A Pleistocene Ice Sheet in the Northern Boulder Mountains Jefferson, Powell, and Lewis and Clark Counties, Montana

By EDWARD T. RUPPEL

CONTRIBUTIONS TO GENERAL GEOLOGY

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A descriptive report of the glacial geology in the northern part of the Boulder Mountains, Montana

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A PLEISTOCENE ICE SHEET IN THE NORTHERN BOULDER MOUNTAINS, JEFFERSON, POWELL, AND LEWIS AND CLARK COUNTIES, MONTANA

By Edward T. Ruppel

ABSTRACT

The northern part of the Boulder Mountains, between Butte and Helena, Mont., is in large part blanketed by glacial deposits and by the products of postglacial frost action and mass-wasting. The glacial deposits, largely till, are probably of early Wisconsin age. These deposits were left by a mountain ice sheet—and associated subsidiary valley glaciers—that attained a thickness, at least locally, of more than 1,000 feet and covered about 200 square miles.

Since glaciation ended, frost action, mass-wasting, and related erosive processes have produced a variety of colluvial and residual accumulations including creep-and-solifluction deposits, stone-banked terrace deposits, protalus ramparts and associated rock streams, talus, landslides, and related forms. The form and distribution of some of these deposits suggest three episodes of intensified frost action since glaciation: an early episode, perhaps contemporaneous with alpine glaciation, probably of late Wisconsin age, in neighboring mountain ranges; an intermediate episode contemporaneous with cirque glaciation in the neighboring ranges; and a late episode that was very recent.

INTRODUCTION

The surficial deposits of the northern part of the Boulder Mountains were investigated as part of a more general study of the Basin quadrangle (fig. 1), which in turn was part of a study of the geology and mineral deposits in and near the Boulder batholith. The general geology of the Basin quadrangle is discussed in detail in another report (Ruppel, 1962). John Rodgers and R. F. Flint, of Yale University, as well as several Geological Survey colleagues, critically reviewed the manuscript, and I am grateful for their helpful suggestions and criticisms.

The Boulder Mountains are mostly low and rounded (figs. 2, 3), and so differ markedly from most of the other mountains in western Montana. Most of the mountain tops are at altitudes ranging from

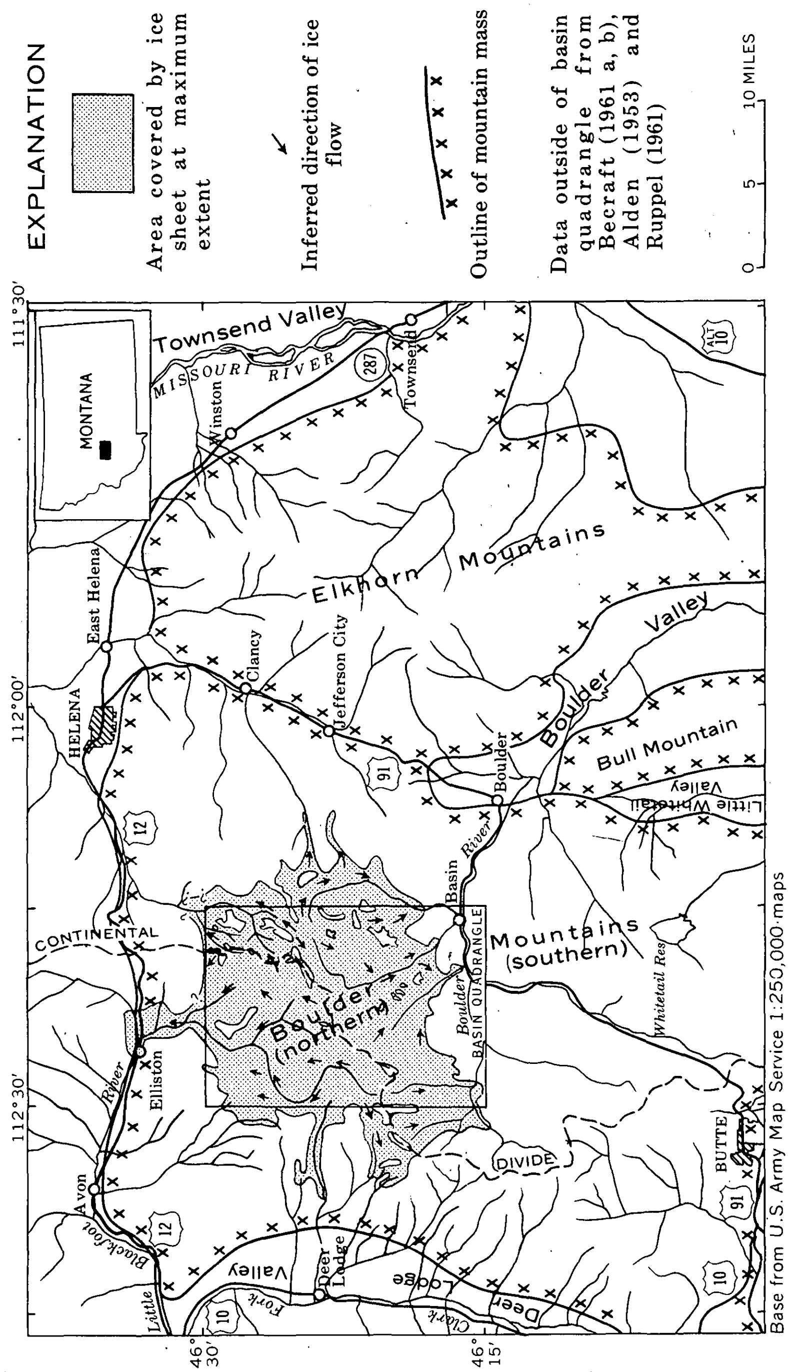

Figure 1.—Inferred limits of northern Boulder Mountains ice sheet, Montana.

