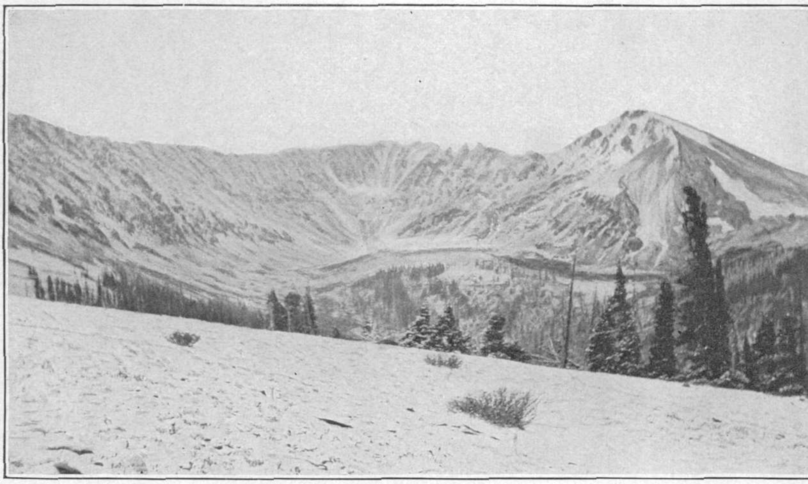


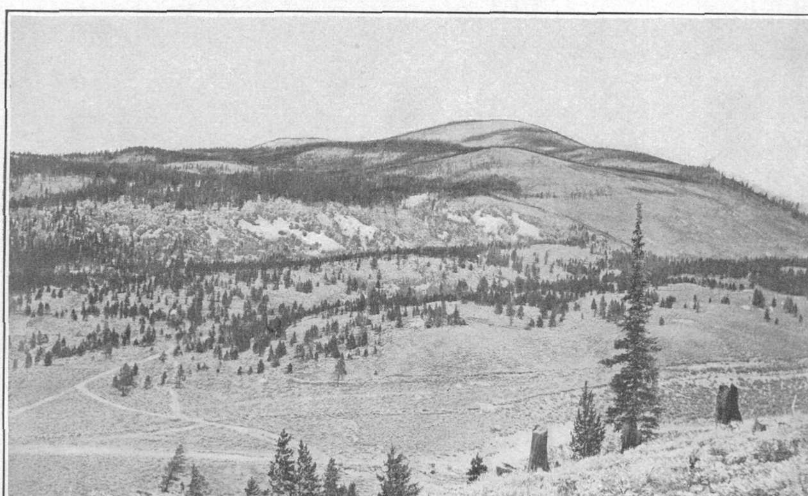
FIGURE 11.—Diagrammatic section south of terminal moraine of East Fork of the Arkansas. *a*, Moraines of last glacial age; *b*, outwash from last glacier; *c*, outwash gravels of older glacial age. Horizontal scale, 1 inch=one-third mile. Vertical scale, 1 inch=one-sixth mile.

moraine was at least partly built out upon the preexisting high terraces. To the west this moraine grades down, without topographic break, into the high terraces. No sharp line can be drawn between the two, the wash from the new moraine so overlying the high terraces that the transition is gradual (fig. 11).

The north lateral moraine is not so well developed as the south lateral. It is lower, and contains much less material. It lies as a bench along the side of Mount Zion, and its crest is considerably below the limit of glaciation as shown on the rock wall above it (Pl. IV, *B*). The small size of this moraine in comparison with the opposite one may result from the difference in exposure of the two sides of the valley. On the south side of this valley there is no rock valley wall, and the ice of the glacier, although indirectly exposed to the sun's rays, was not subjected to the reflected heat from a rock wall. On the north side the rocky slopes of Mount Zion rose above the edge of the glacier, and the heat reflected from this rock wall would have been influential in melting back the ice edge, and may have been in large part responsible for the difference in height of the moraines on the two sides of the valley.



A. HEAD OF CLINTON GULCH.



B. NORTH LATERAL MORAINE OF EAST FORK ARKANSAS SYSTEM OF GLACIERS.

No typical terminal moraine occurs in this system, as the dump from the end of the glacier was carried rapidly away by the vigorous stream. This stream has now a 30-foot cut between the ends of the two laterals, and part of this is in the fractured bed rock.

AMOUNT OF GLACIAL EROSION.

On the northwest slope of Prospect Mountain there is a small hanging gulch tributary to East Fork of the Arkansas. During the last epoch of glaciation the mouth of this gulch was filled with drift, and into this drift the stream has developed a considerable postglacial cut. It is evident from the rock slopes of the sides of this draw that if all the drift were removed there would still be a considerable topographic unconformity between this gulch and the main valley. It is impossible to estimate closely the amount of this unconformity, but it must be from 100 to 200 feet; and these figures indicate roughly the amount of glacial deepening of the main valley at the mouth of this tributary.

HIGH TERRACES.

Beyond the lower end of this system of glaciation there are extensive high-terrace deposits, which are a part of the compound alluvial fan that, in interglacial times, extended from this stream south to Granite Gulch. These deposits are described in connection with the Iowa Gulch system of glaciation. (See pp. 93–94.)

LOW TERRACES.

Associated with the moraines of this system there are a number of remnants of a set of low terraces. The uppermost of these patches lies well within the glaciated area, and extends upstream more than 2 miles above the point that the ice reached at its maximum extension. The gravels form low benches on either side of the river flat, and are all that is left of a gravel plain which once extended across the valley and filled it to some depth. This valley train was built after the ice had retreated some distance, and is conclusive evidence that the building of valley-train deposits continued for some time after the ice had begun to retreat. Below the end of the moraines there is a narrow bench of these gravels on either side of the river. They were laid down in the interglacial gorge in the high terraces, and their surface stands about 100 feet below that of the adjacent high terraces. The materials of the low terraces are fresh and unoxidized, and the extent to which postglacial erosion has reduced them is due to their position in the valley bottom, where the stream cutting is most potent.

UPPER TENMILE CREEK SYSTEM.

Actually in contact with the system of East Fork of the Arkansas, but turning in the opposite direction, on the other side of the continental divide, was the system which occupied the upper end of the Tenmile Valley. This system headed in the little cirque south of Barlett Mountain, and its supply may have been somewhat augmented by ice coming over the pass from the East Fork system. The double cirque at the head of the Tenmile system is deeply excavated, and, although small, was the source of vigorous ice movement. Formed in the pre-Cambrian gneiss, this cirque has suffered severely from postglacial erosion, and the lower walls and the floor are covered with talus. The shape of the valley head, however, is that of a glacially shaped cirque.

Below the mouth of the cirque the floor is covered with heavy drift, and at the lower end of the system the drift takes on characteristic terminal-moraine topography, with hummocks and water-filled kettles. There is no sharp terminal-moraine ridge, and the drift merely flattens out and disappears to the north.

North of the terminal moraine of this system, 1 mile south of the village of Robinson, there is an area covered with drift of the older epoch of glaciation. Here scattered bowlders up to 3 feet in diameter lie beyond the edge of the last moraines. At one point east of the river this drift has some thickness, but it is mostly represented, in the area mapped as "older drift," by scattered bowlders, which are much more deeply weathered and oxidized than the materials of the last moraines.

LOWER TENMILE CREEK SYSTEM.

The lower Tenmile Creek system had its head in Clinton Gulch and occupied the Tenmile Valley from the mouth of Clinton Gulch to the hamlet of Wheeler. It was fed by seven tributary glaciers, the five larger ones joining the main valley from the east and the two smaller from the west. At its maximum the system had a length of 10 miles and an area of 12 square miles.

SOURCES OF THE ICE.

Clinton Gulch is the most important of the tributaries of the lower Tenmile Creek system. This gulch heads back to a mountain ridge which is nowhere less than 13,500 feet high, and received the ice from 2½ miles of the west slope of this ridge. As a result of its favorable topographic position this cirque received a large supply of ice and was severely eroded. The head is broad, and the walls on all sides rise steeply to jagged peaks (Pl. IV, *A*). The upper limit of glaciation is marked by the perpendicular outcrops of the rock, above which the slope is not quite so steep. At the base of Bartlett Mountain the ice failed to erode as deeply on the west side of the cirque as on the east, and left a great broad rock bench, but except for this one break in its symmetry the cirque has the cross section of a typical glaciated valley.

On the southwest side of the gulch the ice pushed over the wall at an elevation of about 10,300 feet and spread down the west side of the ridge to the valley of the Tenmile. Over this ridge, however, there is only a thin coating of drift, as is shown by a number of prospect holes.

Once over the ridge, the ice was just strong enough to reach the valley bottom. The small hill one-fourth mile southeast of Kokomo was surrounded by the thin edge of the ice, but does not appear to have been covered by it, for while granitic and gneissic bowlders occur on the lower slopes of the hill, none occur on its top. From this hill the west limit of the ice runs north and reaches the west side of the Tenmile Valley just north of Kokomo. In the mouth of Clinton Gulch there is a considerable area covered with heavy drift. Here the drift covers the valley bottom and the walls for some distance on either side.

Mayflower Gulch heads in a well-developed cirque. The main cirque is divided into two parts by a low spur which has been almost removed by the glacial cutting from either side. The ice limit is sharply defined by the shape of the valley, the walls above being much more irregular and angular than the walls below the ice limit. The lower walls are almost completely covered with talus, but the flat valley bottom is free from loose materials.

The north fork of Mayflower Creek heads due east and has a small but well-developed cirque at its head. This cirque has much the same characteristics, on a smaller scale, as the main head. Like it, it has steep head walls with jagged peaks, and shows angular outcrops down to the ice limit, which is marked by a sharp topographic break, with perpendicular cliffs below. Below these cliffs there are large accumulations of talus, which obscure the lower walls and the valley floor.

