Quaternary Geology of Boulder Mountain Aquarius Plateau, Utah

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CONTRIBUTIONS TO GENERAL GEOLOGY

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QUATERNARY GEOLOGY OF BOULDER MOUNTAIN, AQUARIUS PLATEAU, UTAH

By Richard F. Flint and Charles S. Denny

ABSTRACT

Boulder Mountain, the northeastern part of the Aquarius Plateau, exceeds 11,000 feet in altitude; it is the highest of the High Plateaus of Utah. The mountain has a nearly flat summit area of about 70 square miles and possesses steep side slopes.

During late Pleistocene time an icecap formed repeatedly on top of the mountain, covering most and possibly all of it. The ice drained off the top through broad canyonlike troughs in the plateau sides. During the most extensive glaciation (Bull Lake? stage), the termini of these outlet glaciers reached down to altitudes as low as 6,600 feet. During the later Pinedale(?) stage the outlet glaciers followed nearly the same paths but were much less extensive. Glaciation of the plateau top is shown mainly by radial grooving, striation, and shaping of bedrock features. Glaciation of the plateau sides is recorded by lobes of glacial drift having morainic topography.

Two sets of conspicuous moraines are identified in Pinedale(?) drift. After Pinedale(?) glaciation ended, rock glaciers were built around the base of the cliff that bounds the summit of the plateau. The rock glaciers probably originated mainly as local drift deposited by ordinary glaciers of small size, and therefore record an episode of cold, wet (Temple Lake? stage of Howard and Hack) climate. Talus overlying the rock glaciers is attributed to a later and less rigorous cold wet episode.

The drift bodies are correlated on a basis of degree of weathering of component material, modification of the topography by surface agencies, and relative vertical positions of drift-lobe termini.

The kinds of soil developed on the successive sheets of glacial drift are not sufficiently well defined to aid in correlating the drift sheets. No undoubted drift of pre-Sangamon age was found, and no soil of Sangamon or older date was positively identified, although some of the weathered mantle in the district probably dates from Sangamon (pre-Bull Lake?) time.

At the base of the plateau at various altitudes are dissected pediments veneered with bouldery deposits. Most of the pediments are believed to have been formed in Sangamon or older time; the sediments that cover them are not believed to be glacial outwash.

In the valley of the Fremont River, which skirts the northern base of the plateau, sections of alluvium record two episodes of filling separated by an episode of erosion. Eolian(?) sand and flaggy colluvium were deposited in the Torrey-Teasdale lowlands during Pinedale and later times.

The most noticeable and widespread deposits on the sides of the plateau are landslides. These deposits mask the bedrock extensively, and include not only a widespread veneer of material that has slumped and flowed down the slopes but also large complex tonguelike landslides as much as 4 miles in individual length. The slides are of several dates; in places sliding is in progress at present.

INTRODUCTION

The Aquarius Plateau, the highest of the High Plateaus of Utah, lies about 200 miles south of Salt Lake City and about 150 miles north of the Grand Canyon (fig. 24). The northeastern part of the plateau, called Boulder Mountain, is a nearly level tableland, most of which was covered repeatedly by an icecap during late Pleistocene time. Tongues of ice flowed outward from the icecap over the cliffs of volcanic rock and down valleys that radiate outward from the mountain.

In 1952, six weeks were devoted to a reconnaissance study of the surficial geology of Boulder Mountain, especially its northern and eastern slopes for which aerial photographs were available. Some of the geologic boundaries on plate 6 were adjusted on the basis of additional field work by Smith and Huff in 1953 and 1954, and to conform with the topography shown on U. S. Geological Survey quadrangle maps made subsequent to the field study.

The reconnaissance was made in conjunction with a detailed study of a larger area, Boulder Mountain, Thousand Lake Mountain, Rabbit Valley, part of the Awapa Plateau, and a segment of the Canyon Lands east of the High Plateaus (fig. 24) by J. Fred Smith, Jr., E. N. Hinrichs, L. C. Huff, and R. G. Luedke to whom we are in debt for assistance. All too infrequently does the surficial geologist have at hand those of his colleagues who are thoroughly acquainted with the rocks from which the surficial deposits are derived. We are under obligation to G. M. Richmond and C. B. Hunt for showing us the surficial geology and soils in Rocky Mountain National Park, Colorado, and in the La Sal Mountains, Utah. C. C. Nikiforoff has been kind enough to criticize the section on weathering and soils.

PHYSICAL GEOGRAPHY

TOPOGRAPHY AND VEGETATION

The summit of Boulder Mountain is a nearly level upland indented by broad, shallow valleys ½ to 1 mile wide and 50 to 200 feet deep. It is a roughly triangular area about 12 miles long, 5 to 10 miles wide, and 70 square miles in area (pl. 6).[1] Its surface is covered partly by forests, mainly of Engelmann spruce, and partly by alpine meadows with myriads of small ponds or grass and sedge marshes (Dixon,

[1] All places referred to in text are shown on plate 6 or figure 24 unless otherwise noted.

1935). The maximum relief is about 300 feet; the highest point, Bluebell Knoll, reaches an altitude of 11,328 feet. In many places low bedrock knobs rise above the tree- or turf-covered upland. Dutton (1880, p. 284) wrote in glowing terms of the beauty of the Aquarius Plateau; he said that it "should be described in blank verse and illustrated on canvas."

A cliff that ranges from 100 to nearly 600 feet in height almost completely surrounds Boulder Mountain. In many places volcanic rocks that cap the plateau are exposed in the cliff whose base is mantled with sliderock and rock glaciers. Elsewhere great masses of volcanic rock have broken off from the cliff and have slid downward and outward to form ridges parallel with the cliff face. Government Point (pls. 6 and 7) is on a block of volcanic rock, nearly a mile long and a quarter of a mile wide, that has slid down about 100 feet, rotating backward toward the cliff from which it was derived.

A gently sloping bench extends outward from the base of the cliff for about a mile in many places. Most of the bench is covered by forests of Douglas fir and aspen with white fir and Colorado spruce, and is dotted with numerous small lakes. The Douglas fir is restricted to the steeper and more rocky slopes (Dixon, 1935). The bench is dissected by valleys radiating outward from Boulder Mountain, but when viewed from a distance the bench is a conspicuous topographic feature, particularly on the north, east, and south flanks of the mountain.

Outward from the bench are steep slopes mantled chiefly by landslide debris. The slopes are covered by open forests of yellow pine that at lower altitudes are replaced by piñon and juniper. There are also grassy openings, oak thickets, and large groves of aspen. In places bedrock hills project through the surficial mantle.

The glaciated valleys of Fish Creek, Pleasant Creek, and Boulder Creek cross the bench and descend to the adjacent lowlands. These valleys contain moraines left by tonguelike outlet glaciers of late Pleistocene age that flowed down from the plateau icecap to altitudes as low as 6,600 feet. At their maximum extent the glaciers reached the Fremont River north of Grover, and outwash from them extended eastward to and probably beyond the Capitol Reef. On the west side of Boulder Mountain one moraine extends a short distance out over the Awapa Plateau.

Due north of Boulder Mountain the Fremont River, a tributary of the Colorado River, passes through the Red Gate, a narrow rock-walled valley that separates the foothills of Boulder Mountain from those of Thousand Lake Mountain to the north. The lowlands east of Red Gate, here called the Teasdale-Torrey lowlands, include broad plains covered by drift of late Pleistocene age, and bedrock

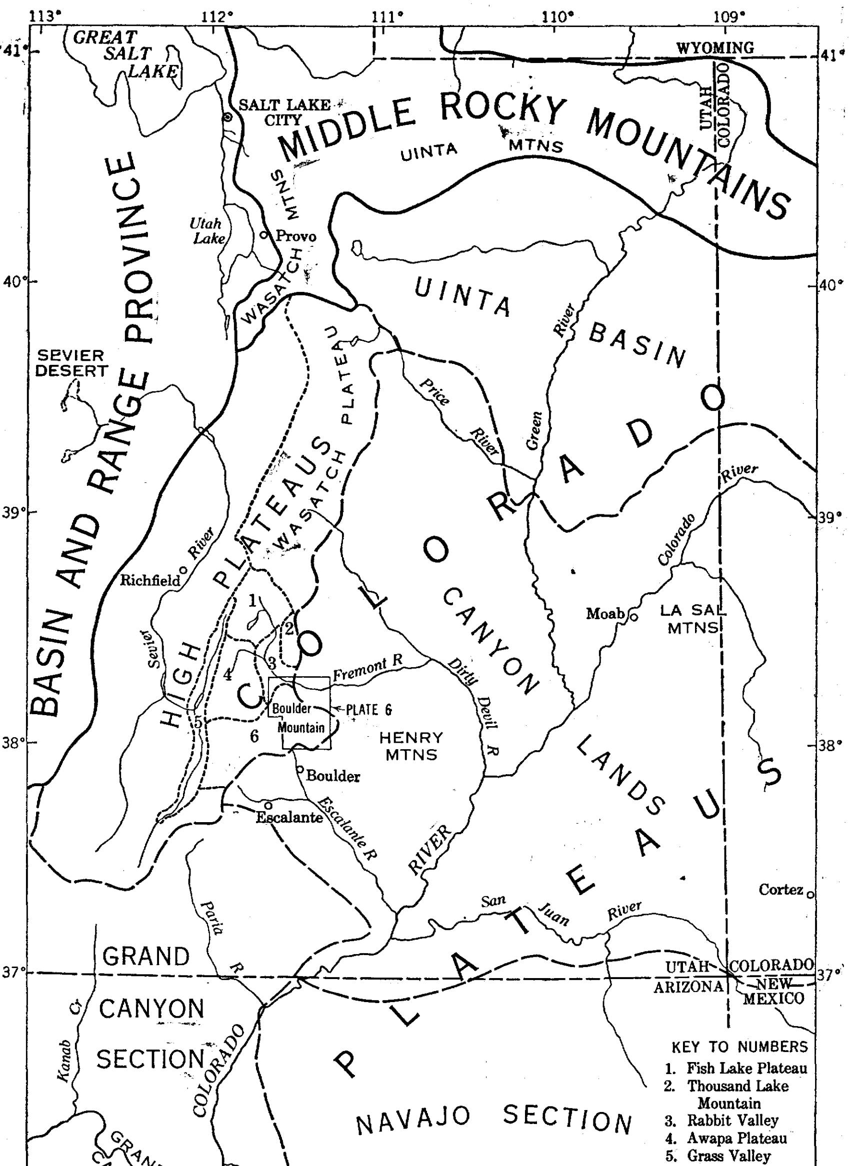


FIGURE 24.—Map of a portion of the Colorado Plateaus and adjacent provinces showing location of Boulder Mountain and area covered by geologic map (pl. 6).