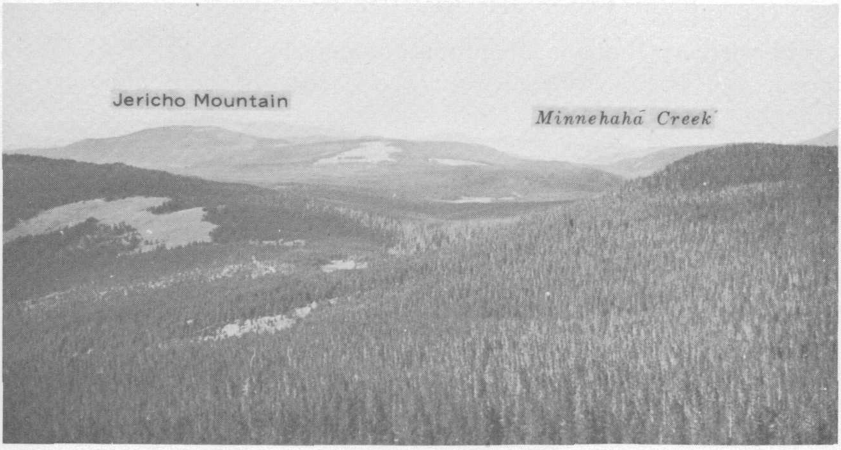

FIGURE 2.—Typical topography along Continental Divide in northern part of Boulder Mountains.

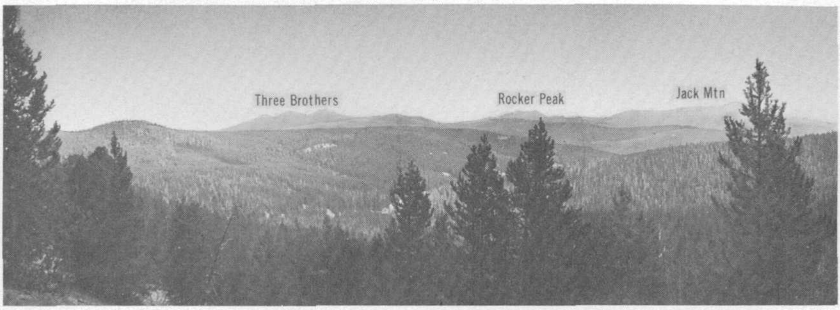

FIGURE 3.—Typical rounded topography east of Thunderbolt Mountain.

7,000 to 7,600 feet. A few peaks, such as Thunderbolt and Jack Mountains, rise above the general level of the range, but even they are not rugged. The local relief in the northern part of the range rarely exceeds 1,500 feet and commonly is less than 1,000 feet; the total relief is about 4,000 feet. The lowest points are in the valleys of Tenmile Creek and the Little Blackfoot River at the north end of the range.

The Continental Divide extends in a general northeast direction across the northern Boulder Mountains. Nearly all the streams flow in valleys that have been glaciated, and most streams head in broad basins that contain large swamps and bogs. In the southeastern and northwestern parts of the area, the valleys of all the major streams and many of their tributaries trend either northeast or northwest, and the drainage patterns are strikingly rectilinear.

SUMMARY OF BEDROCK GEOLOGY

The northern Boulder Mountains are underlain principally by Cretaceous and Tertiary volcanic rocks and by rocks of the Boulder batholith (Ruppel, 1961, 1962). Sedimentary rocks of Jurassic and Cretaceous age that crop out west of the Little Blackfoot River in the northwestern part of the region include mudstone of the Morrison formation of Late Jurassic age; sandstone, shale, mudstone, and limestone of the Kootenai formation of Early Cretaceous age; and shale and sandstone of the lower part of the Colorado formation of Early Cretaceous age.

The sedimentary rocks are unconformably overlain by the Late Cretaceous Elkhorn Mountains volcanics, which consist largely of quartz latitic welded tuff. The volcanic rocks probably are equivalent to the middle member of the formation in the type area (Klepper, Weeks, and Ruppel, 1957, p. 31–41), although representatives of the upper and lower members are thought to be present locally. Basaltic rocks unconformably overlying locally welded tuff and tuff breccia in the northwestern part of the mountains are provisionally assigned to the Elkhorn Mountains volcanics; perhaps they are partly equivalent to the upper member of the formation.

Quartz monzonite, granodiorite, and related rocks of the Boulder batholith were emplaced at or near the close of the Cretaceous period, and throughout most of the map area where these rocks crop out, the top of the batholith is at or near a single stratigraphic horizon in the Elkhorn Mountains volcanics. The volcanic rocks near the batholith were metamorphosed, mainly to hornfelses.

The Tertiary record includes two episodes of erosion, each of which was terminated by an episode of volcanism. Early Tertiary erosion unroofed the batholith and produced a mountainous landscape onto which the quartz latitic Lowland Creek volcanics (Smedes, 1962) were erupted in Oligocene time. After the eruption of the quartz latite, a broad landscape of low relief was carved. This surface was deeply weathered before it was covered by Miocene(?)–Pliocene(?) rhyolitic rocks, and locally saprolite 10 to 20 feet thick was formed on the batholitic rocks. The maximum depth of prerhyolite weathering is not known, but it was probably about 100 feet in most of the batholithic rocks. During the erosional intervals that preceded the Tertiary volcanic eruptions, a drainage system ancestral to the present system was established.

After the eruption of the rhyolite, erosion stripped away part of the volcanics rocks of Tertiary age and formed the present low mountains that have been modified by glaciation.

SURFICIAL GEOLOGY

A large part of the northern Boulder Mountains is covered by surficial sediments that were deposited mainly by glaciers, but which locally include deposits formed by mass-wasting processes and by streams. The surficial sediments are mapped and briefly described elsewhere (Ruppel, 1962).