Below the junction of these two cirques the glaciated area of the valley narrows rapidly and becomes more V-shaped, indicating that this was an area of dissipation of the glacial ice. The valley is free from heavy drift down to its junction with the Tenmile Valley.

Humbug Gulch cirque is of small area, and received most of its snow and ice from the subordinate lateral spurs of the mountain mass. Two small fingerlike cirques head to the east, the larger one having cut deeply into the flank of Bald Mountain. In the cirques themselves the talus has covered much of the walls and floors, but farther down the valley the bare rock appears, rising in rude steps to the east. Toward its head the cirque is broadly U-shaped, but becomes narrower toward the west, and the ice seems to have had barely strength enough to push down to the main Tenmile Glacier. Its mouth is about 400 feet above the present Tenmile Creek, and is filled with a plug of heavy drift, through which Humbug Creek has cut a shallow postglacial channel.

Gulch 1, the next gulch north of Humbug Gulch, opens at its head into a broadly U-shaped valley with steep head walls. Great accumulations of talus cover the bottom and walls of the cirque and obscure the upper limit of glaciation. Its shape, however, shows that glacial erosion was vigorous at the upper end. Like Humbug and Mayflower gulches, it narrows toward its lower end, which hangs about 400 feet above Tenmile Creek. Across the lower end of the valley is a plug of heavy drift, through which the stream has a cut 30 to 50 feet deep.

Gulch 2, next north of 1, is much like 1 in general characters, although it is wider and deeper. The valley has two subordinate heads, both of which have steep head walls, with much talus below. Gulch 2 narrows and becomes V-shaped at its lower end. The glaciated area is almost a mile wide at its greatest width, but is scarcely one-fourth mile wide at its lower end, which hangs 400 feet above Tenmile Creek.

Tucker Gulch, just south of Jacque Peak, was glaciated, but not severely. The upper end of the gulch was not excavated to form a cirque, as it lacks the steep head and side walls. The upper limit of glaciation is not well defined, but the valley bottom in general has less talus than the higher slopes. The ice tongue in the lower end of this valley was only a few hundred yards wide and lay in a narrow V-shaped valley.

Copper Creek has a broadly U-shaped valley and steep head walls but talus and vegetation have now so covered the walls as to make it impossible to determine the upper limit of ice with accuracy. Like the neighboring gulches, this one narrows down greatly before joining the main valley, and the mouth is occupied by a plug of heavy drift.

HEAVY-DRIFT AREA.

In the main valley of the Tenmile, on the east side of the stream, there is a body of heavy drift which extends more or less continuously from the mouth of Clinton Gulch to the lower end of the area occupied by this system of glaciers. Below the mouths of the tributary cirques this drift has considerable thickness, cuts 30 to 50 feet deep, failing to expose the rock below. Here, too, the drift takes on a distinct drift topography, with irregular hummocks and kettles. This drift extends to the upper ice limit along the east valley wall and sometimes is disposed as a bench against the rock wall of the valley. On the east side of Copper Mountain the heavy drift does not reach to the upper limit of glaciation. Large outcrops of rock occur in the glaciated area, but the ice limit can be determined by an occasional pocket of drift or by bowlders.

In general the ice limit on the west side of the valley is 50 to 100 feet lower than on the east side. This is due to the greater supply of ice from the east and to the better exposure of the southeast-facing side of the valley to the sun, with resultant greater melting.

North of Copper Mountain the Tenmile Gorge received no more ice from its tributary gulches. The tributaries from the east are all hanging, and give an idea of the amount of glacial deepening which this valley has undergone. Below the mouth of Gulch 2 the glacier was decreasing in size, but continued down to Wheeler. There is no notable terminal-moraine deposit at this place, for the ice ended just within the mouth of the gorge, and the drift was carried away from the end of the glacier before it accumulated in any quantity.

AMOUNT OF GLACIAL EROSION.

A glance at any one of the strongly glaciated valleys of this region is enough to show that the amount of glacial erosion which it has suffered is very considerable. If this erosion had resulted merely in changing the valley cross section from a **V** shape to a **U** shape the amount of material removed would have been large, but added to this there was in most places a very considerable deepening. In the higher and more severely glaciated regions, where every valley of importance was occupied by a glacier, it is difficult to estimate the amount of glacial deepening, but in the lower courses of some of the glacial troughs we find unglaciated tributary valleys, with normal stream gradients. If the mouths of these tributaries are hanging above the main stream we can estimate, by the amount of the topographic unconformity and by the gradient of the tributary stream, the amount of glacial deepening which the main valley has undergone from glacial erosion. These estimates are subject to error for several reasons (see p. 12), and the results can be only approximate.

East of Copper Mountain and about 2 miles above the terminus of the Tenmile Creek system of glaciation the tributaries which join the Tenmile Valley from the east end about 400 feet above the main stream (fig. 12). By continuing the gradient of the tributary in a normal way to a point above the axis of the main valley we get a difference of about 200 feet, which appears to be approximately the amount of glacial deepening at this point. The ice at this place had, however, descended almost to the 10,000-foot level, and its erosive

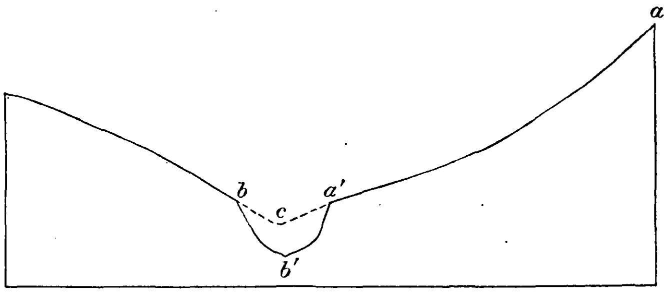


FIGURE 12.—East-west section across Tenmile Valley and an unglaciated, hanging tributary valley, *a*, *a'*. *a'*, *b*, *b'* is the glacially gouged valley. By the continuation of profile *a*, *a'* to *c* we get the approximate position of the preglacial valley axis. *c*, *b'* is the amount of the glacial deepening. Section is taken northeast of Copper Mountain. Horizontal and vertical scale, 1 inch = one-fourth mile.

power must have been less than it was farther up the valley, where the ice was thicker.

RECENT GRAVELS.

North of this system of glaciers, beyond the distal edge, there is a considerable body of recent gravels, deposited by Tenmile Creek as an alluvial fan of low slope. At this place Tenmile Creek and its West Fork emerge from their gorges, and this small park, with its lessened stream gradients, has been an area of stream deposition. The conditions of deposition during the last epoch of glaciation were very similar to the present conditions, and the recent alluvial deposits may be but the continuation of the gravel-train building processes of glacial times.

SYSTEM OF WEST FORK OF TENMILE CREEK.

Part of the valley of West Fork of Tenmile Creek was occupied by glaciers not connected with those in the main valley. This system consists of the glaciers in Jacque and Sugarloaf valleys, which joined to form a small ice tongue in the valley of West Fork.

Jacque Gulch is the eastern of the two tributaries of West Fork. It has two heads, one on either side of Jacque Ridge. The east head has steep head walls and the main valley was severely eroded by ice action. The ice at its maximum was not confined to the cirque itself, but extended up onto the flat west of Union Mountain and left the drift in which the three small lakes now occur. The head west of Jacque Ridge received most of its ice from Jacque Ridge. It is a long, narrow cirque, U-shaped in cross section, but its ice never had great depth.

The valley of Jacque Creek below these two heads is U-shaped, but the glacier it contained was never more than 200 feet thick. The sides of the valley are covered with heavy drift, but the stream has a shallow cut in the rock of the east valley wall. At the lower end of

Jacque Gulch some of the ice cut across the low end of the ridge to the east, as is shown by the bowlders over this ridge.

Sugarloaf Gulch held a very shallow ice body, though it sent its glacier down to the main valley. The supply of ice for this glacier came from Sugarloaf Ridge and from the névé field to the northwest, and it is doubtful if glaciation would have started in this valley if the exposure had been less favorable. The ice from Sugarloaf and Jacque creeks united in the main valley of West Fork of Tenmile, and sent their ice to a point 1 mile west of Wheeler. In this valley the ice reached only 100 feet up on the north valley wall, and left its drift in the form of a prominent bench running parallel with the stream. To the east this bench takes the form of a distinct moraine ridge, which becomes lower and lower downstream and finally merges into some new terrace remnants 15 to 20 feet above the stream.

WHEELER GULCH.

On the northwest slope of Copper Mountain there is an isolated glaciated valley which would have joined West Fork of Tenmile Glacier if its ice had reached down a little farther. This is in Wheeler Gulch. Its glaciated area is only 1½ miles long and one-third mile wide. In this area the ice was 100 feet deep at its maximum, so that its erosive action was slight. The gulch head is broad and shallow and the ice extended up to the col at its head. No definite areas of light and heavy drift could be defined, for the bed rock is nowhere bare, and talus and drift are commonly mingled. Between the forks of the stream there is a patch where the bowlders are numerous and predominate over the talus, but otherwise the loose material could not be characterized as heavy drift.

EAST SIDE OF PARK RANGE.

The lowest point in the valley of Blue River in this quadrangle is below 9,500 feet, and the small glaciers from the tributary valleys west of Breckenridge did not send their ice down to the main valley at this altitude. There were four of these small detached glaciers on the mountains west of Blue River.

SOURCES OF THE ICE.

Glacier 1 had two small heads, which joined in a broad U-shaped valley. The glacier was but little more than 2 miles long, its lower end being just beyond the edge of this quadrangle. The whole area is covered with heavy drift except the heads of the cirques, in which the walls and floor are masked by talus. On the northwest side of the valley there is a well-defined lateral moraine ridge 50 to 60 feet high. On the southeast the lateral moraine has no ridge-like crest, but is a broad belt of kettle-moraine topography covered with bowlders.