mesas some of which are capped with sand and gravel. The lowlands are partly open grassland and partly covered by sagebrush with scattered piñon and juniper. Eastward the Fremont River transects the north end of Miners Mountain through a canyon and enters the Capitol Reef at Fruita.

The east and south slopes of Boulder Mountain descend into a maze of deep valleys, the Canyon Lands of the Colorado Plateaus (fig. 24). Northwest of Boulder Mountain lies Rabbit Valley, a broad lowland floored with alluvium and bordered by volcanic rock. To the west lies the northward-sloping Awapa Plateau and to the southwest the main mass of the Aquarius Plateau.

Streams radiate out from Boulder Mountain in all directions; those on the west side turn northward into Pine Creek which joins the Fremont River just west of the Red Gate. The northeast slopes drain to the Fremont River west of Miners Mountain. Streams on the east slope of Boulder Mountain flow eastward through the Capitol Reef, and those on the southern flanks, such as Boulder Creek, flow southward to the Escalante River. Small streams, especially those on the northeast side of Boulder Mountain, follow irregular courses around or across slump blocks and other landslide features of diverse age and origin. Many streams have not yet excavated their channels to bedrock.

Exposures of both bedrock and surficial deposits are few. A thick sequence of relatively weak strata overlain by massive volcanic rock is favorable for landsliding. Most of the surficial mantle is bouldery rubble, either drift or colluvium.

BEDROCK GEOLOGY

The bedrock in the northeastern Aquarius Plateau district is summarized below.

Generalized section of bedrock in northeastern Aquarius Plateau district

[Based on data supplied by J. Fred Smith, Jr., and others]

System	Group, formation, and member	Thickness (feet)	Lithology
Quaternary.	Alluvium, colluvium, terrace gravel, glacial drift, landslides, pediment gravel.	0–70	Clay, silt, sand, and gravel in alluvium and colluvium; pediment and terrace gravels include some sand; glacial drift and landslides commonly bouldery or gravelly.
	—Unconformity—		
Tertiary.	Volcanic rocks.	500±	Chiefly flows with interbedded tuffaceous sediments.
	—Unconformity—		
	Flagstaff(?) limestone.	200+	Limestone, clay, conglomerate, sandstone, tuff, and tuffaceous sediments.

Generalized section of bedrock in northeastern Aquarius Plateau district—Continued

System	Group	Group, formation, and member	Thickness (feet)	Lithology
Cretaceous.		Mancos(?) shale.		Not exposed.
		Dakota(?) sandstone.		Not exposed.
		—Unconformity—		
Jurassic.		Morrison(?) formation.	350±	Conglomeratic sandstone, sandstone, siltstone, claystone.
		—Unconformity—		
	San Rafael Group	Summerville formation.	1800±	Siltstone.
		—Unconformity—		
		Entrada sandstone.		Earthy sandstone.
		Carmel formation.		Limestone, siltstone, gypsum.
		—Unconformity—		
—?—	Glen Canyon Group	Navajo sandstone.	800±	Crossbedded sandstone, chiefly white.
Jurassic(?).		Kayenta formation.	350	Sandstone, conglomeratic sandstone, shades of red and white.
Triassic.		Wingate sandstone.	330±	Crossbedded sandstone, red.
		—Unconformity—		
		Chinle formation.	450±	Siltstone, claystone, sandstone; variegated.
		Shinarump conglomerate.	0–90	Sandstone, conglomeratic sandstone, claystone.
		—Unconformity—		
		Moenkopi formation.	900±	Siltstone, sandstone, limestone; chiefly red.
		—Unconformity—		
Permian.		Kaibab limestone.	350±	Limestone, sandstone, calcareous siltstone; white.
		Coconino sandstone.	800±	Crossbedded sandstone, white.

CLIMATE [2]

The climate in the northeastern Aquarius Plateau district ranges from arid in the lowlands near Fruita, to humid on the top of the

[2] Abstracted from Climatic summary of the United States to 1930: U. S. Dept. Agriculture Weather Bureau, sec. 21; Dixon (1935); Gregory and Anderson (1939); Woolley (1947).

plateau. In the lowlands the mean annual rainfall ranges from 5 to 10 inches; the summers are long and hot, the winters cool; temperatures of 110° and of —37° have been recorded. There are no climatic records for stations on the plateau top, but the mean annual rainfall may be as much as 30 inches per year. High water occurs on the larger streams during the spring, as snow melts on the watersheds. Cloudburst floods occur in the months of July and August (Woolley, 1947, p. 83–96).

WEATHERING

All profiles of weathering or soils in the Boulder Mountain region are developed on surficial deposits. No exposures were seen where the bedrock had weathered in place into residual mantle. Most profiles of weathering observed are probably of late Pleistocene or Recent date, for it is unlikely that a soil developed in Sangamon or older time could have survived the later mass movements that have affected so large a proportion of the slopes. For this reason special attention was paid to profiles of weathering developed in fluvial deposits capping isolated mesas, localities favorably situated to escape subsequent disturbance by mass movements. These deposits lie hundreds of feet above the present drainage, and on topographic evidence alone are older than other fluvial deposits that now lie only tens of feet above existing streams. No clear evidence was found, however, that the weathering on the fluvial deposits changed with their height above present drainage. No soils seen by the authors resemble those found elsewhere in the Rocky Mountain region (Hunt and Sokoloff, 1950; Hunt, Varnes, and Thomas, 1953; Hunt, 1954) and known from stratigraphic evidence to date from pre-Wisconsin (Sangamon or older) time. For example, some of the soils developed on pre-Wisconsin deposits in the La Sal Mountains (fig. 24) are as much as 15 feet thick, contain deeply weathered rock fragments, and have caliche horizons as much as 10 feet thick (Richmond, written communication).

The soils seen on Boulder Mountain show a rough vertical zonation (Martin and Fletcher, 1943; Nikiforoff, 1937; Thorp, 1931). Below about 8,400 feet most of the soils examined have a subsoil partly cemented with calcium carbonate (caliche); at higher altitudes most of the soils are free of calcium carbonate. The following brief soil-profile descriptions are the generalized impressions of the geologist, and do not include all the types of soil actually present. In the soil descriptions all colors are those of dry material.

SOILS WITH CALICHE

Below altitudes of about 8,400 feet, most of the soils examined consist of 1 or 2 feet of loose, oxidized, and in places leached material

(A horizon?) overlying from 1 to 2 feet of slightly to firmly cemented material having a high content of calcium carbonate and (or) gypsum (B horizon?). The contact between these horizons is fairly sharp. In many places the underlying parent material is also calcareous and gypsiferous. In the profiles studied, the texture of the A horizon(?) is chiefly sandy; that of the B horizon(?) is a mixture of sand and silt with little clay. Colors are primarily dependent on those of the parent material. The A horizon(?) is dominantly pinkish or brownish, the B horizon(?) white to gray, and the parent material dominantly pink to gray. Fragments of rock ranging from a fraction of an inch to many feet in diameter are found throughout the profile in widely varying proportions. Most fragments are fresh, but may have thin weathered rinds. A very few of the small fragments can be crumbled between the fingers. A profile of a soil with caliche is described below.

Profile of soil with caliche exposed in bank along Teasdale-Grover road near Fish Creek[1] *(pl. 6, loc. 4)*

Topography: Broad ridge, slope about 5° to northeast.
Altitude: 6,960 feet.
Vegetation: Scattered piñon and juniper.
Parent material: Till of Carcass Creek drift.

Depth (inches)	*Description*
0–3	Loamy fine sand, pinkish-gray to brown (7.5 *YR* 6/2–5/2); noncalcareous; contains small fragments of volcanic rock and a little organic matter; abundant boulders of volcanic rock on the surface.
	Contact gradational.
3–10	Loamy sand, brown (7.5 *YR* 5/4); loose; noncalcareous; contains numerous small fragments of volcanic rock.
	Contact sharp.
10–22	Loamy fine sand, pinkish-white (7.5 *YR* 8/2); moderately cemented, friable; highly calcareous; contains numerous fragments of volcanic and sedimentary rock.
	Contact gradational through 3 inches.
22–28	Sandy loam, pinkish-white to pink (7.5 *YR* 8/2–7/4); slightly cemented, friable; calcareous; contains numerous fragments of volcanic and sedimentary rock.
	Contact gradational through 3 inches.
28–60+	Sandy loam, pinkish-gray (7.5 *YR* 7/2); moderately firm, friable; calcareous; contains numerous fragments of volcanic and sedimentary rock; interpreted as till.