The glacial deposits are the product of a single glacial episode, probably of Wisconsin age. The glaciation included three phases: an initial valley-glacier phase, an intermediate mountain-ice-sheet phase, and a final phase in which the mountain ice sheet thinned and the glaciers retreated. During the ice-sheet phase, the major centers of ice accumulation and the central part of the sheet were in the vicinity of Thunderbolt and Bison Mountains, where the ice attained a thickness of more than 1,000 feet. At its maximum development (fig. 1; pl. 1), the ice sheet blanketed most of the Basin quadrangle. The southern limit of the ice sheet was north of the Boulder River, and only ice streams in the major valleys extended far beyond the east and north margins of the quadrangle. The ice sheet at its maximum development covered about 200 square miles.

Glaciation was preceded, probably in Pliocene and early Pleistocene time, by the cutting of the Boulder River valley. This early erosional episode is represented along the present river valley (Ruppel, 1962) by paired strath terraces and associated veneers of stream gravel.

Mass-wasting processes have dominated postglacial erosion, forming protalus ramparts, small rock streams, talus, landslides, and swamp and bog deposits. Frost-formed fields of angular boulders and fields of rounded boulders of disintegration are locally common. The glacial deposits have been dissected and smoothed by mass-wasting and by streams.

Postglacial stream deposits are present only along the courses of the major streams and as small alluvial fans built into the major valleys by tributary streams.

NORTHERN BOULDER MOUNTAINS ICE SHEET

Glacial drift is by far the most abundant surficial deposit in the northern Boulder Mountains. It conceals the bedrock in at least one-third of the Basin quadrangle, floors the major valleys, extends high on the flanking valley walls, and in many places blankets interstream divides. The drift consists mainly of remnants of a widespread till sheet, but it includes small lateral, medial, and end moraines and stratified drift in valley trains.

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The principal areas of ice accumulation almost certainly were in the western part of the Basin quadrangle, for ice-transported boulders from known source areas, ice-carved outcrops, some with stoss and lee sides, and glacial deposits having directional features indicate that ice flowed more or less radially (pl. 1) from the vicinity of Thunderbolt Mountain and the area along the Continental Divide between Thunderbolt and Bison Mountains. Ice-carved rock bosses, which indicate the direction of ice movement (pl. 1), and the form, distribution (Ruppel, 1962), and rock content of the till point to many subsidiary ice-accumulation centers; for example, at the heads of Tenmile and Basin Creeks and on Jack Mountain.

Nearly all the interstream divides in the central and eastern parts of the Basin quadrangle were stripped and carved by ice, and some were left mantled with till as the ice receded. Scattered erratic boulders lie on many carved interstream divides that otherwise are nearly free of till. These divides probably were left as bare rock surfaces by the retreat of the ice, for there is no indication of postglacial erosion that could have removed or destroyed an original mantle of glacial debris.

The distribution of the erosional and depositional features indicates the former presence of a mountain ice sheet, which at its maximum extent covered an area of about 200 square miles. Although it is reasonable to assume that the mountain ice sheet was preceded by cirque and valley glaciers, no deposits of such an initial phase have been recognized. The poorly defined cirques and broad shallow theaters at the heads of most of the major stream valleys probably originated during such an initial phase of glaciation and later were smoothed under the mountain ice sheet.

The ice fields feeding the early valley glaciers must have slowly thickened until they coalesced to form the mountain ice sheet above which rose only a few peaks. The distribution of glacial erosional and depositional features indicates that although a large amount of ice moved across the divides, it was all ultimately channeled into ice streams that occupied the valleys, carving them into typical U-shaped troughs that have been modified only slightly by postglacial erosion. Near the margin of the sheet, subsidiary ice accumulation centers fed glaciers tributary to the main ice streams.

The lower limit of glacial deposits and ice-carved features, other than those formed by the major ice streams, and of deposits or features suggesting perennial snow accumulations, is at an altitude of about 7,000 feet in the southern part of the ice-sheet area, and at altitudes of 6,000 to 6,500 feet on the east, north, and west. The floors of the rounded cirques and glacial theaters are at altitudes of 6,800 to 7,200 feet, except for the shallow, south-facing cirque at the head of Thunderbolt Creek, which has an altitude of 7,400 feet.

The valley-glacier phase and the mountain-ice-sheet phase together may have lasted through nearly all the glacial period. The final phase, that of the thinning of the sheet and retreat of the glaciers, probably was relatively short, for the upland topography and the cirques that had been smoothed under the mountain ice sheet were not sharpened by the later alpine glaciation that would be expected to accompany a waning mountain ice sheet.

GLACIAL EROSION

Features characteristic of glacial erosion are common in much of the northern Boulder Mountains. They include smoothed and subdued cirques; the prominent glacial troughs that now form the stream valleys; rock steps in the stream valleys; hanging valleys; truncated spurs; ice-cut channels across ridge crests; ice-carved and striated rock bosses, some with stoss and lee sides; ice-planed surfaces on canyon walls; ice-stripped surfaces; and melt-water channels cut on valley walls.

The poorly defined cirques and broad glacial theaters at the heads of most of the major stream valleys probably were formed by alpine glaciers early in the glacial stage, smoothed during the mountain-ice-sheet phase, but not resharpened by alpine glaciers during the recessional phase of glaciation. The smoothed cirques contrast strikingly with the well-defined glacial troughs that form the present stream valleys. The present depths and forms of many of the canyons and the distribution of glacial debris and erosional features indicate that the ice streams were locally more than 1,000 feet thick during the ice-sheet phase of glaciation. The deepest glaciated valleys are those of Thunderbolt Creek, the Little Blackfoot River, Red Rock Creek and Bison Creek. East of these deep valleys, the ice streams were not fed as directly from the central part of the mountain ice sheet, but rather received ice from (a) tributary ice streams fed by the central part of the sheet, for example, through the South Fork of Basin Creek, (b) the ice blanket moving across interstream divides, as in the upper parts of Basin Creek and Tenmile Creek, and (c) tributary ice streams fed from subsidiary accumulation centers near the margin of the ice sheet, as in the vicinity of Jack Mountain. Perhaps as a result of their less direct source of supply, these ice streams generally were not as thick as those farther west. Although their thickness may locally have approached 1,000 feet, the present form of the valleys and the distribution of glacial drift and of ice-carved features suggest that the most common thickness of the ice streams was probably appreciably less, perhaps on the order of 500 feet.