Glacier 2, just southeast of glacier 1, was a feeble glacier about a mile long, and its erosion was slight. The whole area, except the head of the cirque, is covered with drift, which at one place is continuous with that of glacier 3. The topography of this area is that of a weak terminal moraine, but a distinctive terminal-moraine ridge is lacking.

Glacier 3 was a very vigorous little glacier, for it has a good cirque at its head, a well-developed U-shaped valley, strong lateral moraines, and an area of typical terminal moraine, yet the whole system is little more than 3 miles in length. The head of the cirque shows evidences of rather severe ice erosion, the west and northwest walls rising steeply to the limit of glaciation, and somewhat less steeply above it. On the southwest side the walls are not so high and the supply of ice was more limited, which accounts for the less severe erosion on this side. High up on the northwest side, just below the peak, there is a small hanging cirque in the mountain side, the ice from which evidently eroded its valley but little below the level to which the ice stood in the main valley. On the north side of the valley there is a fine lateral moraine, with a sharp, unbroken crest, extending from the mouth of the rock gorge to the point where the stream emerges from the glaciated area. This ridge, though not so high as the map indicates, is in places more than 200 feet above the valley, but rises only a little above the old drift against which it is banked on the outside. There is also a good lateral moraine on the southeast side of the valley, but this has not so high or so even a crest as its counterpart. It stands 150 feet above the stream and has an irregular surface, full of kettles and hummocks strewn with bowlders of granite and gneiss. The light-drift area of this valley includes only the rock walls of the gorge and the valley floor at the head of the cirque; otherwise the drift masks the rock in the whole of the glaciated area. At the lower end of the system is a small area of true terminal moraine piled up at the very edge of a patch of old drift. The relief of this terminal moraine is slight, with shallow lake-filled basins and low hillocks.

Glacier 4 was in what is now a small talus-filled valley which from above scarcely appears to be glaciated at all. Below, however, there is a definite terminal moraine which just touches the moraines of the Spruce Creek lobe. The whole of the lower end of the valley is covered with a thick coating of bowlder-strewn kettle moraine, which at the east forms two parallel crescentic ridges 20 to 30 feet high.

OLDER DRIFT.

Below the moraines of glaciers 1, 2, and 3 there are found patches of drift which both erosion and the condition of its material show to be distinctly older than the new moraines. In these patches are seen the same materials as in the new moraines, but in a more advanced state of decay and of oxidation. The surface, too, is under control by the streams, and no signs of kettles remain. This drift has long since disappeared from the valleys and is now found only on the tops of the intervening ridges.

BLUE RIVER SYSTEM.

This system occupied the valley of Blue River from its head to a point one-half mile north of Breckenridge. It had a maximum length of 12 miles and an area of 14 square miles, and was formed by the ice from four cirques from the west joining in the valley of Blue River. No ice was contributed to this system from the east, probably because the mountains on that side are not so high as those on the west.

SOURCES OF THE ICE.

Spruce Gulch.—The northernmost of these tributary valleys is that of Spruce Creek, which has two distinct heads. The north head was very severely glaciated, the walls on the south side being particularly steep, so that the top of the ridge is in places reduced to ragged séracs. The rock is banded gneiss, and its weathering has developed

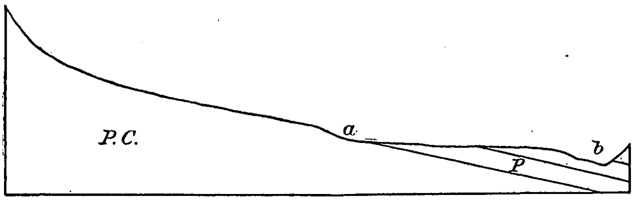


FIGURE 13.—Longitudinal profile of Spruce Gulch. *a*, Increased gradient of valley at point where stream flows from pre-Cambrian crystalline rocks (*P. C.*) onto lower Paleozoic beds (*P*). *b*, Valley of Blue River. Horizontal scale, 1 inch=1 mile. Vertical scale, 1 inch=one-half mile.

large heaps of talus at the base of the steep walls. On the north side there are few steep outcrops, the wall consisting of a more gentle, talus-covered slope. In the bottom of this head there is a beautiful little lake, the basin of which was made, in part at least, by talus from the slope above.

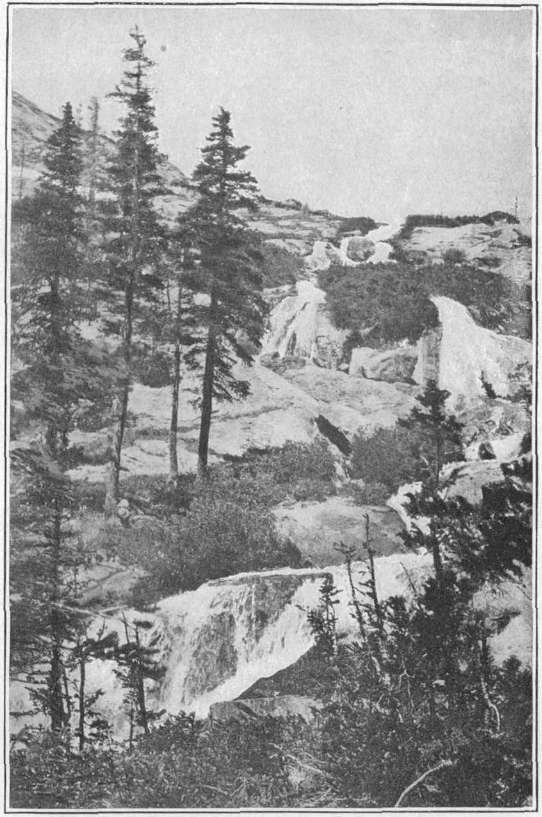
The south head of Spruce Creek is larger than the north head. Both walls are steep, and the valley bottom is free from large accumulations of drift. Even some rather large talus heaps fail to rob it of its "cleaned-out" appearance.

A noticeable feature of this cirque is the abrupt way in which the gradient of the valley floor increases just above the heavy-drift line, giving rise to cascades. There is a similar pitch in the valley floor of the north fork of Spruce Creek (Pl. V, *B*), and in Monte Cristo, Quandary, and Platte gulches. This pitch occurs in each case just above the contact of the sedimentary beds with the pre-Cambrian rocks, and is due to the lesser resistance of the sedimentary beds to glacial erosion (fig. 13). The heavy-drift area in Spruce Gulch extends up to the junction of the two cirques and reached a little way into them in the valley bottoms. On the north side of the valley the ice, emerging from the rock gorge above, stood too high to be confined by the lower valley wall and pushed over the ridge to the north, at an altitude of about 11,800 feet, and spread out in a broad, shallow lobe. Over this area there is now a thick deposit of drift lying in a series of parallel ridges with a relief of 20 to 50 feet, all running in a northeast-southwest direction. The surface is thickly strewn with bowlders 6 feet and less in diameter, and the topography is of the strong hillock-and-kettle type. This lobe extended to the north for almost a mile. On the south side of Spruce Creek the only lateral moraine is the ridge which was interlobate between the ice in Spruce Gulch and that in the Blue Valley. On the Spruce Creek side this ridge is only 25 to 50 feet high, but on the Blue River side it stands 200 and 300 above the stream. Spruce Creek is in places so blocked with bowlders that it is unable further to lower its bed (Pl. V, *B*).

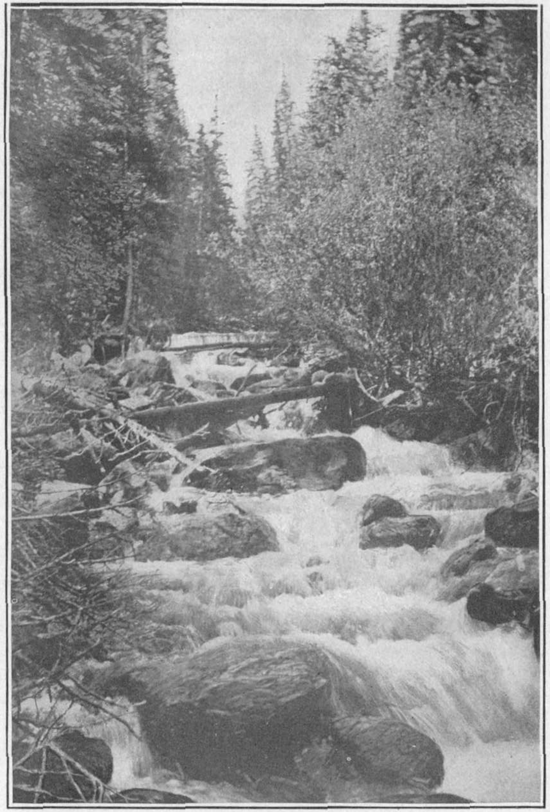
Quandary Gulch.—The head of Quandary Valley is a beautiful cirque. The head and side walls are bare gneiss and rise very steeply, often terminating in a serrate crest. Above the limit of the heavy drift the valley is exceptionally free from loose materials, and with the exception of talus heaps at the base of the steep walls the bed rock is exposed over the whole valley. All these bare outcrops are smoothed and rounded, and from a distance the postglacial weathering is inconspicuous, but the rock has rarely preserved glacial striæ or polishing.