Remarks: Boulders of volcanic rock 1–6 feet in diameter are found throughout the profile.

[1] The descriptions of color use the numerical symbols of the Munsell system and were determined with the color chart used by soil scientists (Soil Survey Staff, 1951, p. 194–203) rather than with the Rock-Color Chart of the National Research Council (Goddard and others, 1948). The former contains a wider variety of color chips that correspond to colors in surficial deposits than does the latter. Both charts use the numerical symbols of the Munsell system.

The soils with caliche are developed on Carcass Creek drift, on pediment and terrace gravel and sand deposited in Carcass Creek and in earlier (Sangamon? and older) times, on bouldery accumulations of undetermined origin, and on landslides. In places the soils with caliche are overlain by several feet of loose sand believed to be eolian.

The vegetation is dominantly piñon, juniper, and sagebrush. On Lion Mountain soils with caliche occur under yellow pine (*Pinus ponderosa*).

A soil with a thick, massive horizon of caliche is developed in the gravel and sand that caps the high pediment on the north side of Lion Mountain. This pediment remnant is about 700 feet above the adjacent lowlands, suggesting that the gravel and sand may be considerably older than the Carcass Creek drift, the oldest drift recognized in the lowlands. However, rock fragments in the soil are not more weathered than those found elsewhere and the profile differs but little from that on the Carcass Creek drift except in thickness and cementation of the caliche horizon. The soil on Lion Mountain is described below.

Some of the pediment remnants in the Teasdale-Torrey lowlands rise more than 300 feet above adjacent valley floors that are mantled by Carcass Creek drift; hence, such remnants may also be older than the Carcass Creek drift and may date from Sangamon or earlier times. However, the soil developed in the veneer on one of these pediments is similar to that on the adjacent Carcass Creek drift except that the caliche horizon is thicker (about 18 to 24 inches) in the pediment cover than in the drift.

Profile of soil with caliche exposed in pit on top of mesa on north side of Lion Mountain (pl. 6, loc. 11)

Topography: Undulating plain sloping northeastward at angle of about 4°.
Altitude: 8,400 feet.
Vegetation: Open forest of yellow pine.
Parent material: Pediment sand and gravel, perhaps deposited in Sangamon or earlier times.

Depth (inches)	*Description*	*Range in thickness (inches)*
0–1	Loamy fine sand, dark grayish-brown (10 *YR* 4/2) loose; calcareous; contains organic matter.	0–2
	Contact sharp.	
1–4	Loamy sand, reddish-brown to yellowish-red (5 *YR* 4/4–4/6); loose to slightly firm, very friable; calcareous; contains numerous fragments of volcanic and sedimentary rocks; roots.	
	Contact grades through 1 inch.	
4–10	Loamy coarse sand, grayish-brown (10 *YR* 5/2); loose, calcareous; contains numerous fragments of volcanic and sedimentary rocks; roots.	
	Contact gradational through 5 inches.	

Profile of soil with caliche exposed in pit on top of mesa on north side of Lion Mountain (pl. 6, loc. 11)—Continued

Depth (inches)	*Description*	*Range in thickness (inches)*
10–15	Loamy coarse sand, grayish-brown (10 *YR* 5/2), contains a few fragments of lime about one-half inch in diameter; loose; calcareous; contains numerous fragments of volcanic and sedimentary rocks; roots.	3–8
	Contact sharp.	
15–36	Loamy sand, pink (7.5 *YR* 7/4); firmly cemented, difficult to excavate with shovel, unstratified; highly calcareous; contains numerous angular fragments of volcanic rock 1–3 inches in diameter, a few as much as 1 foot in diameter, fragments covered with ½–1 inch layer of lime; scattered roots.	20–25
	Contact gradational.	
36–48	Silt, pink (7.5 *YR* 8/4); slightly cemented, unstratified; calcareous and gypsiferous; contains numerous fragments of volcanic and sedimentary rocks; roots; probably is slightly weathered veneer on pediment.	

Remarks: A sample of 62 rock fragments from the upper 2 feet of profile contained the following rock types:

	Percent
Volcanic rock	60
Chert and quartzite	21
Conglomerate and sandstone	16
Calcareous sandstone	3

Of the 37 fragments of volcanic rock, one was weathered throughout, 5 were slightly weathered, and 31 were fresh. All rock fragments were more or less covered by a rind of caliche ½–1 inch thick, especially on the under side.

SOILS WITHOUT CALICHE

Most of the caliche-free soils were found above an altitude of about 8,400 feet. The soil consists of a surface layer high in organic matter (A horizon), ranging from a few inches to 1 foot in thickness, overlying from 1 to 3 feet of pale yellowish-brown material (B horizon) that grades downward into the grayish-brown parent material (C horizon). The contact between the A and B horizons is sharp, that between the B and C horizons may grade through a distance of about 1 foot. In a few places a thin (about 1 inch) grayish-brown horizon (A_2?) separates the surface layer of organic material from the B horizon below. No marked textural development or increase in clay content was noted in the B horizon. The soil material is loose, and boulders, cobbles, and pebbles are found throughout the profile. Most of the fragments are of volcanic rock, and are fresh or have thin weathered rinds; a few of the small fragments can be crumbled between the fingers. Most parent material is noncalcareous; its matrix is dominantly sandy or silty, and ranges from pale yellowish-brown to gray or red, depending on the character of local surficial deposits. A profile of a soil without a caliche is described below.

Profile of soil without caliche exposed in a morainic ridge (Blind Lake drift) on northeast side of Blind Lake (pl. 6, loc. 10). Exposure in artificial outlet channel

Topography: Ridge about 100 feet wide and 15 feet high. Profile taken near center of ridge, slope about 2° to the southwest.
Altitude: 10,250 feet.
Vegetation: Open spruce woods with scattered aspen.
Parent material: Till.

Depth (inches)	*Description*	*Range in thickness (inches)*
0–6	Organic matter, very dark gray (10 *YR* 3/1); occurs as a filling around pebbles, cobbles, and boulders of volcanic rock; roots.	0–6
	Contact sharp, wavy.	
6–13	Silt loam, mixture of mineral and organic matter, grayish-brown to dark grayish-brown (10 *YR* 5/2–4/2); loose; noncalcareous; contains numerous pebbles of volcanic rock; roots.	
	Contact sharp, wavy.	
13–18	Loamy fine sand, light-gray (10 *YR* 7/2); massive; noncalcareous; contains a few pebbles of volcanic rock; roots.	0–6
	Contact sharp, wavy.	
18–40	Loamy sand, pale-brown (10 *YR* 6/3); moderately firm, friable, structureless; noncalcareous; contains numerous pebbles, cobbles, and boulders of volcanic rock; roots.	20–26
	Contact gradational through 6 inches.	
40–72+	Loamy sand, light-gray (10 *YR* 7/2); moderately firm, friable, structureless; noncalcareous; contains numerous pebbles, cobbles, and boulders of volcanic rock; a 3-foot boulder striated; no roots.	

The vegetation is dominantly spruce, but caliche-free soils are present also under yellow pine (*Pinus ponderosa*).

Soils without caliche are developed on all three of the late Pleistocene drifts recognized in the area and on landslides, and occur in both glaciated and nonglaciated areas of the plateau top. They were not observed buried beneath later deposits.

EXFOLIATION

Most of the ubiquitous boulders of volcanic rock that mantle much of the surface (drift, pediment veneers, bouldery accumulations of undetermined origin, and landslides) are surrounded by shells or spalls that range from 1 to 20 inches in thickness and from a few inches to 2 feet in length. The boulders have rough, pitted, and lichen-covered surfaces, except those that are being or recently have been polished by wind-driven sand or form part of the modern sliderock. The exfoliated boulders have weathered (oxidized?) rinds generally not more than 1 inch thick. Most boulders on Carcass Creek drift are more exfoliated than those on Donkey Creek and

Blind Lake drifts, but the difference is slight. Boulders at the surfaces of the rock glaciers are only slightly exfoliated. Weathered rinds are usually absent, but many of the boulders have a partial covering of crustose lichens on their exposed surfaces.

SOLUTION

Solution pits a few inches in diameter and ranging from a fraction of an inch to 2 inches in depth occur on many boulders of volcanic rock. However, some exceptionally large solution pits are in boulders of volcanic rock found on a nonglaciated(?) part of the summit of Boulder Mountain, about 2 miles west of Chokecherry Point along Willow Draw (pl. 7). The boulders lie in a grassy meadow on slopes that range from about 1° to 5°. The pits range from 2 inches to 3 feet in diameter, and from a few inches to 2 feet in depth. The rims of some pits are overhanging. The pits contain a mixture of water, mineral grains, organisms, and excrement, and are believed to have originated initially from a small depression on the upper surface of a boulder. This initial depression could originate in various ways: through frost breakup, through solution around a patch of lichens, as a vesicle, or as an initial irregularity on a joint face. The initial depression was enlarged by various processes such as frost breakup and solution aided by lichens, organisms, and excrement. Fines and solutes were decanted or washed out of the pit.