Rock steps are common in the valleys (fig. 4) in the eastern part of the ice-sheet area, but they are absent in the valleys farther west. Without exception the rock steps are slightly upstream from the confluence of a tributary glacier with the main ice stream. This consistent relation and the absence of bedrock control in any of the rock steps indicates that the steps were cut by the main ice streams in response to the increased volume of ice where the tributary ice streams entered the main stream. The treads of the steps have been hollowed out and are now filled with outwash; the risers are commonly steep and are less than 100 to about 400 feet high. The rounded risers in Basin Creek south of Jack Creek probably reflect lesser amounts of ice entering the main ice stream from the tributary streams in this area and perhaps, as well, the coarser grain size of the bedrock in this

FIGURE 4.—Entrenched rock step in the canyon of Basin Creek at its junction with Jack Creek and South Fork Creek. Light-colored area is eroded till mantle on riser of rock step.

vicinity. Since glaciation, the rock steps have been trenched by stream erosion.

The absence of rock steps in the valleys in the western part of the ice-sheet area almost certainly is a result of the absence of tributary glaciers from secondary accumulation centers, for all the ice in these valleys was derived from the central part of the mountain ice sheet.

Truncated spurs and hanging valleys are best developed in the valley of Basin Creek and its tributaries, but they are common in many other valleys. Three prominent channels have been cut along structurally weak zones by ice flowing across the ridge east of the junction of Jack and Basin Creeks. Ice-carved and ice-planed bosses and surfaces are common on valley walls, and streamlined bosses are especially abundant locally on the ice-stripped interstream divides in the central part of the ice-sheet area. Stoss and lee sides are clearly evident on only a small number of the streamlined bosses. Glacial striae other than grooves an inch or more deep have been destroyed by postglacial weathering except in the very fine grained volcanic rocks at the north end of Jack Creek Ridge, and glacial polish has been similarly destroyed except locally on fine grained batholithic and volcanic rocks on the west valley wall of Thunderbolt Creek.

Melt-water channels cut in bedrock or partly in bedrock and partly in drift are common at different altitudes on the valley walls flanking the middle and lower parts of Basin and Red Rock Creeks, but they were not recognized elsewhere. The location of the larger channels is shown on plate 1. The channels typically are less than 100 feet wide, 20 to 40 feet deep, and only a few hundred feet long. They are thought to have been cut by melt-water along the edge of the receding ice.

GLACIAL DEPOSITS

The glacial deposits in this region include till and outwash. Till forms a broad, rather thin blanket that covers valley walls and much of the broad, flat region in the central part of the map area. The assumed initial morainic topography of the till has been smoothed and dissected, and the form of the deposits on some valley walls has been modified by mass-wasting processes. The composition of such smoothed or mass-wasted deposits clearly indicates, however, that they are till. Lateral moraines are conspicuous locally in the valleys of Tenmile, Jack, and Red Rock Creeks, but they are inconspicuous or absent elsewhere. Medial moraines are present in a few places where separate ice streams merged, as at the junction of Monitor and Tenmile Creeks and at the junction of the north- and northeast-trending branches of Jack Creek. A prominent end moraine was deposited by the combined Red Rock and Basin Creeks ice streams

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near the mouth of Red Rock Creek, and a second large end moraine was deposited at the mouth of Thunderbolt Creek by the combined ice streams from the valley of Thunderbolt Creek and the valley of Rock Creek, the next major valley to the west.

The glacial deposits are weathered to an observed depth of at least 6 feet and possibly to as much as 10 feet. The depth of weathering is estimated on poor exposures, however, so the actual depth is somewhat uncertain.

The till is composed primarily of material derived from the local bedrock, the most abundant materials being batholithic rocks, Elkhorn Mountain volcanics, and, rarely, massive white quartz. Where volcanic rocks of Tertiary age crop out they are abundant in the till, but away from the outcrop areas they are represented only by sand and finer grained material. The larger rock fragments in the till range from a few inches to many feet in diameter, the size being controlled primarily by the jointing in the bedrock in the source area and by the degree of granular disintegration of the coarser grained rocks. Fragments of volcanic rocks are comparatively small, typically 6 inches to 1 foot across, and those of granitic rocks characteristically are about 1 foot to 6 feet across. In the vicinity of Vacchiou Gulch and Clay Creek, the till contains exceptionally large boulders derived from the coarsely jointed batholithic rocks on the west side of Jack Mountain; blocks 5 to 8 feet in maximum dimension are abundant, and larger blocks, one 35 feet long, are common. Fragments of batholithic rocks in the upper few feet of till typically are disintegrated to depths of 3 to 6 inches, and those exposed on the surface commonly are surrounded by exfoliation shells and by sand produced by granular disintegration. Very few cobbles and pebbles of batholithic rocks are present in the till, apparently because they have been completely destroyed by granular disintegration.

Outwash deposits occupy a few valleys. The outwash in the Boulder River valley was derived mainly from the western part of the map area. Like that along Red Rock Creek, the outwash consists of poorly sorted cobbles and small boulders of volcanic rocks of Cretaceous age and sparse boulders of batholithic rocks. The outwash in the valleys of Basin Creek and the Little Blackfoot River, on the other hand, is better sorted and finer grained and contains more sand and gravel lenses. Batholithic rocks are nearly absent in the outwash gravels of Basin Creek, which consist almost wholly of pebbles, cobbles, and small boulders of Elkhorn Mountains volcanics and a small proportion of massive quartz in a matrix of sand that was derived principally from the disintegrated quartz monzonite.