In the cirque the upper limit reached by the ice is easily seen, as there is a sharp contrast between the steep, smoothed slopes below and the more gentle slope above, with its rough outcrops and prevailing covering of talus. The rock is banded gneiss, and this determines the character of bowlders in the drift below. In the tributary valley on the north, a mile above the junction with the Blue River system, the glacial action was feeble and failed to deepen the valley to any considerable extent, and the rock is free from heavy drift on the head walls only. The lower end of this tributary hangs 300 feet above Quandary Creek. To the east of this draw the ice limit is about 400 feet above the stream. The upper limit is marked by a slight topographic bench with bowlders 10 feet and less in diameter. On the south side of the valley the ice reached to about the same height as on the north. The only approach to a lateral moraine is the occurrence in places of a bench-like deposit of drift high up on the valley wall.

Monte Cristo Gulch.—The east-west part of this valley is a type of a severely glaciated valley. Above the 11,000-foot level the bed rock, a banded gneiss, outcrops over the whole of the sides and floor of the valley. The valley has a beautiful **U** shape, the walls rising steeply to the upper limit of glaciation and somewhat less steeply



A. CASCADES IN QUANDARY GULCH.



B. SPRUCE CREEK.

So filled with bowlders that the erosive action of the stream is almost blocked.

above. Below the ice limit the bare rock is smoothed and rounded and the talus heaps, though numerous, are not large enough to spoil the perfect U shape of the valley. Above the ice limit the rock is almost completely covered by talus. Two beautiful lakes occur in the valley bottom, and the basin of the upper one is in rock. The lower lake is bordered by rock on one side, but below it there are talus heaps which may be responsible for its basin. At its upper end this cirque divides into two heads which curve back to the northwest. These heads become shallow toward their upper ends without decreasing much in width, so that at their heads the cross section is a much wider U shape. They are free from drift, and their walls were eaten back in places till they have jagged, serrate crests.

The little draw which fed its ice into the lower end of Monte Cristo Gulch from the south is only feebly glaciated and was little shaped by the ice. It has no cliff-like walls, and the whole area is covered with heavy drift. In the absence of drift the shape of this valley is not characteristic enough to show that it was glaciated.

Cirque south of Monte Cristo.—The southernmost tributary to the Blue Valley Glacier is a small cirque lying between Monte Cristo Gulch and Hoosier Pass. It is only a mile long and gave out an ice tongue of only moderate size. The head walls to the west are steep and cliff-like, but below these the ice did not profoundly alter the preglacial shape of the valley. Only the head of the cirque is free from a heavy-drift covering.

MAIN VALLEY AND ITS MORAINES.

The main valley of the Blue, from the Hoosier Pass road to the terminal moraine, is everywhere covered with heavy drift, except a part of the east valley wall. The trough has everywhere a broad U shape, and the river often meanders over the flat valley floor. The spurs from the rock ridges on both sides are truncated, and the unglaciated tributary valleys from the east are all hanging valleys. Above the mouth of Spruce Creek there is no good lateral moraine, and below Spruce Creek the lateral moraine stands up only a few feet above the old drift area against which it is built. The surface of this moraine shows a strong drift topography, and the new drift is apparently rather thick in many places.

The drift in this valley ends one-half mile south of Breckenridge, at which place the terminal moraine has a ridgelike front, rising abruptly above the fluviatile gravels below. The terminal-moraine area extends 2 miles upstream from the terminus of the glaciated area, and the topography is most irregular, as is characteristic of such deposits.

Beyond the terminal moraine the Blue Valley is filled with gravels, which are probably a result of the continued deposition since glacial times.

OLDER DRIFT.

West of the terminus of the Blue River system there is a long, narrow patch of older drift on the top of a ridge to the west of the new lateral moraine. Like the other patches of older drift, it is different from the new drift in being more weathered and in having lost its drift topography. The ridge form of this drift is not its original topography, but is the result of the cutting of the stream to the east and west, leaving the drift along the crest of the ridge.

SOUTH PLATTE SYSTEM.

The South Platte system of glaciers occupied the valley of South Platte River for 15 miles below the head of that stream, and had an area of 49 square miles. This is two and one-half times as large as the next largest system of the Park Range, that of East Fork of the Arkansas. All the ice came from the valleys of the Park Range, the lower mountains to the east being unglaciated. The area drained by these tributaries includes the east slope of the highest part of the range for 12 miles north and south, and the tributary valleys are correspondingly well developed and strongly glaciated.

SOURCES OF THE ICE.

Platte Gulch.—The head of this system and of South Platte River is the amphitheater at the head of Platte Gulch, a beautifully formed cirque. The floor of the upper part of the valley is for the most part devoid of loose material, and rounded outcrops of the bed rock, a banded gneiss, abound. There is very little talus in the head of this valley, and the surrounding walls were worn back till the divide is very narrow, hardly more than a line of serrate peaks. Most of the cirque is in the pre-Cambrian gneiss, but the tops of some of the surrounding peaks and ridges show the lower Paleozoic beds. In the north lobe of this valley the two little lakes are in rock basins. In the middle of July (1905) the upper one was still frozen over.

Just west of the bend in the Hoosier Pass road, above the point where the Paleozoic beds cross the valley, a spur of gneiss projects down into the valley from the north wall, constricting the valley and causing a steeper gradient around and below it. This seems to be correlated with the steep pitch of the valleys to the north, just above the contact of the igneous and the sedimentary rocks.

Lincoln Amphitheater.—In the east side of Mount Lincoln there is a small cirque called Lincoln Amphitheater. It is deeply eroded and its side and head walls are perpendicular in places, but great quantities of talus completely cover its lower walls and floor and fill it to such an extent as to alter considerably the shape of the cross section of the valley as left by the ice. The head of this cirque shows beautifully the contact between the pre-Cambrian rocks and the Paleozoic.

Buckskin Cirque is a broadly U-shaped cirque divided into a number of subheads by minor spurs which were themselves covered and rounded off by the ice. The walls and floor of the head of the cirque, especially on the east side, are so heavily masked by talus that no evidence of glaciation, other than that of the general shape of the valley, remains; but on the west and north sides parts of the walls have been cut back into steep cliffs.

In the lower end of the valley, at the point where the stream turns toward the east, the glacier emerged from its rock gorge and the lateral moraines appear. On the north side of the valley the lateral moraine begins as a bench of drift on the side of the rock ridge. This bench is not always very definite, and as the side of the valley is heavily timbered it is difficult in some places to trace the upper edge of the drift, obscured as it is by talus and wash from above. One mile northwest of Alma the ridge is so low that the ice from the South Platte and from Buckskin Creek joined, and below this point the ridge is covered by a veneer of drift. On the south side of the valley the moraine ridge begins one-half mile northwest of Park City. Here the ice from Mosquito Gulch met that from Buckskin, and what from each valley appears to be a lateral moraine is in fact the interlobate moraine between the two. The crest of this ridge is broad and is strewn with bowlders up to 6 feet in diameter. The crest consists of a number of minor ridges from 8 to 20 feet high, running parallel with the two valleys. In the Buckskin Valley a mile above Alma is a thick deposit of drift just above the point where the ice from Buckskin met the southward-moving ice from the Platte, and this seems to be the terminal moraine of the Buckskin Glacier, when, during the retreat of the ice, it first became separated from the main glacier and became distinct. For one-half mile below this point there is little heavy drift in the valley of the Buckskin.

Mosquito cirques.—Mosquito Gulch has a fan-shaped head, and received ice from 4½ miles of the highest part of the Park Range. The head of the valley is divided by London Hill into two great heads, both strongly glaciated. The south cirque is wide, but the walls at the head are not very high and steep. The floor of the cirque rises, between London and Pennsylvania hills, toward the crest of the range in a series of huge, irregular steps, with no cliff at the head. This lack of steep cliffs may account for the comparative scarcity of postglacial talus in this valley. The bed rock of gneiss, everywhere rounded, shows throughout the valley floor.

On the northwest base of Pennsylvania Hill conditions are different. The wall is an almost perpendicular cliff to the top of the hill, and is steep all the way down to the stream. Below this cliff there is a great talus heap, and on this wall the rounded glacial surfaces have disappeared.

London Hill stands between the two great heads of Mosquito Gulch. Once almost surrounded by the ice, its sides were smoothed off and steepened. On the west side of London Hill the ice from the two heads almost joined at the col, and moved downward on either side of the hill to join at its eastern end. Even above its glaciated flanks the hill is rounded, and the top is buried in the products of weathering.

The north head of Mosquito Gulch has much the same general characteristics as the south head. It is a broad cirque at the east base of London Hill, but becomes even broaded to the west. The wall to the northeast rises steeply and at the north a row of jagged peaks forms the dividing wall between this cirque and that at the head of East Fork of the Arkansas. The walls to the west, however, nowhere rise steeply, the valley having a nearly uniform gradient from the end of the railroad to the top of the ridge to the west. The bare rock, rounded and smoothed, is exposed over most of the valley floor, there being little talus. East of London Hill the ice from the two heads joined. The valley of the Mosquito below this point has a fine U shape. Heavy drift covers the valley bottom from London Hill to the terminal moraine, but the valley walls show the bare rock or talus slopes down to the point where the stream emerges from its rock canyon. One mile west of Park City a great granite spur runs down into the valley from the north. It shows evidences of severe glaciation, but was able to resist the erosion by the ice better than the other rocks on account of its superior hardness and freedom from fractures. Below the confines of the narrow gorge the ice flattened out and spread laterally until it met the ice from Buckskin Cirque, and with it formed a great interlobate ridge (p. 81). This bridge runs to the southeast for more than a mile, and then flattens out, as the ice from Mosquito Valley merged with the main Platte Glacier. In the lower end of the Mosquito Valley are several small lakes in depressions in the drift. On the south side of the Mosquito Valley the ice moved eastward along the flank of Pennsylvania Hill to a point almost due south of Alma, at which place it turned sharply to the south and joined the main Platte Glacier.