Many bare surfaces of limestone or calcareous sandstone are grooved or pitted by solution. Such solution-faceted surfaces have a microrelief as great as 3 inches but are not as pronounced as in other areas in Southwestern United States (Smith and Albritton, 1941).

PATTERNED GROUND

A few areas of patterned ground (Washburn, 1950) were noted on the summit of Boulder Mountain, but the areas are small and the patterns are not clearly expressed. Something like half the summit area is forest covered; the remainder is turf interspersed with numerous exposures of bedrock. In a few places are clumps of boulders and imperfect boulder rings surrounded by turf and suggestive of ancient frost action. One small ancient boulder field was observed near the north end of Willow Draw in the nonglaciated portion of the summit. However, this boulder field is very small in comparison with the ancient boulder fields in areas of landsliding and slumping on the northeast slope of Boulder Mountain.

No terracettes that might be the result of mass-wasting were observed on the glaciated portions of the summit. There is little or no evidence of the disturbance of turf by frost action during the last few years. On the sides of Willow Draw, boulders as much as 6 feet in diameter have moved a few inches down 3°–5° slopes during the last year or two. Each boulder has a 6-inch ridge of turf on its downhill side and a narrow break in the surrounding turf on its uphill side.

Considerable areas near Bluebell Knoll, within the glaciated portion of the plateau top, have patterned ground. Subcircular patches of turf ranging from 2 to 6 inches across are separated by shallow troughs 3 inches to 3 feet in diameter, about 1 inch deep, and floored by small rock fragments. The troughs form roughly polygonal patterns on gentle turf-covered slopes. These patterns are analogous to some on tropical mountains described by Troll (1944, figs. 38–40, "Kuchenboden") and attributed to daily temperature changes across the freezing point. Such a hypothesis is reasonable, although rain-wash is also a factor at least after a trough is once formed.

The scarcity of present-day patterned ground indicates that modern frost disturbance of the mantle is largely inhibited by the vegetative cover despite an altitude of more than 11,000 feet.

GLACIAL FEATURES OF THE PLATEAU TOP

A small ice cap covered the nearly level top of Boulder Mountain as indicated by both erosional and depositional features. The general character of the area has been described by Gould (1939). The most conspicuous erosional feature consists of streamlined lineation of the surface of the volcanic rocks. Lineation is expressed in subparallel flutings a few feet in height and of variable length, minor grooves, and coarse striations, all oriented radially to the central part of the plateau top. Such erosional features are best developed near the heads of the reentrants of Pleasant, Fish, and Donkey Creeks (pl. 7), and also near the head of the Miller Creek canyon on the western edge of the plateau. They are essentially absent from the central area. All the striated surfaces seen are rough rather than polished. No evidence of more than one generation of striations was seen.

The flutings undoubtedly mark the areas of most effective glacial erosion, in which the chief factor probably was a high rate of flow. Maximum flow is to be expected at the reentrants, through which the ice cap drained off the plateau top (pl. 8). In places the flutings exhibit stoss-and-lee topography that indicates movement radially outward from the center of the plateau.

Many basins, mostly shallow, dot the plateau top; some are rock basins, but others are rimmed partly by grass-covered or forested ridges that may consist wholly or partly of drift. Because of the general cover of vegetation and almost total lack of exposures, it was not possible to determine the thickness or extent of the drift. The large areas of exposed bedrock and the general absence of a characteristic drift topography implies that the drift is patchy and thin. In a few places fresh boulders of volcanic rock were seen lying on volcanic bedrock of a different kind. Evidently the boulders are glacial erratics.

The aggregate of small areas with interior drainage is considerable. Probably such areas are the result of glaciation. Evidently they are drained by percolation downward through the jointed lava flows, with emergence on the plateau slopes where underlying less permeable rocks are exposed, because the volume of water flowing down the middle slopes far exceeds that which flows over the summit cliff. Indeed, only Pleasant Creek flows over the summit cliff throughout the summer season.

The only end moraine observed on the plateau top is a faint irregular ridge, a few feet high, a few tens of feet wide, and about 2 miles long. Its northern end is about 2 miles east of the head of Miller Creek canyon. This faint moraine does not represent the outer limit of the icecap margin because flutings occur between it and the cliff. Evidently the moraine was built by a thin glacier of relatively late date. Although the age of the moraine is unknown, its position suggests correlation with the Donkey Creek or Blind Lake drifts on the sides of the plateau.

The limit of conspicuous glaciation on the plateau top is only approximately located (pl. 6 and fig. 25). The evidence is chiefly topographic. Inside the limit are basins, flutings, striations and other features attributed to glacial action. Outside the line the topography is gently rolling, with lesser relief, gentler slopes and fewer exposures of bare rock than in the glaciated area. The surficial material is an unsorted mantle. In places boulder-strewn steplike forms suggest the eroded edges of lava flows. Most of the exposed boulders are exfoliated and roughened in detail by weathering, and are covered with lichens.

The line separating these groups of features is only the approximation of an indistinct zone. The indistinctness may result in part from variations in the area of the icecap during late Pleistocene time. However, the inferred approximate line is reasonable, for it delimits the broad main area of the plateau top from the principal cusplike points. Bown's Point and Chokecherry Point, each with an area of several square miles, as well as the much smaller tips of Trail Point and Government Point, apparently were not glaciated since Carcass Creek time. The evidence of glaciation on the top agrees in areal distribution with the evidence of Donkey Creek, Blind Lake, and later glaciations on the sides of the plateau, as described in the next section of this paper.

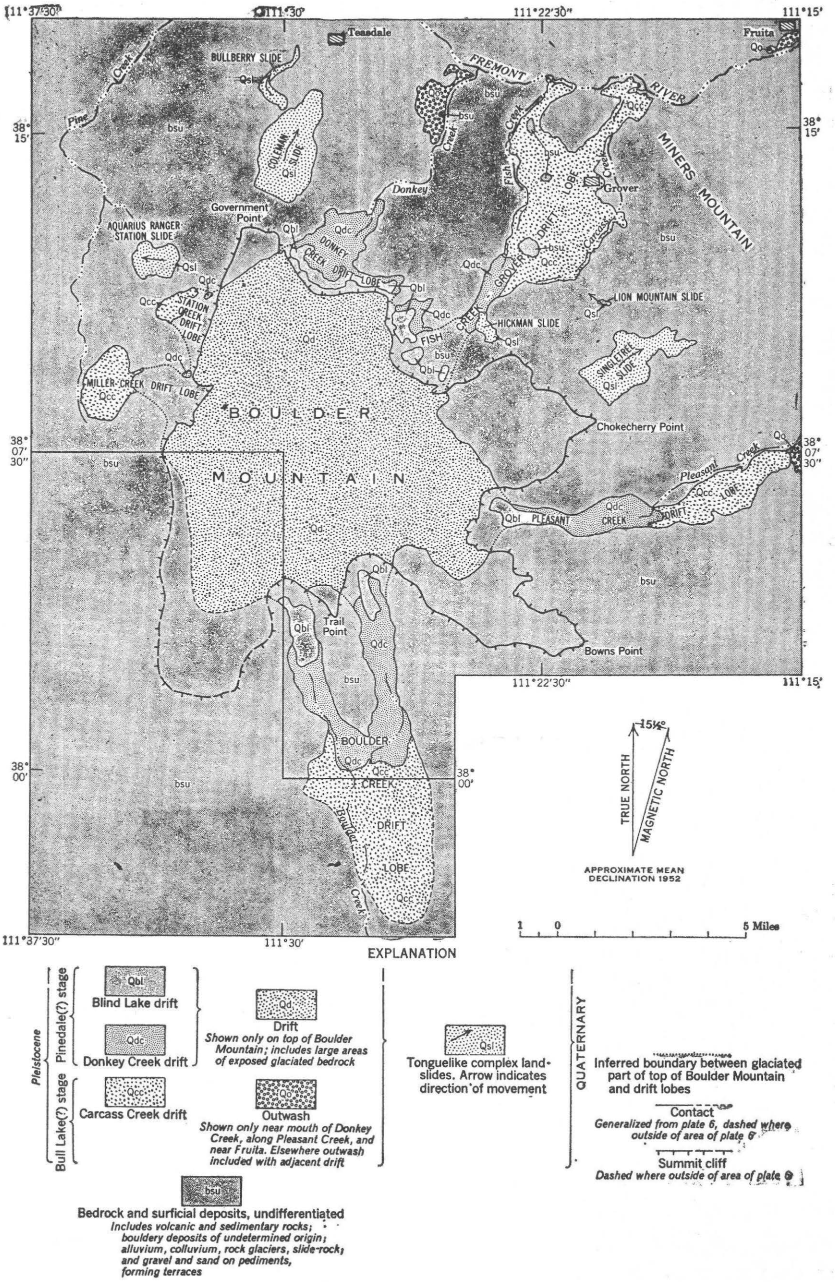
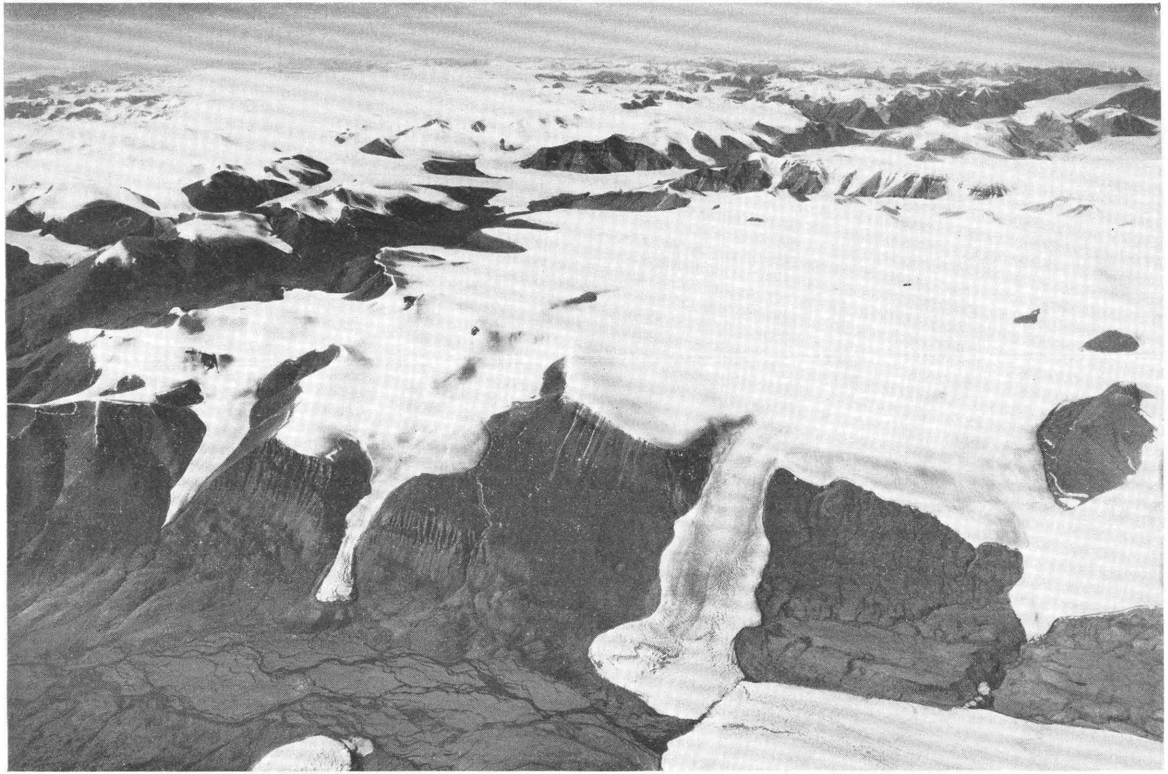