Well-sorted finely layered sands containing many small clusters of ice-rafted pebbles are present northwest of Pole Mountain. They apparently were deposited in a pond behind a moraine dam during the waning phase of glaciation.

AGE AND REGIONAL RELATIONS OF GLACIATION

The glacial history of the northern part of the Boulder Mountains is rather simple, as it includes only one period of glaciation. The history of glaciation elsewhere in the Boulder Mountains and in the Elkhorn Mountains (Klepper, Weeks, and Ruppel, 1957, p. 62) farther east is different but the sequence of glacial events in the entire northern Boulder batholith region can be reconstructed and correlations can be made with reasonable certainty (fig. 1; pl. 2). Correlations with other glacial deposits in western Montana are less certain.

The correlation of glacial deposits is based on comparisons of the extent of postglacial erosion and destruction of initial ridges, knobs, and depressions in morainic deposits; the thickness of weathering rinds on boulders of quartz monzonite in the till and on stripped and carved surfaces of quartz monzonite; and, to a lesser extent, on the depth of postglacial weathering in the till. The surface of the till in the Basin quadrangle is relatively smooth and retains few of the original depositional irregularities. Drainage is well integrated in and across the areas covered by till, and no undrained depressions remain except those that were carved in the bedrock by the glacier. Quartz monzonite boulders in the till typically are disintegrated to a depth of 3 to 6 inches, and most fragments of quartz monzonite that were less than 1 foot in diameter have been completely destroyed by granular disintegration and are represented by sand and clay in the till. The weathering rinds on ice-carved outcrops of quartz monzonite similarly are 3 to 6 inches deep. The fragments of Elkhorn Mountains volcanics and of lava flows and other very fine grained volcanic rocks of Tertiary age that form the bulk of the drift are not noticeably weathered. Fragments of coarser grained or more porous volcanic rocks of Tertiary age—tuff, lapilli tuff, or welded tuff—are not in the drift, probably because they have been destroyed by postglacial weathering. Boulders of quartz monzonite are the most satisfactory for comparison of postglacial weathering effects because of the wide area of their occurrence in the northern part of the Boulder batholith. Because of poor exposures, the depth of postglacial weathering in the till is only of very general use in comparing glacial deposits in the northern Boulder Mountains. The local correlations were made in the field. Correlations with deposits and events elsewhere in Montana and adjacent states are based on the descriptions and conclusions of Alden (1932, 1953), Horberg (1954), and Holmes and Moss (1955).

The earliest glaciation, perhaps of early Pleistocene age, in the region underlain by the northern part of the Boulder batholith is thought to have been in the Elkhorn Mountains (fig. 1), where it is represented by course boulder deposits that are locally preserved on Bull Mountain southeast of Boulder (R. A. Weeks, oral communication, 1956). The glaciation is probably also represented by the older Pleistocene fan deposits near Winston in the northern part of the Townsend Valley (Freeman, Ruppel, and Klepper, 1958, p. 513–514). The quartzite and aplite boulders in the Bull Mountain deposits could have been derived only from the central part of the Elkhorn Mountains, about 10 miles to the north, but the interpretation of the bouldery sediment as a glacial deposit is not certain. The older Pleistocene fan deposits in the Townsend Valley have been considered early Wisconsin in age (Freeman, Ruppel, and Klepper, 1958, p. 514), but the degree of erosion and weathering of the deposits suggest that they are more probably early Pleistocene. Other glacial deposits in western Montana that are thought to be of early Pleistocene age have been discussed by Alden (1932, p. 40–44; 1953, p. 62–68), Pardee (1925, p. 37–38), and Atwood and Atwood (1938, p. 243–244). Alden (1953, p. 88) suggested that some of the glacial deposits near Elliston were deposited in pre-Wisconsin time by an early glacier extending down the valley of the Little Blackfoot River, presumably from the vicinity of Cliff and Thunderbolt Mountains, but these deposits do not differ in any major respect from the younger deposits in or adjacent to the ice sheet area to the south.

Glaciation in the northern part of the Boulder Mountains almost certainly was contemporaneous with the second or early period of glaciation in the Elkhorn Mountains,[1] for the glacial deposits in the ice-sheet area are similar in degree of erosion and depth of weathering to the deposits of the second glaciation in the Elkhorn Mountains. The deposits in the Elkhorn Mountains are possibly early Wisconsin in age (Klepper, Weeks, and Ruppel, 1957, p. 43). Alden (1953, p. 87–88) dated part of the moraine near Elliston as Illinoian or early Wisconsin, although he (1953, p. 106, 185) considered glacial deposits in the ice-sheet area to be later Wisconsin. As mentioned earlier, the moraine near Elliston is similar to that in the ice-sheet area, and probably the deposits in the two areas are of the same age, possibly early Wisconsin.

[1] At the time (1949–52) of the fieldwork leading to the report on the southern Elkhorn Mountains by Klepper, Weeks, and Ruppel (1957), only two glaciations (older and younger, or early and late) were recognized. Since that time, additional mapping by R. A. Weeks on Bull Mountain, southwest of the Elkhorn Mountains, has suggested an earlier, perhaps early Pleistocene, glaciation, and further work in the Elkhorn Mountains has led to the conclusion that there was also a later cirque glaciation. Thus, only 2 of the 4 glaciations now thought to have taken place in these mountains are discussed in the report on the southern Elkhorn Mountains.