Sacramento and Little Sacramento gulches.—The ice from Sacramento Gulch was the southernmost tributary of the South Platte system. The ice came from the east slopes of Mounts Evans, Dyer, and Sherman and the Gemini Peaks, and the south slope of Pennsylvania Hill. This gulch has two heads, the smaller being called Little Sacramento Ampitheater. The main head is much the same in character as the south head of Mosquito Gulch and is connected with it by a low col. Looking down from Pennsylvania Hill upon this col one can discern no sharp dividing line between the two cirques. The rock at the top of the col is smoothed and rounded, and the ice must have been thick over the col, reducing it to a low, rounded divide. With variations in the snowfall in the cirques on either side, the ice perhaps moved sometimes to the north and sometimes to the south over the crest of the col.

From the junction of Sacramento and Little Sacramento creeks the valley floor slopes upward with a rather uniform gradient to the col on the north and to the crest of the Mosquito Range on the west. There are no steep head walls, and the head of the valley is broad and shallow. In the absence of cliffs there is little talus, and the floor is of bare, rounded gneiss, with lakes in rock basins. South of Pennsylvania Hill the walls become cliff-like and there is much talus at their bases.

Little Sacramento Gulch is not so strongly glaciated as Sacramento Gulch, and like it has no steep walls. It contains considerable postglacial talus and does not give the impression of very severe ice erosion.

The lateral moraine on the south side of the Sacramento Valley is an extraordinary one. It begins at the point where the ice emerged from the narrow gorge and extends eastward with an almost unbroken crest to South Platte River. At its upper end it is 400 feet above Sacramento Creek, but becomes lower to the east until it is less than 100 feet above the Platte at the point where that stream cuts through it. Over the surface bowlders of crystalline and lower Paleozoic rocks abound.

The lateral moraine on the north side of the valley is not so striking as that to the south. It begins somewhat farther east, and its crest is not so sharp and lacks the even, uninterrupted character of that of the south lateral moraine. The moraine material is scattered over the top of the ridge on the north side of the valley, the crest often showing a series of minor ridges 6 to 15 feet high, parallel with one another and with the stream. Rock outcrops beyond the ice limit show that the moraine is a drift deposit over a preexisting rock ridge, while the south lateral gives one the impression that it is composed entirely of the drift itself, irrespective of previous topography. No rock outcrops occur in the lower 4 miles of this moraine.

On the north side of the valley the ice covered the divide and showed a tendency to spread down into the next valley to the north. This probably accounts for the absence of a sharply defined lateral moraine ridge. Toward the lower end of the gulch the ice spread over the ridge to the northeast until it met the ice in the main valley of the Platte.

Between the lateral moraines the valley is broadly U-shaped. The stream meanders through a flat, except at the lower end of the valley, at the point where it enters the Platte Valley, at which place it has a cut 20 to 30 feet deep through the drift.

In the area mapped as covered with heavy drift there are occasional rock outcrops, but these are infrequent, and the drift in this area completely masks the topography of the underlying rock.

MAIN VALLEY AND ITS MORAINES.

In the main valley of the South Platte the upper end of the area of heavy drift below Hoosier Pass marks the division line between the area of accumulation and that of dissipation. Below this line the valley bottom is covered with heavy drift down to the lower end of the system. The east wall of the valley, however, is steep, and numerous outcrops of rock along it show that the drift is thin down

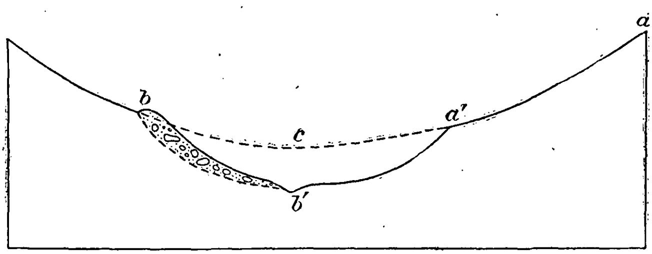


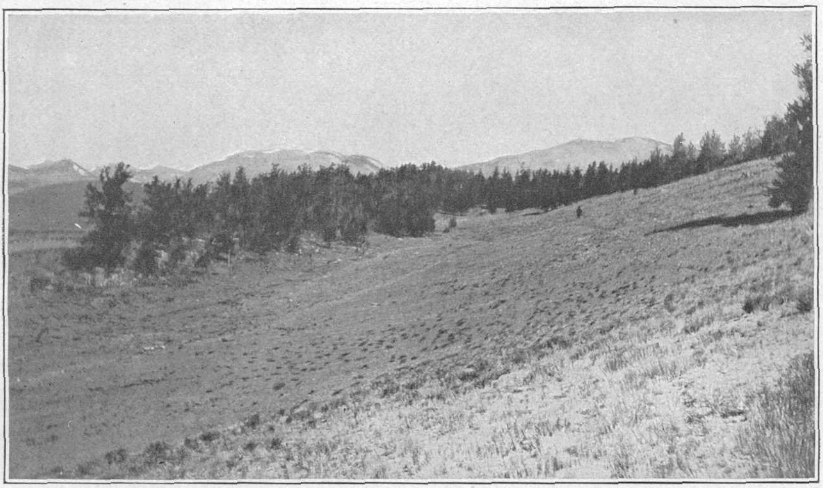
FIGURE 14.—East-west section of South Platte Valley between Mounts Lincoln and Silverheels. *a, a'*, Unglaciated tributary valley; *c, b'*, amount of glacial deepening of main valley. The west valley wall between *b* and *b'* is covered with drift. Horizontal scale, 1 inch=one-half mile. Vertical scale, 1 inch=one-fourth mile.

to a point within a mile of Alma. Above the limit of glaciation are a number of unglaciated hanging valleys which indicate the extent of glacial deepening this valley has suffered (fig. 14).

The west slope of the valley, above Alma, is covered with heavy drift up to the limit reached by the ice. The drift shows a low ridge form locally, but more often lies in a bench against the mountain slope. This drift has filled up the lower ends of the small draws which run into the main valley, and through this drift the streams have cut channels to depths of 50 feet and less.

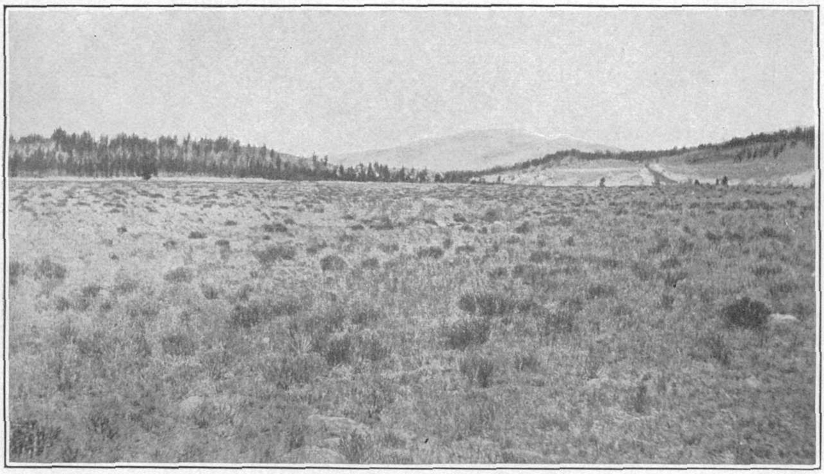
Below Alma the drift on the east side of the valley becomes more prominent, and is disposed as a bench down to the 200-foot hill 1 mile southeast of London Junction. South of this hill a fine lateral-moraine ridge appears. At its upper end it rises 400 feet above the river, and its outer slope is 20 to 60 feet high. This moraine ridge continues southward, with a more or less regular crest, to the lower end of the system, where the Platte flows out of the glaciated area.

In the valley bottom, between Hoosier Pass and London Junction, there are patches of partially stratified drift which individually look



A. VIEW NORTH FROM POINT BEYOND END OF PLATTE SYSTEM OF GLACIATION.

The high terraces occupy the foreground, with the moraines of the last glaciers above. The ridge to the extreme right is covered with older drift.



B. SHALLOW DRAW BETWEEN TIMBERED NEW MORAINE CREST ON LEFT AND MATURE OLD DRIFT RIDGE ON THE RIGHT.

This locality is on the east side of Platte River, near the lower end of the Platte system of glaciation.

like terrace remnants. Taken collectively they have no definite relations between themselves, and cuts in them show the materials to be poorly or not at all stratified, so they seem to be merely phases of the heavy-drift deposit which covers the bottom of the entire north-south valley of the Platte within the glaciated area.

Little drift of distinctly terminal-moraine origin occurs in connection with this system. Across the Platte Valley there is a ridge of material which extends westward from the Platte and is continuous with the Sacramento south lateral moraine. This ridge is of drift, and shows some hummock-kettle topography on its north slope, but it can be considered as a continuation of the south lateral moraine of the Sacramento Glacier as well as the terminal moraine of the Platte system.

GLACIAL EROSION.

Besides the profound change in the cross section of the valleys of this system, which was due to glacial erosion, there was very considerable deepening of most of them by glacial scour and pluck. In the higher parts of the mountains, where every valley of considerable size contained a glacier, it is difficult to estimate the amount of this glacial deepening, but in the lower course of the glacier, where the tributary valleys were unglaciated, we have a basis from which to calculate the deepening. Such calculations are subject to error (see p. 12), but we can at least get an idea of the order of magnitude of this erosion. In the valley of the South Platte, 2 miles south-southeast of Hoosier Pass, a sketch made in the field shows the cross section to be as shown in figure 14. A tributary valley from the east ends 500 feet above the Platte, and a continuation of the stream profile would give a glacial deepening here of about 300 feet.

OLDER DRIFT.