FIGURE 25.—Generalized map of Boulder Mountain region, Utah, showing drift lobes, three drifts of late Pleistocene age, and tonguelike complex landslides. Compiled from plate 6. Southwest part based on map of Powell National Forest, U. S. Forest Service.

GLACIAL DRIFT ON THE SIDES OF THE PLATEAU

Most of the drift is till, although small bodies of outwash are present also. The till is composed of fragments of volcanic rock with small amounts of sandstone, siltstone, shale, conglomerate, limestone, and gypsum, the proportion varying from place to place with differences in the local bedrock. Most fragments are of fresh, unweathered rock. A few fragments are soft and crumble between the fingers; nevertheless individual grains seem to be little altered. The matrix is generally calcareous and is composed largely of sand and silt. The fragments of rock range from ½ inch to as much as 30 feet in diameter; boulders from 1 to 6 feet in diameter are common. Almost without exception large boulders are of volcanic rock. The fragments are dominantly angular to subangular; water-worn fragments are scarce. Many large fragments have smooth abraded edges and corners between joint faces. Striated or soled fragments are rare. The percentage of fragments to matrix ranges roughly from 20 to 30 percent by volume. Most unweathered till is light gray, varying toward white or pink according to the nature of the local bedrock. No stratified material was observed enclosed within the till. No fissility, cleavage, or evidences of fabric were noted. The maximum exposed thickness of till is 10 feet, but the maximum inferred thickness, based on heights of morainic ridges and on scattered exposures near the Fremont River, is about 40 feet. It is difficult to distinguish till from debris transported by mass movement (p. 143). On plate 6 drift is shown only in those areas where it has morainic topography recognizable on the ground or on aerial photographs.

The outwash has lithologic characteristics similar to the till, and ranges in grain size from silt to boulders which, near the mouth of Carcass Creek and along the Fremont River near Fruita, reach a maximum of more than 12 feet in diameter. The boulders and cobbles are angular to slightly rounded, the pebbles subangular to well rounded. Some layers of bouldery outwash are as much as 10 feet thick. Pebbly and cobbly outwash forms irregular beds from 1 to several feet thick. Most outwash has a calcareous sandy matrix. The maximum observed thickness of outwash is 10 feet, but a thickness of about 50 feet is inferred from scattered outcrops near the mouth of Carcass Creek and along the Fremont River near Fruita. Outwash has been observed to overlie bedrock and also till (near the mouth of Fish Creek along the Grover-Torrey road). Outwash underlies narrow valley floors and terraces and has been mapped principally along Fish Creek, Carcass Creek, Fremont River, and Pleasant Creek. In this region outwash, terrace gravel, and pediment veneers are indistinguishable on the basis of internal character.



PLATEAU ICECAP WITH OUTLET GLACIERS, CONGER RANGE, ELLESMERE ISLAND.

The icecap on Boulder Mountain and the outlet glaciers flowing down the steep plateau slopes probably resembled those shown in this view. Photograph by Royal Canadian Air Force.

On plate 6 outwash is shown only where it occurs downstream from areas covered by drift.

Drift on the sides of the plateau forms lobes of varied shape extending radially outward from the plateau top (fig. 25). Most drift lobes include deposits of all three late Pleistocene glaciations recognized on Boulder Mountain. The ice tongues that formed these lobes apparently originated in the plateau icecap and spilled downward over the summit cliff (pl. 8). Some lobes are confined to the shelf at the base of the summit cliff; other lobes extend down the steep slopes beyond the shelf to more gently sloping terrain. The lobes are broader and more irregular than most tongues of drift deposited by valley glaciers in the Cordilleran region (table below). The difference results from extensive landsliding during the Quaternary period that widened valley sides and aggraded valley floors, thus tending to inhibit the excavation of deep valleys. Quite evidently glacier ice that spilled down over the summit cliff followed diverse paths created by various combinations of stream cutting and landslide modification; accordingly, some ice lobes were narrow tongues, and others were broad sheets.

Dimensions and altitudes of drift lobes

Name of drift lobe	Restored length (in miles)	Maximum width (in miles)	Altitude (in feet)		Total descent of lobe (in feet)	Average slope (in feet per mile)
			At terminus	At base of summit cliff		
Fish Creek-Grover	9	2½	6, 600	10, 200	3, 600	400
Pleasant Creek	9	1¼	7, 200	10, 200	3, 000	333
Boulder Creek	9	2	[1] 7, 000	10, 200	3, 200	[1] 355
Miller Creek	3	2	8, 500	10, 500	2, 000	666
Station Creek	1¼	¾	9, 800	10, 600	800	640
Donkey Creek	3	1¼	9, 000	10, 400	1, 400	466

[1] Estimated.

AGE

All the drift is probably of late Pleistocene age. This belief is based on three kinds of evidence: weathering of the drift, topography of the drift, and position of the drift with respect to topography of the bedrock. However, Smith and Huff (written communication) believe that some of the drift near the mouths of Fish and Carcass Creeks and along parts of Pleasant Creek is older than the Carcass Creek drift and is perhaps of pre-Sangamon age.

WEATHERING

Weathering of the drift is slight to moderate. Pebbles and cobbles within 2 feet of the surface show no more than superficial decomposition. Although boulders lying on the ground are considerably exfoliated, the accompanying chemical alteration is apparently slight. Soils developed in the drift record the movement of carbonates and sulfates, some development of secondary oxides, but apparently little or no production of secondary clay minerals.

Such weathering and soils are similar to those found in drift attributed to the Wisconsin stage in the Ruby-East Humboldt Range, Nev. (Sharp, 1938, p. 302), Wasatch Plateau, Utah (Spieker and Billings, 1940, p. 1193), La Sal Mountains, Utah (Richmond, written communication), San Francisco Mountains, Ariz. (Sharp, 1942), Rocky Mountains in Colorado (Bryan and Ray, 1940, p. 1856), Grand Mesa, Colo. (Retzer, 1954), and Fish Lake Plateau, Utah (Hardy and Muessig, 1952).

Along Pleasant Creek, L. C. Huff (written communication) found what he believes is the remnant of a soil formed in pre-Wisconsin (pre-Carcass Creek) time on what the authors have mapped as Carcass Creek drift.

TOPOGRAPHY

All known drift in the district is little dissected and has distinct morainal topography. The younger drift appears to have been modified very little since deposition. The older drift, although clearly modified by soil creep and other processes of mass-wasting, has lost neither its ridges nor all its basins. Owing to the lack of modification, the drift is tentatively assigned to late Pleistocene (post-Sangamon) time.

RELATION TO BEDROCK TOPOGRAPHY

The drift occurs principally within the present canyonlike valleys that drain the plateau, and hence postdates most of the erosion of these valleys. Near the mouths of Carcass and Fish creeks, where its base is exposed, the drift overlies a bedrock surface with a relief of about 150 feet. The Fremont River has incised that surface to a depth of about 250 feet near the mouth of Carcass Creek, and to a smaller depth near the mouth of Fish Creek. These depths of erosion are less than those generally reported (Richmond, written communication; Sharp, 1942, p. 486) to have followed the deposition of pre-Bull Lake (pre-Wisconsin?) drift in other Cordilleran mountain areas; such depths are more nearly commensurate with the erosion that postdates Bull Lake (lower Wisconsin?) drift in the mountains.