In the southern part of the Boulder Mountains, east and northeast of Butte and south of the Boulder River, there are no clear indications of glaciation. The two parts of the Boulder Mountain mass now are similar in altitude, but the southern part lacks the rounded cirques, well-defined glacial troughs, and widespread glacial deposits so prominent farther north. Rather, the southern part of the Boulder Mountains appears to be a deeply weathered upland erosion surface, underlain mainly by granitic rocks of the Boulder batholith, now dissected by rejuvenated streams. Similarly, no glacial deposits like those in the northern Boulder Mountains or the contemporaneous deposits in the Elkhorn Mountains are known on Bull Mountain, which now reaches to about the same altitude as the Boulder Mountains. Unlike the Boulder Mountains, however, small glacial deposits thought to be contemporaneous with the "Late," perhaps late Wisconsin, stage in the Elkhorn Mountains have been recognized on Bull Mountain (R. A. Weeks, oral communication, 1956). Thus, in the northern part of the Boulder batholith there appears to have been an early Pleistocene(?) glaciation only in the Elkhorn Mountains, an early Wisconsin(?) glaciation only in the Elkhorn Mountains and the northern part of the Boulder Mountains, and a late Wisconsin(?) glaciation only in the Elkhorn Mountains and on Bull Mountain; no ice seems to have accumulated at any time in the southern part of the Boulder Mountains. The Pleistocene history of these adjacent mountain masses has been strikingly different; perhaps the differences are due to locally controlled climatic conditions, but it seems more likely to me that they reflect recurrent differential uplift of the individual mountain masses, particularly of the southern Boulder Mountains and Bull Mountain, during late Pleistocene time.

POSTGLACIAL EROSION

The glacial deposits in the northern Boulder Mountains have been strongly modified locally and other deposits have been formed by the mass-wasting and related processes that have dominated postglacial erosion. The products of these processes include irregularly hummocky and locally boggy creep-and-solifluction deposits, stone-banked terrace deposits, protalus ramparts and associated rock streams, talus, landslides, fields of frost-heaved angular pieces of volcanic rocks, fields of boulders of disintegration, and bog and swamp deposits that choke the upstream parts of some valleys. Although the effect of mass-wasting is apparent throughout the ice-sheet area, it is most conspicuous in the east half of the area, where the till blanket on many valley walls supplied abundant surficial debris in a topographic setting conducive to mass-wasting, and where volcanic and batholithic rocks are exposed to frost action. In contrast, the glacial deposits in the west half of the area largely mantle relatively flat areas, where there is little or no downslope movement due to gravity and much of the bedrock is protected by the concealing drift.

CREEP-AND-SOLIFLUCTION DEPOSITS AND STONE-BANKED TERRACE DEPOSITS

The most widespread mass-wasting deposits in the northern Boulder Mountains are creep-and-solifluction deposits. The areas underlain by these deposits are commonly swampy and are characterized especially by their irregular, hummocky surfaces. Most of the deposits are now covered with dense vegetation. Most commonly the deposits were derived from till that veneered valley walls, and they are composed of similar material. The largest deposit of this type that is not composed of till is on the north and west slopes of Pole Mountain. It is composed of soft, disintegrated rock from the underlying volcanic sandstone and of abundant small angular fragments derived from the tuff and lapilli tuff that cap Pole Mountain. This deposit is grass covered and none of the depressions on its surface are swampy.

Stone-banked terrace deposits occur only in association with creep-and-solifluction deposits. They are most common near Tenmile and Basin Creeks. The typical terrace deposit includes three zones: an inner zone of fine-grained material, an intermediate zone of mixed coarse- and fine-grained material, and an outer rim of coarse rock fragments nearly free of finer grained material and standing at the angle of repose. The part of the terrace underlain by the inner and intermediate zones is flat or nearly so and is bounded by a steep scarp formed by the outer rim. The inner part of the terrace is swampy; farther out on the terrace, water is less abundant and at the rim is absent. The long dimension of the terraces invariably is parallel to the contour of the slope. The terraces range in size from a few feet wide, less than 100 feet long, and less than 5 feet high to rare ones at the south end of Lee Mountain that are as much as 400 feet wide, about ½ mile long, and 50 feet high. The moderately dense vegetation that now covers nearly all the terraces indicates that the terraces are not growing under the present climatic conditions; dissection has begun only in a few places, and most of the terraces and associated creep-and-solifluction slopes appear nearly stable. The vegetation even extends over the stone rims of the terraces, and the fine- and coarse-debris zones below the smaller terraces have been completely obscured. Below nearly all the terraces that are at least a few tens of feet wide, however, the inner fine-grained zone is swampy, and the rim is roughly delimited by coarse fragments.

Features similar in form and composition to the stone-banked terraces in the northern Boulder Mountains have been described by other writers. Among the names proposed for these features are: altiplanation terraces (Eakin, 1916, p. 78–82); solifluction benches or platforms (Russell, 1933, p. 943); sorted steps (Washburn, 1956, p. 833–834); and, adopted in this report, stone-banked terraces (Antevs, 1932, p. 61–64). The names "altiplanation terrace" and "solifluction bench or platform" carry genetic connotations that cannot be demonstrated here, and the definition of sorted steps given by Washburn (1956, p. 833–834) excludes such features as the stone-banked terraces described above. The stone-banked terraces described by Antevs (1932, p. 61–64) are somewhat smaller features than those in the northern Boulder Mountains but are otherwise similar, and the name is the most applicable of those proposed by earlier writers.

The processes that formed the creep-and-solifluction deposits and the stone-banked terrace deposits are uncertainly known inasmuch as they are not active now, but the common association of both types of deposits suggests a common origin. The sorting of fine and coarse material in altiplanation terraces, stone-banked terraces, and sorted steps has been attributed to frost action, although the exact mechanism remains obscure. (See Washburn, 1956, pp. 823–866.) The stone-banked terrace deposits in the northern Boulder Mountains probably have also been formed by frost sorting of earlier glacial debris, especially as many of the other mass-wasting deposits indicate extensive postglacial frost action. The creep-and-solifluction debris is not sorted except where there are stone-banked terraces. The irregular, hummocky form of the debris suggests accelerated downslope movement, perhaps through solifluction, which is defined by Andersson (1906, p. 95–96) as the slow flowing from higher to lower ground of masses of waste saturated with water. Whether or not permanently frozen ground formerly existed beneath the debris is not known, but because the deposits are derived mainly from earlier glacial deposits veneered on ice-smoothed valley walls, the bedrock of the valley walls could have served as a hard, smooth, impermeable base to saturated debris and thus could have promoted solifluction.