At the lower end of the South Platte system there are two patches of older drift, lying just outside of the later moraines, one on the east side of the stream and one on the west (Pl. VI, *A* and *B*). The east patch covers the ridge between the Platte and Beaver Creek, and occupies the position the new moraine would have had if the ice had pushed a mile farther downstream. This drift is separated from the new moraine by a shallow draw, but is distinct from it in its surface configuration. The surface shows bowlders deeply decayed, with the more resistant crystals weathered into prominence. At the south end of this patch the drift forms a thin veneer over the red grits of the ridge, and the drift itself shows a strong red tinge, due to the grits which the ice has incorporated into the drift here.

The patch west of the Platte lies for the most part between the East Leadville road and the moraines of the last epoch. No cuts were observed, but the bowlder-strewn surface has much the same appearance as the older drift has in other places. This patch shows that the older ice extended at least a mile farther south than the last ice.

During the summer of 1906 the excavations at the Snowstorm placer mine, in the moraines of the Platte system, southeast of London Junction, showed the fresh, unoxidized drift of the last ice epoch overlying a body of oxidized and decayed drift of notably greater age.

HIGH TERRACES.

Beyond the end of the moraines of this system there is an extensive deposit of gravels, which bears the same relations to the older drift deposits of this system as the high terraces in the Arkansas Valley bear to the older drift there. These gravels are very imperfectly stratified and slope away from the lower end of the Platte and Horseshoe Gulch systems of glaciation, with an angle of 3° to 3½° (Pl. VI, *A*), which decreases to 2° a few miles below these moraines. The gravels are deeply oxidized, and many of the pebbles are decayed and crumbling.

Platte River, unlike the Arkansas, has not been able to intrench itself deeply into these gravels, and they have not been reduced to terraces, so characteristic of similar gravels in the Arkansas Valley.

CLIFF GLACIERS ON MOUNTS LINCOLN AND BROSS.

Cameron Amphitheater.—On the east side of the Mounts Lincoln and Bross ridge there are two small glaciated valleys, in which the glaciers were never strong enough to push down to join the glacier in the valley of the Platte. Of these tributaries the northern one, called by Emmons "Cameron Amphitheater," received the ice from the sides of Mounts Lincoln and Bross. Despite the fact that these are the two highest peaks in the range, the glaciation in this valley was very feeble. The ice was probably never more than 100 feet thick in this gulch, and the shape of the valley was not profoundly altered. The maximum length of this glacier was less than 1½ miles, and the materials of the drift are angular and little worn.

The slight development of the ice at this point was doubtless due to the small collecting area. The deep cirques to the north, west, and southwest received most of the snow from the mountains.

Bross Amphitheater.—The southernmost of these two cirques is cut into the east side of Mount Bross. The cirque walls are composed of the sedimentary beds, but the bottom is in the pre-Cambrian rocks. The head walls rise cliff-like above the valley floor, and the cirque head, though small, is U-shaped. Only the upper end of the valley is free from a covering of drift. The lower part of the glaciated area is covered with glacial débris, which lies as a broad lobe on the mountain flank. This drift shows a marked morainic topography, though of slight relief, and is thickly strewn with bowlders up to 6 feet in diameter. At its lower edge the drift from this glacier comes within a few hundred feet of the drift in the main valley, but the two ice bodies were never connected.

HORSESHOE GULCH GLACIER.

The Horseshoe Gulch Glacier occupied the valley of Fourmile Creek for 10 miles below the head of that valley, and had an area of about 11 square miles. Its head was double and the southernmost part was again subdivided.

The north head of this valley shows the result of vigorous ice erosion and contains little loose material. To the north and toward Mount Sherman the head walls are steep and the deepening of the valley by the ice was considerable. To the west the valley floor rises more gently toward the crest of the range, and the ice failed to excavate this side of its bed sufficiently to form steep cliffs at its border.

The north half of the south head is cut into the steeply dipping sedimentary beds, which impart to the cirque head the beautiful arched appearance that has given it the name "Horseshoe." At the Horseshoe the head and side walls are cliff-like and have large talus slopes at their base. The south division of this head is much like the one to the north, and gives the same arched appearance to the beds, though in a much less striking way. The head is less perfectly formed, and its symmetry is marred by quantities of postglacial talus.

Along the Sheep Mountain ridge the upper ice limit can be located rather sharply by the topographic break in the slope, the walls rising steeply to the upper limit of glaciation and less steeply above it. On the north side of the valley this upper limit is much less sharply defined. Below Sheep Mountain the walls are very steep and deeply weathered, so that the ice limit has become indistinct and the base of the cliff is buried deeply by talus. East of Sheep Mountain the ice emerged from its narrow gorge and spread out to form a great broad lobe flanked by strong lateral moraines.

On the northeast side of the valley the lateral moraine begins at the point where the ice emerged from its narrow canyon. It swings away from the rock ridge and runs to the southeast, with a fine, level-crested ridge. At its upper end this ridge is 400 feet above the stream, but becomes lower downstream. In many places the crest is composed of a number of minor ridges, 10 to 20 feet high, parallel with one another and with the main valley. Bowlders are scattered thickly over the surface of this moraine, and the ridge seems to be almost entirely composed of drift, as there are no rock outcrops east of East Leadville.

The southwest lateral moraine lies against the rock valley wall and is not so striking a topographic feature as the opposite ridge, although of about the same height. It lacks the fine ridge form of the northeast moraine and appears as a bench of drift on the rock valley wall.

The Horseshoe Glacier left no good terminal moraine. The lateral moraines become lower and swing in toward the stream, and the drift gradually thins out to the southeast.

TWELVEMILE CREEK GLACIER.

The Twelvemile Creek Glacier headed back to the crest of the Park Range and occupied a tract 7 miles long, with an area of 6 square miles. The glacier was peculiar in that the ice in its head moved directly east while in its rock gorge, but below turned to the south, almost at right angles to the axis of the cirque.

The head of the system is partially divided by minor spurs into three divisions. Of these the south division has a steep wall a few hundred feet high at the very head, and below this the floor slopes with a uniform but steep gradient to the east. The middle division has a higher head wall, and here the glacial erosion was more severe, so that the slope is steep at the head, while the gradient of the valley below is more gentle. In the north division the head wall is steep, but the steepness resulted from the resistant quartzite beds more than from glacial cutting, for the head as a whole gives the impression of only slight glacial deepening, and the profile of the stream was not greatly altered by the erosion of the ice.

At the point where the small streams join to form Twelvemile Creek the valley becomes narrow. Here the ice was never more than 300 feet deep, and the shape of the valley was not profoundly changed by the ice. The walls show perpendicular outcrops up to the upper limit of glaciation, but no smoothed or striated surfaces remain.

Heavy drift occupies the valley bottom well up into the north and middle heads, and below the bend of the creek the whole of the glaciated area is covered with drift, which shows the hummock-kettle topography of a typical terminal moraine. No ice came down from Sheep Park. East of the bend in Twelvemile Creek, at the point where the ice pushed across the valley of Sheep Park Creek, it built up a good moraine ridge and forced the creek over to the east.

The whole north-south portion of this system is deeply covered with heavy drift. No good lateral-moraine ridge appears along the valley wall to the west, but between Twelvemile and Sheep creeks there is a great mass of drift formed of parallel north-south ridges having a strong terminal-moraine topography. This deposit becomes thinner to the south and finally disappears.

SOUTH FORK OF SOUTH PLATTE GLACIER.

The valley of South Fork of South Platte River held a glacier for 4½ miles below Weston Pass. It was fed by two shallow tributary gulches from the west and by the head of the main valley, but in none of these areas of accumulation was the ice of great depth or the glaciation severe. The head of the cirque below Weston Pass is covered with talus. The steep southwest slope of Weston Peak is so fractured and broken up that the upper limit of glaciation can not be located exactly, although ice certainly moved down the valley from this head.

The two tributaries from the west are shallow, the ice erosion being insufficient to convert them into cirques. The ice from the southernmost of these was not more than 75 feet thick where it joined the main glacier.

For 2 miles below the pass there is a rock ridge on the northeast side of the road, running parallel with it. There is but little drift on this ridge, although it was covered by the ice. Southwest of this ridge the heavy-drift area runs well up toward the valley head. Below the junction of the tributary valleys the main valley floor is covered with heavy drift. On the southwest wall there is an area where rock outcrops show through the drift, and another on the northeast wall, but as a whole the main valley contains sufficient drift to mask the surface of the bed rock.

Below the fork of the stream the ice was only 300 feet thick, and became thinner to the southeast. This small glacier did not build strong lateral moraines, and an occasional bench of drift on the rock wall is all that now appears. On the southwest side of the valley, above the thin-drift area, the drift has some depth, and takes on a hummock-kettle topography, with bowlders up to 6 feet in diameter scattered over the surface. Toward the lower end of the system the ice limit along the valley sides gradually approaches the stream, and the glacier ended at the point where the stream enters its narrow V-shaped gorge. No terminal moraine occurs, for any terminal materials deposited in the narrow gorge would naturally have been carried away rapidly by the stream, perhaps as fast as they were dropped by the ice.

WESTON GULCH GLACIER.

The Weston Gulch Glacier had a maximum length of 5 miles and an area of 3¾ square miles. It was fed by ice from two heads, one from the north and one from the south. The north head is a broad, comparatively flat area in which the amount of ice was barely sufficient to start movement. The head is wide and the ice affected the shape of the valley but little. Only the head walls are free from a covering of talus and drift.