PROBABLE SUBSTAGES OF GLACIATION

The drift (pl. 6) is subdivided into drift of the Carcass Creek glacial advance, probably of Bull Lake age, drifts of the Donkey Creek and Blind Lake glacial advances, probably of Pinedale age, and rock glaciers probably of Recent age. Direct and conclusive evidence of the age and correlation of drift sheets, i. e., stratigraphic superposition exposed in section, is lacking in the Aquarius Plateau district because there are virtually no deep exposures. Evidence derived from soils, although useful in other regions, is unsatisfactory here because the known differences in soils could be entirely the result of differences of climate (altitude) and vegetation rather than of age of parent materials. Therefore drift-sheet correlation is based primarily on relative areal extent and altitude, degree of weathering, and amount of postdrift erosion.

Lobes of Carcass Creek drift (fig. 25) are longer than lobes of Donkey Creek drift by a ratio ranging from 2:1 to 2½:1. The morainic topography is subdued: Slopes are relatively gentle, as much as 25° but averaging nearer 15°, and are comparatively smooth and free from minor irregularities. Basins are few and shallow; many are partly filled with colluvium. Boulders on the ground are somewhat pitted by solution, and are deeply exfoliated; they retain little or none of the surface they possessed at the time of deposition and have shells as much as 20 inches thick in process of detachment. The ground between the boulders is littered with angular spalls and oxidized fine-grained disintegration products nearly to the exclusion of other material.

Lobes of Donkey Creek drift are longer than lobes of Blind Lake drift in a ratio from 3:1 to 4:1. Morainic topography is bold and only moderately smooth, with local relief as much as 200 feet and with slopes as steep as 30° but averaging nearer 20°. Basins are plentiful and show little evidence of filling with colluvium. Boulders are little affected by solution and only moderately exfoliated.

Lobes of Blind Lake drift are small, extending only ½ to 1½ miles outward from the summit cliff. Morainic topography is bold but is on a small scale, consisting of sharp ridges commonly 8 to 15 feet high, and numerous subrounded basins some of which contain lakes. The basins show little evidence of filling. Surface boulders are very numerous and show little effect of either solution or exfoliation; glacially abraded surfaces and even crude striations are visible on a few of them. Topographic expression of the Blind Lake and Donkey Creek drifts are similar, and differ from that of Carcass Creek drift. Post-Blind Lake drift consists entirely of rock glaciers whose component boulders are virtually unaltered by weathering. In summary, the evidence suggests that the Donkey Creek and Blind Lake drift sheets are more closely related in time to each other than to the Carcass Creek drift.

DRIFT LOBES

FISH CREEK-GROVER DRIFT LOBE

DIMENSIONS

The lobe (fig. 25, table p. 119) which extends from the reentrant in the plateau top at the head of Fish and Spring Creeks northeastward to the Fremont River is about 2½ miles wide at its upper end; it narrows to less than ½ mile near Hickman Pasture and widens to about 2½ miles near the tiny community of Grover. The distal segment of this Fish Creek-Grover drift lobe, 1½ to 2 miles long, is split into two sublobes separated by bedrock hills. The eastern sublobe occupies the valley of Carcass Creek; the western, that of Fish Creek.

The thickness of the drift is unknown. At the mouths of the two creeks mentioned above about 40 feet of till is exposed or can be confidently inferred. However, the maximum thickness of the lobe is probably larger than its greatest exposed thickness.

The Fish Creek-Grover drift lobe includes drift of three glaciations—Carcass Creek, Donkey Creek, and Blind Lake.

CARCASS CREEK DRIFT

Internal character and topographic expression.—The distal half of the Fish Creek-Grover drift lobe consists of Carcass Creek drift. It is composed chiefly of till with morainal topography. Many exposures of till are seen in cuts along the roads that traverse the lobe; elsewhere the presence of till is inferred from the ubiquitous end-moraine topography and from great numbers of surficial boulders of all sizes.

Carcass Creek drift commonly has a subparallel series of looped, boulder-covered end moraines consisting of long laterals curving into incomplete, nested terminals. The laterals approximate 50 feet in height in their upstream segments and gradually become lower in the downstream direction, curving into terminal ridges no more than 10 or 15 feet high. Successive moraine ridges are separated by narrow swales floored with sandy alluvium and colluvium.

The end moraines are interrupted only in places, mainly by buttes of Navajo sandstone. This fact suggests that the bedrock surface beneath the drift is of moderate relief with small steep-sided hills. One conspicuous interruption to the pattern is caused by a hill (presumably bedrock, but covered by bouldery accumulations, pl. 6) 2½ miles southwest of Grover. End-moraine ridges are wrapped around this hill which probably parted the flowing glacier into two streams.

Drainage.—In the Fish Creek–Grover lobe, Carcass Creek drift has marginal drainage. In general, Carcass Creek follows the eastern margin of the drift, Fish Creek, the western; however, where the drift splits into two sublobes, each stream follows the axis, rather than the margin, of a sublobe. Evidently the creeks originated as melt-water streams following the lateral margins of the glacier.

The tonguelike form of the Carcass Creek drift in the Fish Creek–Grover lobe implies a former glacier of similar outline, filling a preexisting valley whose axis was probably parallel with and about a mile east of Fish Creek. Presumably this inferred valley, now largely obliterated by drift, carried the pre-Carcass Creek drainage of this sector of the plateau.

Outwash.—Drift of the Carcass Creek glacial advance contains little outwash. Narrow tongues of outwash occur along the downstream parts of Fish and Carcass Creeks, largely between the Teasdale–Grover road and the Fremont River. Fanlike bodies and small-scale fills with flat surfaces are present at several places within the drift lobe, commonly between adjacent end-moraine ridges. Probably these are outwash; they are included with drift on the map (pl. 6). The scarcity of outwash and the fact that exposures of till show little sorted material convey the impression that melt water may have been scanty. However, large boulders of volcanic rock are found on the walls of the Fremont River canyon through Miners Mountain (J. F. Smith and R. G. Luedke, oral communication), and Johnson Mesa near Fruita is capped by gravel. These boulders and this gravel are believed to be outwash from the Carcass Creek glacier and suggest large volumes of fast-moving melt water at least for short periods.

Near the mouth of Fish Creek, bouldery outwash underlies a fan-shaped surface graded to a level about 100 feet above Fremont River. Some of the surfaces of the outwash are original; others appear to have been cut below the original outwash profiles. In places outwash is overlain by eolian(?) sand and by colluvium.

Johnson Mesa (Gregory and Anderson, 1939, p. 1848) has a cap of pebble and cobble gravel, composed chiefly of fragments of volcanic rock, that ranges in thickness from 10 to perhaps 50 feet. The gravel contains a few angular to subangular boulders, most of which range in size from 1 to 3 feet; a few are more than 12 feet in diameter. Lenses of white to gray silty sand are present. The surface of the mesa is littered with exfoliated boulders of volcanic rock. No ventifacts were seen. The surface is faintly channelled, has a local relief of about 10 feet, slopes gently northeastward, and stands 250 to 300 feet above the Fremont River.

Weathering, soils, and erosion.—Drift of the Carcass Creek glaciation constitutes parent material of soils with caliche. This fact is compatible with but does not support the hypothesis that this glaciation is the probable correlative of the Bull Lake stage in the Rocky Mountains

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(table, p. 158). However, one possible remnant of a pre-Carcass Creek (Sangamon or older) soil is exposed near the mouth of Carcass Creek (table below). Perhaps the 5 feet of silty material (caliche) is the B horizon or part of the B horizon of a soil profile whose upper part was removed by erosion prior to deposition of the overlying outwash. This horizon of caliche is thicker than that in soils with caliche described in this paper and suggests the caliche typical of the pre-Wisconsin paleosol of Hunt and Sokoloff (1950). Perhaps the till was deposited and weathered in pre-Carcass Creek (Sangamon and older) time. Erosion was followed by outwash deposition in Carcass Creek time. Thus the drift near the mouths of Fish Creek and Carcass Creek may possibly be pre-Carcass Creek in age.

Outwash of Carcass Creek age, derived from the Fish Creek–Grover lobe is considerably dissected. Along the downstream parts of Fish and Carcass Creeks the dissection ranges from 30 to 60 feet; along the Fremont River it is about 100 feet near Fish Creek and more than 250 feet near Fruita.

Section of surficial deposits exposed near mouth of Carcass Creek (NW¼NW¼ sec. 26, T. 29 S., R. 5 E.) (pl. 6, loc. 9)

	Feet
Top.	
Slumped	8
Gravel, pebbly, and sand, calcareous and moderately cemented; probably outwash of Carcass Creek glacier	4
Silty material, heterogeneous, loose, fluffy, white; apparently contains abundant caliche; includes numerous essentially unweathered fragments of volcanic rock; perhaps the material is a horizon or part of a horizon caliche developed in upper part of underlying till(?)	5
Silty sand, unsorted, compact, pink, highly calcareous; contains many angular fragments of volcanic rock; possibly till of pre-Carcass Creek (pre-Sangamon?) age	3
Total	20
Base.	