FROST-WEDGED ROCK WASTE AND BOULDERS OF DISINTEGRATION

Accumulations of rock waste in protalus ramparts, rock streams, block fields, and talus are common in areas of rhyolite outcrop, especially in the northeastern part of the Basin quadrangle; block fields and, locally, talus are present where other volcanic rocks crop out; and fields of boulders of disintegration have been formed in some areas underlain by quartz monzonite. Destruction of the bedrock and accumlation of rock waste has almost certainly been a result of frost action that loosened angular fragments of the platy and (or) closely jointed volcanic rocks or individual crystals of the batholithic rocks.

Protalus ramparts were described by Howe (1909, p. 35–36) as slide-rock deposits that formed in front of snowbanks lying against high cliffs. The name "protalus rampart" was applied to such accumulations by Bryan (1934) to replace a variety of earlier names, among them, winter talus ridges and nivation ridges. In the ice sheet area, the largest protalus ramparts are on the flanks of Luttrell Peak, but there are many smaller ramparts in the eastern part of the area and a few farther west.

The ramparts have formed only where cliff headwalls are composed of fine-grained platy closely jointed rocks. Where the geographic setting is similar but the rock is coarser grained and coarsely jointed, weathering occurs mainly by granular disintegration. The growth of protalus ramparts depends not only on the jointing of the rock in the headwall supplying the waste, but also on the amount of precipitation and the number of times the freezing point is crossed in a given period. These features, therefore, probably are comparatively sensitive climate indicators.

The protalus ramparts on the east side of Luttrell Peak are in three distinct sets: An old partially dissected set covered by thick soil and dense vegetation, an intermediate little-dissected set covered by thin soil and sparse vegetation, and a young fresh-appearing set that probably still receives debris during severe winters. On the north side of Luttrell Peak and on Lee Mountain, the intermediate and young sets are also present, but elsewhere only the young set is found; the older sets, if they ever were formed, have been either buried or destroyed. The three sets of protalus ramparts on Luttrell Peak suggest at least three periods of increased cold and (or) moisture since glaciation.

Talus is common wherever volcanic rocks crop out, but most of the deposits are rather small. All are bare, unstable accumulations of small angular unweathered fragments and the deposits are actively growing.

Small rock streams (fig. 5) have formed at the toes of several protalus ramparts on Luttrell Peak, the most prominent of which is near the Monte Cristo mine, and a small rock stream is present in the valley of the Boulder River east of Bernice. All the rock streams are broad as compared to their length because none of them have moved material far from the talus and protalus ramparts that feed them; all are characterized by flowage wrinkles, by frontal slopes as steep as 40°, and by a complete absence of vegetation. The rock streams contain only rocks from the cliffy outcrops immediately upslope, and they cover glacial deposits, outwash, and younger alluvium. The steep frontal slopes and the lack of vegetation suggest that movement has occurred in the comparatively recent past. The rock streams in the northern Boulder Mountains therefore are not related in any way to the earlier glaciers, a mode of origin suggested for similar deposits by Capps (1910), Hole (1912), Kesseli (1941), and Wahrhaftig and Cox (1959). On the contrary, the rock streams grade imperceptibly into protalus ramparts and talus near the foot of cliffy outcrops and are clearly accumulations of frost-wedged rock waste. The principal factors causing the flow seem to be: (1) large supplies of rock waste in unstable equilibrium at the head of each rock stream; (2) favorable topographic and geologic settings including gentle slopes beneath high north- or east-facing headwalls composed of platy and closely jointed rocks, rapidly transformed to rock waste by frost wedging; and probably (3) lubrication of the rock stream by small amounts of interstitial ice or by melt water from snow.

Large fields of frost-riven angular blocks and slabs are common on interstreams divides that are capped by volcanic rocks, especially south of Cliff Mountain, between Thunderbolt and Bison Mountains, and on the rhyolite-capped divides and mountaintops in the northeastern part of the Basin quadrangle (fig. 6). The block fields represent bedrock virtually in place.

Most of the quartz monzonite in the area weathers in a manner distinctly different from that of the much finer grained platy and closely jointed volcanic rocks, although weathering of both types of rock is largely by disintegration. The effect of disintegration by frost wedging is most pronounced in quartz monzonite that crops out in unglaciated areas or in areas exhumed from beneath the rhyolite since glaciation, for in these areas the quartz monzonite is more decomposed than in the areas stripped and carved by ice. The decomposition, a result of preglacial weathering, has altered the feldspars to clay along grain boundaries and cleavages and has produced openings along which water can penetrate deeply into the rock. The partially decomposed quartz monzonite is thus especially vulnerable to frost wedging of mineral grains and cleavage fragments, so that disintegration of angular joint blocks to rounded boulders must be a rather rapid process in the still rigorous climate. Where fresh quartz monzonite has been bared by ice scour, disintegration and postglacial decomposition have been less effective; but even in these areas, all the surface features of glaciation except grooves an inch or more deep have been destroyed, and weathered rinds are as much as 6 inches thick.

FIGURE 5.—*A*, small rock stream on east flank of Luttrell Peak. *B*, Steep frontal slope at toe of rock stream on northeast slope of Luttrell Peak.