The south head was in a narrow valley to the west of the main head of Weston Creek. In this valley the ice, accumulating on the east slope of the mountain, was higher on the west wall than on the east, and the surface of the glacier here sloped both to the east and to the north. In pushing north to join the other glacier this lobe crossed the main valley of Weston Creek, as is shown by the distribution of bowlders and drift. The ice from this head was barely strong enough to join that in the east-west valley of Weston Creek. Below the junction of the two heads the gulch is U-shaped for some distance downstream. The ice here was never more than 300 feet deep at its maximum, and this depth decreased rapidly to the west. The upper limit to which the ice reached is almost everywhere indistinct and could be determined only approximately. At an altitude of about 10,000 feet a drift plug lies across the valley, marking the lower limit of the ice. This drift has no terminal-moraine topography, but this was not to be expected where the glacier ended in a narrow gorge. The floor of the east-west gulch is everywhere drift covered, and bowlders of quartzite and pink and gray granite are numerous. Between Granite and Weston gulches, on the lower slopes of the rock valley wall, there are gravels of apparently the same age as the high-terrace gravels, but they occur as a thin veneer over the surface of the rock.

Near the mouth of Little Union Gulch the terrace materials have been cemented by calcium carbonate into a rather firm conglomerate, but this is a local phenomenon. Some of the beds here are rather well stratified and suggest the former presence of local lakes.

SLUMPED AREA.

East of the river near Crystal Lake station there is an area where extensive slumping has taken place in the terrace materials, giving rise to a topography which resembles that of a terminal-moraine area. There are many small lakes, with irregular hummocks between. Toward the upper end of the slumped area the material has taken the form of parallel ridges, parallel to the face from which the material slipped. The slope from the source of the material to the lower edge of the slumped area, a distance of about 2 miles, is only 4°.

EMPIRE GULCH GLACIER.

TOPOGRAPHY.

The Empire Gulch Glacier occupied the valley of Empire Gulch above an elevation of about 10,000 feet. This glacier was a little less than 5 miles long and had an area of only 3 square miles, yet it was vigorous, and profoundly altered the valley in which it lay. It was fed by the ice from but one cirque head. This head is in the pre-Cambrian rocks, and the head walls rise to steep, angular peaks. The rock, easily weathered, retains no striated or polished surfaces, but the broad U shape of the valley bears testimony to the severity of the ice action (Pl. VII, *B*). Only a moderate amount of talus occurs at the base of the clifflike head walls, and the bed rock, smoothed and rounded, outcrops over much of the cirque floor.

From the southwest flank of Long and Derry Hill a fine lateral-moraine ridge, 300 feet high at its head, swings down the valley side. West of Long and Derry Hill this ridge does not lie against the valley wall, but stands as a great ridge away from the rock ridge, 100 feet high on the outside and 200 feet on the inside.

The south lateral moraine is not very prominent. On the north flank of Empire Hill there is no drift, and the moraine takes on a low ridge form for only 1 mile above the terminal. West of the Union Gulch road the two lateral moraines converge rapidly, and join at about the 10,000-foot level to form a distinct terminal moraine (Pl. VII, *A*). In the terminal-moraine area the topography is most irregular and some of the larger kettles are occupied by lakes. The

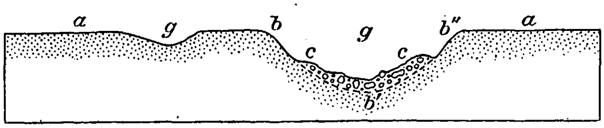


FIGURE 15.—Cross section across Empire Gulch one-half mile above lower end of Empire Gulch system. *a*, *a*, Plane of the high terraces, with plane of gulches (*g*, *g*) cut into it before the last ice epoch; *b*, *b′*, *b″*, cross section of the gulch before last ice advance; *c*, *c*, moraine of last epoch. Horizontal and vertical scale, 1 inch=one-third mile.

terminal moraine lies in a postglacial cut in the high-terrace gravels, and the terrace level is well above the top of the moraine at this place (fig. 15).

OLDER DRIFT.

At only two places on the west slope of the Park Range was any evidence of older drift discovered. One of these occurs in connection with the Empire Gulch Glacier. Just south of the terminal moraine of the last glacial epoch, at the base of Empire Hill, there is a patch of somewhat weathered erratic bowlders, most of them composed of the pink granite found farther to the east, which lie about 100 yards south of the edge of the new drift and 30 to 50 feet above it, on the opposite side of a low rock ridge. These bowlders could not have been brought to their present position by streams, and were probably left by the ice of an earlier epoch, which rose higher in the valley than did the last ice. The bowlders are much weathered and are deeply embedded in the soil.

Estimates of the amount of glacial deepening in Empire Gulch were made, based upon the same assumptions as were the estimates made for the Tenmile Valley. (See p. 9.) Here the tributary from the north side of Empire Hill ends 800 feet above the stream, which would indicate a glacial deepening of about 400 feet (fig. 16).

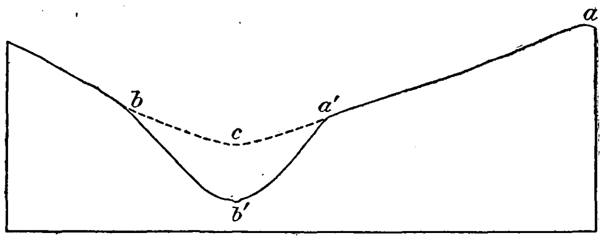


FIGURE 16.—North-south section of Empire Gulch south of Long and Derry Hill. *a, a′*, Unglaciated tributary; *c, b′*, glacial deepening of Empire Gulch. Horizontal and vertical scale, 1 inch=one-half mile.

HIGH TERRACES.

In connection with this glacial system there is a great development of high-terrace gravels. These terraces originally formed a gravel plain, which extended on the east side of Arkansas River from Granite Gulch to a point 2 miles north of East Fork of the Arkansas. As these gravels were originally deposited as a compound alluvial fan by the streams flowing from Weston, Empire, Iowa, Evans, and East Fork gulches, it is impossible to limit the materials which came from any one of these streams. This whole terrace area will therefore be described under the next heading.

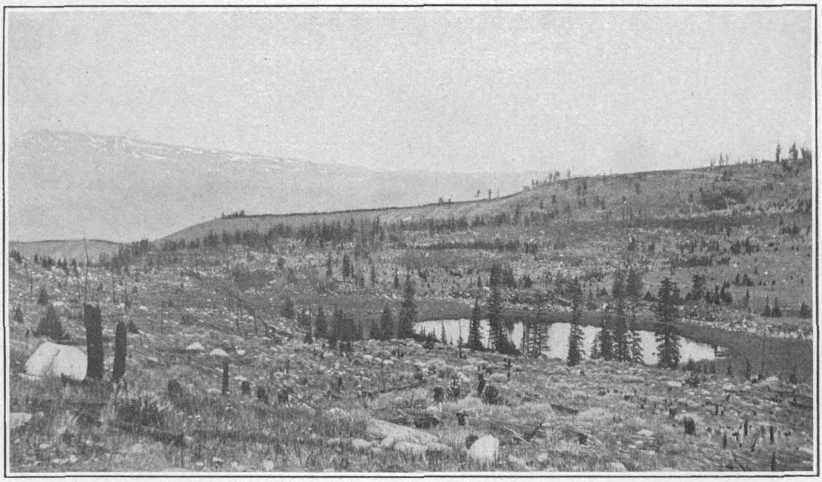
IOWA GULCH GLACIER.

TOPOGRAPHY.

Iowa Gulch contained a glacier more than 7 miles long, which extended down to an altitude of 9,850 feet. The head of this gulch is roughly divided into three cirques, which received the ice from the west slopes of Dyer Mountain, Mount Sheridan, and the Gemini Peaks. The head southwest of Dyer Mountain has its walls in the Paleozoic beds, but the valley bottom is in the pre-Cambrian rocks. The valley has a well-developed U shape, and the bottom is fairly free from talus, except at the base of the steep walls. The ice in this cirque extended almost to the col at the valley head.

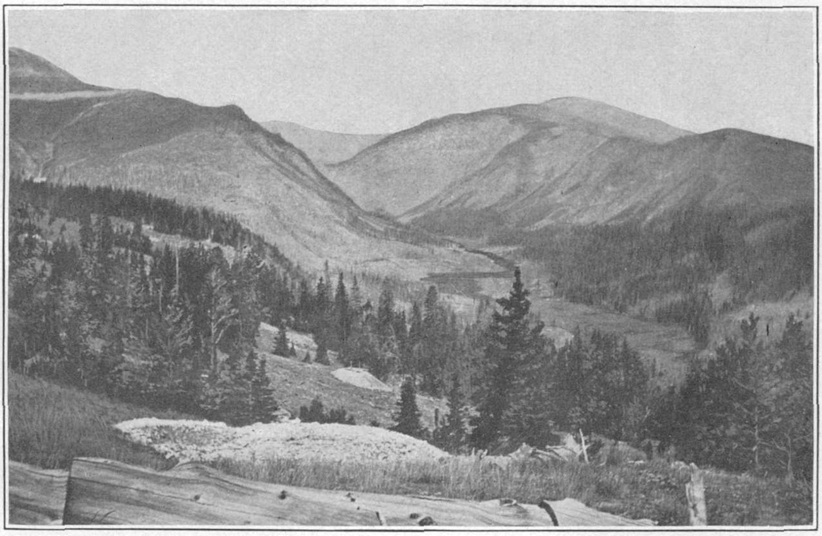
The head southeast of Dyer Mountain is in the crystalline rocks and is deeply eroded, though not of a very broad U shape. The bed rock is exposed over much of the valley floor, but it is concealed by talus at the foot of the cliffs.

The south head is only a slight reentrant into the south valley wall. The entire south wall of the valley, above the lateral-moraine deposits, is composed of fractured and broken outcrops of rock above and of deep talus heaps below, so that the limit to which the ice reached could be determined only approximately.



A. TERMINAL MORAINE OF EMPIRE GULCH SYSTEM.

Lying in a gulch cut in the high terraces before the last glacial epoch.