Possible stratigraphic subdivisions.—The Carcass Creek drift in the Carcass Creek and Fish Creek sublobes of the Fish Creek-Grover lobe is perhaps slightly older than Carcass Creek drift of the main Fish Creek-Grover lobe to the south. The evidence for this possibility is: (1) End-moraine ridges in the sublobes are fainter and less numerous than those in the main lobe. (2) A faint drift border, consisting of both end moraine and the proximal end of outwash bodies, separates the sublobes from the main lobe. (3) Outwash is more abundant in the sublobes than in the main lobe. These facts indicate that a glacier margin may have stood at the heads of the sublobes for a relatively long time. However, the only indication that this position might be the culmination of a significant readvance is the comparative faintness of the moraines north of this position.

DONKEY CREEK DRIFT

The southern part of the Fish Creek-Grover drift lobe is composed of drift assigned to the Donkey Creek and Blind Lake glaciations. Near the base of the summit cliff, Donkey Creek drift covers an area about 3 miles wide. Conspicuous end moraines outline a lobe of drift reaching down to an altitude of about 8,400 feet in the valley of Fish Creek and a shorter lobe in the headwater area of Spring Creek. The lateral moraines along Fish Creek are 150 feet high in places; where they merge into terminal moraines their pattern is discordant with that of the older moraines of the Carcass Creek drift. The end moraine in the valley of Spring Creek is less massive but clearly a continuation of the western lateral moraine along Fish Creek, from which it is separated abruptly by a gap half a mile long. Postmoraine slumping probably is responsible for the discontinuity, because slumping is evident in and near the gap. Extensive slumping has also destroyed the proximal end of the eastern lateral along Fish Creek.

Near Hickman Pasture, Donkey Creek drift narrows to a width of less than 1,200 feet, probably because of massive slumping on the eastern side of the valley. The slumping antedates the moraines of the Donkey Creek drift and may have narrowed the valley from a former width of more than a mile to its present width, forcing the Donkey Creek glacier to accommodate itself to the slump blocks. In addition, near Hickman Pasture the eastern lateral moraine of Donkey Creek drift is cut by an earthflow; hence landslide movements occurred here both before and after the Donkey Creek glacial maximum.

Outwash probably derived from the Donkey Creek glacier occurs along Fish Creek downstream from Donkey Creek drift. A surface apparently cut by melt water during Donkey Creek deglaciation occurs at and upstream from Hickman Pasture.

BLIND LAKE DRIFT

Drift of the Blind Lake glaciation, the type locality of which is in the Fish Creek-Grover drift lobe, consists of 3 small deposits marked at their peripheries by end moraines varying from a few feet to 60 feet in height. The largest mass extends only 1 mile beyond the toe of the cliff, down to an altitude of 9,900 to 10,200 feet and includes the basins of Blind and Pear Lakes. The lakes are dammed by end moraines; other indistinct moraines are present close to the summit cliff.

The second deposit is marked by a moraine that forms the basin of Fish Creek Lake; the third and smallest, includes the small basin of

Clark Lake (not shown on pl. 6). These small deposits seem to conform to topography created by slumping; it is inferred, therefore, that they postdate the landslides that have locally affected the Donkey Creek drift in the vicinity.

PLEASANT CREEK DRIFT LOBE

The Pleasant Creek drift lobe includes Carcass Creek and Donkey Creek drifts (fig. 25, table, p. 119) and occupies the capacious valley drained by Pleasant Creek on the east flank of the plateau. Its headward segment is particularly narrow, apparently because the valley had been narrowed by slumping before the drift was deposited.

The drift is believed to consist mainly of till rich in large boulders of volcanic rock. However, natural exposures are few and superficial, and the boulder-covered slopes defy excavation with ordinary field tools.

In the distal 4-mile segment of the lobe the drift is characterized by subparallel lateral moraines, some of which curve around to form incomplete terminals. The moraines are low with smooth, gentle sideslopes and few closed depressions. All are mantled with boulders. Between the moraines are swales in which stream channels expose several feet of sandy alluvium.

The surface drift in this 4-mile sector is believed to be the Carcass Creek drift. L. C. Huff (written communication) found an exposure in this sector showing alluvium overlying a caliche zone more than 5 feet thick in a bouldery mass that may be till. As the caliche may be a remnant of a pre-Carcass Creek (Sangamon or older) soil (Hunt and Sokoloff, 1950), it is possible that pre-Carcass Creek drift is present at this place. However, the surface drift in this sector is probably of Carcass Creek age, because degree of weathering, topography, and altitude of terminus are comparable with those of drift of the Carcass Creek glaciation in the Fish Creek-Grover lobe.

The Pleasant Creek drift lobe is flanked, at distances of less than a mile, by remnants of a pediment that stand high above present drainage and that appear to antedate the drift lobe. The altitudes of the remnants suggest that the drift lobe was deposited in a shallow valley cut into the pediment. However, the pediment is so nearly destroyed by dissection that this relationship could not be established.

The outer part of the Pleasant Creek drift lobe is drained by Pleasant Creek on the north, and, throughout all but the last 2½ miles, by Oak Creek on the south. These streams must have assumed their courses while the drift lobe was accumulating. The lobe is also drained medially by a short stream now impounded to form Bown's Reservoir.

Drift of the Donkey Creek glaciation forms the Pleasant Creek drift lobe from near the base of the summit cliff down the valley drained by Pleasant Creek to the vicinity of the Wildcat Ranger Station, where the drift reaches a minimum altitude of about 8,400 feet. This drift is characterized by discontinuous lateral moraines generally 50 to 75 feet high, with steep sideslopes. In places there are two laterals about 500 feet apart. Close to its terminus the lobe is marked by outwash accumulations at its two lateral margins. Through a distance of more than a mile outward from the summit cliff moraines are absent, and there is much evidence of slumping that probably destroyed most Donkey Creek drift in this segment.

Although destroyed by slumping or covered by younger drift in its headward part, drift of the Carcass Creek glaciation in the Pleasant Creek lobe evidently is the product of glacier ice that originated on the plateau top and that flowed down over the summit cliff, probably between Meeks Lake and a point one mile east of Pleasant Creek Meadows. No evidence has been found that the plateau top outside the area between these two points was ever covered by glacier ice.

A small mass of drift ascribed to the Blind Lake glaciation forms the head of the Pleasant Creek drift lobe near the junction of Meeks Draw with Pleasant Creek. The mass is bordered by a miniature end moraine at an altitude of about 9,500 feet. Its areal position suggests a small lobe of glacier ice flowing down Meeks Draw from the plateau top. There is no evidence of a contemporaneous glacier in the headwaters of Pleasant Creek.

BOULDER CREEK DRIFT LOBE

The Boulder Creek drift lobe lies in the valley of Boulder Creek, the principal stream draining the south side of the plateau (fig. 25) and is much like the lobes described previously (table, p. 119).

In the distal 3 miles of the lobe, drift tentatively correlated with the Carcass Creek glaciation is at the surface. The drift forms faint subparallel moraines and is apparently buried in part by its outwash so that it is difficult to fix closely the outer limit of the former glacier.

The lobe had its source in glacier ice which poured over the summit cliff into the deep valleys of East Boulder Creek and West Boulder Creek, leaving the intervening projection, Trail Point, unglaciated.

Drift in the form of massive moraines occupies both branches of the Boulder Creek valley to the vicinity of their junction, 5 miles southward from the summit cliff. Because the extent, morphology, and terminal altitude of this drift are similar to Donkey Creek drift in the other major lobes, this drift is tentatively assigned to the Donkey Creek glaciation.

In both branches of the valley, 1½ to 2 miles downstream from the summit cliff, fresh miniature end-moraines reach altitudes of 9,200 to

9,600 feet. These are assigned by analogy to the Blind Lake drift. The moraine in the valley of West Boulder Creek forms the basin of Baker Lake.

MILLER CREEK DRIFT LOBE

The Miller Creek lobe occupies the short, very deep canyon that drains the west-facing scarp of Boulder Mountain 1 mile south of Lookout Peak, and extends out over the adjacent lowland (table, p. 119). This lobe is believed to be drift, but a landslide origin has not been entirely excluded. The problem is discussed in the section on "Tonguelike Complex Landslides (p. 137)."

The canyon portion of the lobe is barely 2 miles long, but the lobe abruptly widens on the flat floor of Dark Valley into a terminal bulb more than 2 miles in diameter. With a maximum height of about 100 feet above the floor, the bulb is a remarkably symmetrical mass with discontinuous concentric ridges having a local relief of about 50 feet. The ridges are more irregular and more closely spaced than those in the other lobes; individual knolls and basins are more distinct, and although slopes are generally gentle, some, including the distal slope itself, have angles as much as 30°. The ridges are underlain by material that is probably a bouldery till.

The distal slope of the bulb is cut by two reentrants that contain partly dissected fanshaped deposits, probably outwash (not shown on pl. 6). The deposits merge with a thin, broad apron of alluvium that originates along the distal slopes of the bulb and sweeps clockwise around its perimeter, draining northward along Dark Valley Draw.