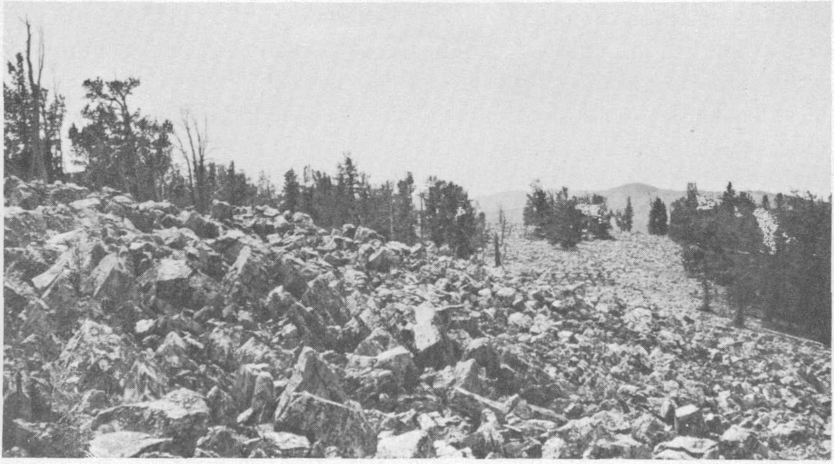

FIGURE 6.—Frost-riven angular blocks and slabs of rhyolite south of the Josephine mine.

Boulders of disintegration (Larsen, 1948, p. 114–119); Chapman and Greenfield, 1949) form extensive fields on Old Baldy Mountain, on the Three Brothers, and southwest of Iron Mountain. In these areas, the sand or gruss produced by frost wedging has been removed by streams flowing, now beneath the boulders, on gradients steepened by faulting (Three Brothers), glaciation (Old Baldy Mountain), or valley deepening (southwest of Iron Mountain). The fields typically are broken by a few ribs of bedrock, and all stages of the disintegration process can be seen in examples that range from only slightly rounded joint blocks in place to well-rounded boulders of disintegration. The only downslope movement in the fields of boulders of disintegration is that produced by the toppling of joint blocks as they disintegrate to rounded boulders; there is no indication of mass downslope movement.

In relatively flat places, the boulders are widely spaced and partly buried by gruss. The poor drainage plus the tendency for the gruss to retain water that would evaporate in open boulder fields accelerates the destruction of the boulders.

Regardless of topographic setting, fields of boulders of disintegration form only in batholithic rocks cut by widely spaced joints, for the joint blocks are too rapidly destroyed by disintegration in the batholithic rocks cut by joints less than 2 or 3 feet apart.

LANDSLIDES

Landslides have formed accumulations of rock waste on the east slope of Lee Mountain, on the south slope of Old Baldy Mountain, and on the east slope of Fox Mountain. The Old Baldy Mountain and Fox Mountain landslides are deposits of rock waste that accumulated as talus before sliding; the landslides are thus debris slides in the classification proposed by Sharpe (1960, p. 74–76). The Lee Mountain slide was a rockslide (Sharpe, 1960, p. 74–76) in which a mass of rhyolite apparently slipped from the prerhyolite surface (Ruppel, 1962) into the valley of Tenmile Creek, at least partly as a result of glacial steepening of the canyon wall.

The Old Baldy Mountain and Fox Mountain slides are now smoothed, rounded, and covered with vegetation, although they are not appreciably dissected. The Lee Mountain slide appears to be much younger, for it is an open rubble of angular rhyolite blocks that retains the fresh hummocky appearance of a recent landslide; it has no soil and supports no vegetation other than a few scattered trees. The Fox Mountain slide dammed Red Rock Creek, and an alluvial fill accumulated behind the dam almost as high as its rim; the creek is now cutting a new channel in bedrock around the east margin of the slide. The Lee Mountain slide extends east of the map area where it once dammed Tenmile Creek, but the creek must have breached the dam rapidly because no alluvial fill accumulated. The creek has cut away part of the landslide and now flows approximately in its prelandslide course.

BOG AND SWAMP DEPOSITS

The upper part of most major stream valleys in the northern Boulder Mountains is occupied by bogs and swamps that indicate valley clogging. The source of the material clogging the valleys is the glacial deposits which are slipping from the valley walls, probably both by soil creep and by solifluction. The glacial deposits on the valley walls characteristically have retained many of their morainic features despite the downslope movement indicated by valley clogging.

AGE OF MASS-WASTING DEPOSITS

Most of or all the mass-wasting deposits are younger than the glacial deposits and appear to have accumulated largely as a result of frost action. The three sets of protalus ramparts suggest three periods of intensified frost action since glaciation. The oldest set of protalus ramparts is more extensive than the younger sets, and it is similar in degrees of erosional destruction and in amount of vegetation to the moraines of alpine glaciers deposited during the later, probably late Wisconsin, period of glaciation in neighboring mountains (pl. 2). No glacial deposits of this age have been recognized in the northern Boulder mountains, and it seems likely that the climatic cooling that led to alpine glaciation elsewhere is represented here by the lower set of protalus ramparts on Luttrell Peak, by the widespread creep-and-solifluction deposits and associated stone-banked terrace deposits, and perhaps by the debris slides on the Fox and Old Baldy Mountains.

The intermediate set of protalus ramparts on Luttrell Peak is similar in degree of erosional destruction to the cirque moraines that represent the latest period of glaciation in the Elkhorn Mountains (pl. 2), and the upper set of protalus ramparts and its associated rock streams on Luttrell Peak probably began to accumulate in comparatively recent times. The Lee Mountain rockslide is also probably a comparatively recent deposit.

The talus in the area has accumulated in glaciated valleys or other topographic settings that indicate it has formed since glaciation. The block fields and fields of boulders of disintegration may have formed partially during or before glaciation, as they are, in part, in areas that were not covered by glacier ice. At present, rock waste is being added to the upper set of protalus ramparts, the rock streams, and the talus, and block fields and boulders of disintegration are continuing to form.

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