B. UPPER EMPIRE GULCH, FROM LONG AND DERRY HILL.

The south lateral moraine begins about 3 miles above the terminus, and at its upper end takes on a ridge form above the high-terrace gravels which form the walls of the valley at this place (fig. 17).

On the north side of the valley the drift first appears as a covering of the rock wall, but becomes thicker to the west, and locally shows a ridge form. A little below the 10,000-foot level the laterals converge to form a terminal moraine, consisting of a large body of drift lying across the valley, which is here a cut into the high terraces. To avoid the highest part of this moraine the stream makes a bend to the south and flows around the obstruction. This drift has a strong, irregular topography, and at its highest point it stands about 100 feet above the stream to the south of it.

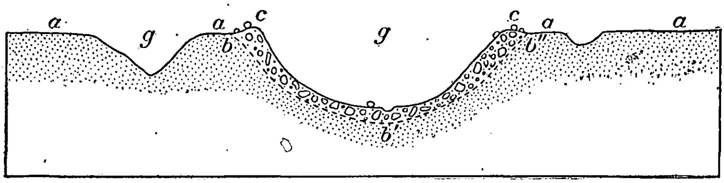


FIGURE 17.—Cross section across Iowa Gulch 4½ miles east of Arkansas River. *a, a,* Plane of high terraces, with gulches (*g*) cut into terraces after older ice epoch but before last ice epoch; *c, c,* moraines of last glacial epoch built within one of the gulches. The section from north to south is 1½ miles long. Horizontal scale, 1 inch=one-half mile. Vertical scale, 1 inch=one-quarter mile.

HIGH TERRACES.

The high terraces are seen at their best between Little Union Gulch and East Fork of the Arkansas, and are continuous along the Arkansas between these streams, although deeply cut into by a number of gulches. They are of the same order as those west of the river, and were doubtless once continuous with them, with the river at the axis of the two slopes.

Although a part of the terrace area has been reduced in height and there are gulches up to 600 feet deep in them, the flat-topped ridges between the gulches are part of the same plain, and were once continuous with one another (fig. 17).

It is impossible, with our present knowledge, to estimate the amount of detritus which was necessary to form these terraces. Gulches cut several hundred feet into the gravels fail to show rock, while shafts sunk in the Arkansas flat to depths of more than 100 feet do not reach the bottom of this material.

The materials here are much like those of the terraces already described. The gravels are coarsest near the mountains and become finer toward Arkansas River. In general the materials are oxidized and yellow, though some sections show a pinkish gray. Everywhere the granite bowlders are decayed and falling to pieces, while the quartzites remain sound.

Interbedded with the gravels in places are lenses of clay and sand, and there are suggestions of stratification in the gravels, but nothing approaching the perfect stratification of lake deposits was observed in any of the numerous sections offered by prospect holes and other cuts, and continuous beds of fine lancinated clays are altogether lacking.

The surface of the terraces has a profile, drawn from the mountains to the Arkansas, which is concave upward, and varies in slope from 1½° to 2° at the lower edge of the plane to 3½° at the upper edge. The whole area seems to be a great compound alluvial fan, with its principal foci at the points where Empire and Iowa gulches emerge from their rock gorges, while the smaller gulches north and south of these added their quota to the general plain.

The terraces on the Leadville side of the river can not, like those on the west, be traced directly back to bodies of older drift, for no such bodies now exist on the east side. The only older drift found here consisted of a few scattered bowlders south of Empire Gulch, which were just above the upper edge of the terrace gravels. These deposits, however, are contemporaneous with the terraces west of the river, as is shown by the correspondence in the weathered condition of the materials, in the height of the terraces, and in their stage of dissection. As the terraces west of the river are directly traceable to older drift at their upper ends, those east of the river are doubtless the product of that same period of abundant waters and vast quantities of detrital materials.

LOW TERRACES.

In Iowa Gulch, below the moraines of the last glaciers, there are two small areas of low terrace gravels which rise 20 to 30 feet above

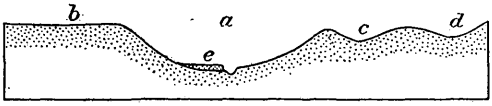
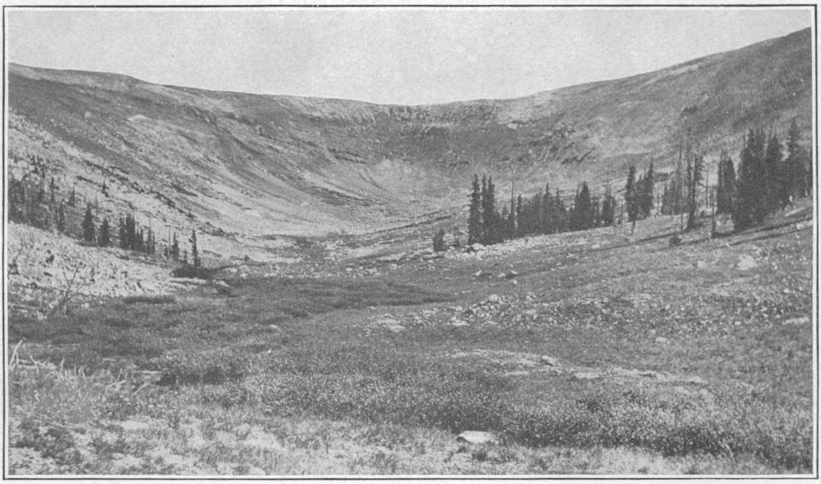


FIGURE 18.—Section across Iowa Gulch (*a*), showing high-terrace level (*b*), remnant of low terrace (*e*), and portion of high terrace reduced in height by development of contiguous gulches (*a*, *c*, and *d*). Horizontal scale, 1 inch=one-half mile. Vertical scale, 1 inch=one-fourth mile.

the flat of the gulch bottom (fig. 18). These terraces are 150 feet below the level of the high terraces, and are the remnants of a gravel train deposited during the last glacial epoch. In age and amount of erosion these gravels can be correlated with the latest moraines, but the waters of Iowa Creek, confined in the bottom of the narrow gulch, have in postglacial time removed all of the low-terrace gravels but these two patches.



A. LITTLE EVANS CIRQUE.

B. POSTGLACIAL CUT IN DRIFT AT MOUTH OF LITTLE EVANS GULCH.

EVANS GULCH SYSTEM.

Evans Gulch was occupied by a glacier from its head down to Leadville, a distance of 6½ miles. Two large cirques and one small one contributed ice to this glacier, which had a total area of 6½ square miles.

The head of this system took its ice from the slopes of Mount Evans and Dyer Mountain. This cirque is large and broadly U-shaped and is cut down into the pre-Cambrian gneiss. At its upper end the east wall of this valley rises in an almost perpendicular cliff below Dyer Mountain. Between Dyer Mountain and Mount Evans the divide shows serrate peaks where the Sacramento and Evans glaciers have worked their head walls back to the crest of the ridge. The lower and more gentle slopes of the cirque walls are deeply buried in talus.

For the upper 2 miles of its course Evans Creek flows to the northwest; then it turns sharply to the southwest. North of this bend there is a small valley running back to the north which was occupied by ice, but the erosion in it was never strong enough to excavate it into a cirque.

South Evans Gulch had an ice lobe of some size, but the ice here was never very deep or of very great erosive power. Some drift covers the lower valley floor, and the talus-covered slopes above the ice limit are in contrast with the steeper glaciated slopes below.

On the south side of Evans Gulch the heavy-drift deposits first become prominent one-half mile east of Yankee Hill. Here the south valley wall becomes lower and the ice spread out in a spatulate lobe, covering Fryer and Yankee hills and reaching south a little beyond Stray Horse Gulch. Over Fryer and Yankee hills it left drift of varying thickness, cuts in which show fresh drift and striated subangular bowlders. The west base of Fryer Hill marks the edge of the glaciated area, and the terrace gravels slope away below.

On the north side of Evans Gulch the lateral moraine is much more definite. From the spur on the east side of Little Evans Amphitheater the lateral moraine swings to the west with a high, distinct ridge. This ridge extends without a break across the mouth of Little Evans Amphitheater, its crest 400 feet above the valley floor, and continues westward as a distinct ridge for more than 3 miles. Toward its western end this ridge becomes lower and wider and takes on a hummock-kettle topography, showing a number of low ridges running parallel with the stream. On the north this moraine extends to the bottom of Little Evans Valley, which was formed by the building up of this ridge of drift at the foot of the rock slope. At one place near the lower end of Little Evans there is a post-glacial cut 30 feet deep into the rock, where the moraines of the glacier forced its extraglacial stream onto the slope of the rock valley wall.

Little Evans Amphitheater is cited by Emmons as a cirque cut by the ice of an earlier epoch of glaciation, because the Evans lateral moraine of the last epoch crosses the mouth of Little Evans Amphitheater without a break, and forced the drainage from Little Evans cirque to find a new outlet north of the Evans moraine. There is no doubt, however, that Little Evans cirque was occupied by a glacier of the last epoch (Pl. VIII, *A*). This glacier was not long enough to reach the ice in the main valley of Evans Creek, so the Evans Gulch Glacier built its lateral moraine without interruption across the Little Evans Valley, and the Little Evans Glacier pushed down to the edge of the Evans Gulch moraine and deposited its drift against the outside of this moraine. Little Evans Amphitheater itself is as fresh in appearance as any of the cirques of this neighborhood, and the drift at its mouth has the fresh, hummocky topography and uneroded surfaces of the last drift. The stream from the cirque has a shallow V-shaped cut in this drift (Pl. VIII, *B*), and the bowlders of the moraine are fresh and firm. The ice from this cirque barely failed to connect with the Evans Glacier.

INDEX.

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