Most of the drift of the Miller Creek lobe probably is of Carcass Creek age despite the fact that its terminus is more than 2,000 feet above that of the other lobes of that age (table, p. 119). The boulders on the surface of Miller Creek lobe are similar in degree of weathering to those on Carcass Creek drift on the northeastern side of Boulder Mountain. Basins in the Miller Creek lobe, despite locally steep slopes, are partly filled with colluvium; some contain small alluvial fans. The broad terminus of the Miller Creek drift lobe differs from that of the other drift lobes in width and in altitude. The difference in form is attributed to the spreading-out of ice on a flat floor. Because the glacier was shorter than the others, its terminus occupied each position during a relatively long time; hence, the lobe has somewhat steeper slopes and more distinct morainic expression than the other lobes. Most of the canyon portion of the drift lobe has been removed by landsliding, but near the canyon mouth are truncated stumps of lateral moraines.

Younger drift in this lobe is represented only by a small patch of end moraine, with a local relief of about 15 feet, that forms the basin of Miller Lake at an altitude of about 10,500 feet (pl. 6). Slopes are steeper than those in the piedmont bulb, and the degree of exfoliation is less. These facts, coupled with the high altitude of the mass, suggest that this drift probably belongs to the Donkey Creek glaciation. The rest of the drift deposited at this substage has been obscured or removed by landsliding.

STATION CREEK DRIFT LOBE

The Station Creek drift lobe [3] is a crudely semicircular mass of drift that covers part of the nearly flat surface of a fault or slump block 2½ miles north of Miller Creek and 1½ miles southeast of the Aquarius Ranger Station (table, p. 119). Its headward part has been destroyed or obscured by landsliding. The lobe does not, and apparently never did, occupy a canyon or other obvious depression; it simply covers an area of irregular topography resulting from slumping and possibly also faulting.

A few exposures suggest that the lobe is built of till consisting of pebbles, cobbles, and boulders in a matrix of sandy grit. The larger fragments are abraded, but their shapes are not diagnostic of abrasion by glacier ice.

The outer part of the lobe consists of low and very bouldery concentric ridges, low knolls, and basins; these features together have a local relief of about 25 feet. The apronlike distal slope of the lobe is steep and is strewn with boulders. The inner part of the lobe has very low relief and gentle slopes and probably is ground moraine.

Drift of the Station Creek lobe is tentatively correlated with the Carcass Creek glaciation because the extent of exfoliation of its boulders is comparable with that of the Carcass Creek drift of the Fish Creek-Grover drift lobe. The high altitude of the Station Creek drift lobe terminus, which is 700 to 800 feet above the Miller Creeks bulb (table, p. 119), does not preclude such correlation, because the paths of the corresponding glaciers were different. Both glaciers are believed to have originated on the plateau top because neither had an adequate catchment area beneath the summit cliff. The flow of Miller Creek glacier was facilitated, however, by the presence of a deep canyon, whereas the Station Creek ice lobe had no canyon, and furthermore flowed from a narrow part of the plateau top where the ice supply would have been relatively small. Accordingly a smaller volume of ice had to make its way over an irregular topography consisting of dislocated blocks, without benefit of any channel. This seems an adequate explanation of the relatively high altitude of the terminus of the Station Creek lobe.

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[3] The name is not entirely appropriate because Station Creek does not actually drain any part of the lobe. However, the headward part of the creek lies close to the north flank of the lobe, and is the nearest feature bearing a name on existing maps.

A small body of end moraine on the northwest side of a small unnamed lake half a mile north of Cook Lake is much like that at Miller Lake, although it appears to be slightly less weathered and mass-wasted. On the basis of weathering and degree of slope modification it is tentatively correlated with the Donkey Creek drift.

The fine-textured topography of the Station Creek drift lobe implies an origin in a small, thin glacier. The position of the drift body is unusual in that it is unrelated to a recess in the summit cliff. Apparently it represents a small and short-lived stream of ice that spilled over the cliff from the plateau icecap.

DONKEY CREEK DRIFT LOBE

The Donkey Creek drift lobe (fig. 25) occupies the headwater area of Donkey Creek in a broad reentrant in the summit cliff between Government Point and Donkey Point (pl. 7). Like the Station Creek drift lobe it lies on a mass of slump blocks rather than in a definite valley.

The periphery of the lobe is marked by a nearly continuous end-moraine 15 to 35 feet high that is hummocky and covered with boulders. At Donkey Creek the moraine attains an extreme distance of 3 miles from the summit cliff (table, p. 119). Two local and discontinuous inner moraines in the vicinity of Round Lake probably record later readvances of the Donkey Creek glacier.

A pronounced though somewhat less continuous end moraine, 5 to 20 feet high, lies much closer to the cliff. It retains Donkey Lake (now artificially heightened by a dam), Green Lake, and smaller lakes between them.

On a basis of position, altitude, topography, and extent of weathering the outer moraine is tentatively correlated with the Donkey Creek drift, and the inner moraine, near the cliff, with the Blind Lake drift.

The Donkey Creek lobe apparently includes no drift of Carcass Creek age. Two possible explanations suggest themselves. One is that a Carcass Creek glacier tongue occupied approximately this area, probably extended northward beyond the present Donkey Creek drift border, and left deposits that were completely disrupted by landsliding in Donkey Creek time. Favoring this explanation is the presence of continuous landslide topography outside of, and controlling the detailed trend of, the moraine of the Donkey Creek glaciation. The other explanation notes that the Donkey Creek drift lobe is northeast of the narrow northern end of the plateau summit. The plateau ice on this narrow projection may have drained chiefly eastward into the Fish Creek-Grover lobe, leaving little ice to flow northward into the Donkey Creek area. As a result, in the latter area the Carcass Creek ice may have been no more extensive than the Donkey Creek ice. Of the two explanations the first seems the more probable, but no firm basis has been found for eliminating either one.

DISTRIBUTION OF DRIFT AROUND THE PLATEAU

The extent of the drift is almost equal on the south, east, and north sides of the plateau (table, p. 119, and fig. 25). On the west side the drift is much less extensive. This distribution of drift is unlike that on many mountain ranges in the Cordilleran region where glaciation is dominant on the north and east flanks.

The explanation is probably as follows: The regimen of glaciers heading in cirques below the narrow crest of a mountain range depends in part on wind-drifting of snow on the lee (usually east) side of the range, and on conservation of snow and ice owing to more shade offered by the range crest from southern and western exposure to the sun. In contrast, the element of topographic protection is less important in the regimen of the icecap outlet glacier (pl. 8), because the source ice-body stands above the bedrock surface. Furthermore, the thickness and activity of an icecap from place to place is affected by the distribution of snowfall on it. On a high plateau this depends on the direction from which air masses bring orographic precipitation to the highland. Today, on the Aquarius Plateau, this direction is west and southwest. There is no reason to believe that during the glacial ages the direction was significantly different. Hence the icecap may have been somewhat thicker over the western and southwestern parts than over other parts of the plateau.

These considerations possibly explain why the Boulder Creek drift lobe, on the south side of the plateau is as long and bulky as the Pleasant Creek and Fish Creek-Grover drift lobes, and why drift is fairly extensive on the west side of the highland.

ROCK GLACIERS

Rock glaciers (Capps, 1910; Sharpe, 1938, p. 42) occur on all sides of the plateau near the base of the summit cliff, at altitudes approximating 10,500 to 10,700 feet. They are apparently largest and most abundant on the north side, in the Fish Creek and Donkey Creek reentrants. The rock glaciers are uni- or multi-lobate, with widths (parallel with the cliff) of 200 to 2,500 feet, and with lengths (normal to the cliff toe) up to 1,200 feet. They have steep terminal slopes, commonly 38° to 42°, and terminal heights of 30 to 110 feet.

The surface material of the rock glaciers consists of large angular boulders of volcanic rock derived from the adjacent cliffs. No fragments smaller than boulder size are visible. Some boulders exceed 12 feet in diameter; many of them are inequidimensional, and no preferred orientation was observed. No exposure of the interior of a rock glacier was found.

Most of the rock glaciers have concentric ridges, as much as 15 feet high, around their lateral and terminal margins. Some of the larger glaciers have low, irregular knolls and shallow basins near the center of their upper surfaces. All surfaces are bare and free of vegetation except for lichens. The boulders are superficially oxidized and some are slightly exfoliated.

The rock glaciers are overlapped commonly by talus composed of smaller fragments of volcanic rock that are generally less weathered than those of the rock glaciers, although the differences are small. Some rock glaciers overlie Blind Lake drift with marked topographic discordance.

The rock glaciers originated below the rim of the summit cliff and in general are largest and most numerous beneath high cliffs that face northeast. They are absent below some conspicuous notches in the cliff which are ideal avenues for the movement of ice downward from the plateau top.

Two principal hypotheses of origin of rock glaciers have been put forward. One is that these features are the surface moraines of vanished true glaciers (Capps, 1910; Kesseli, 1941). The other is that they are mass-wasting phenomena. There is evidence that some rock glaciers are moving at present in the absence of underlying glacier ice. Such rock glaciers are bodies of slide-rock that flow with the aid of an interstitial lubricant such as ice other than glacier ice (Roots, 1954, p. 24–29).

The distribution of the rock glaciers around the Aquarius Plateau favors the view that they are mainly frost-weathered cliff debris incorporated in and transported downslope by small glaciers which were nourished by snow that collected at the base of the escarpment. The Pleistocene drift lobes, on the other hand, were built by ice that flowed down over the summit cliff from a plateau icecap. Some additional movement of rock glaciers, caused by interstitial ice of nonglacial origin, may have preceded and may also have followed glacial movement. For example, in a climate becoming colder, ice might form in the voids within an existing body of boulders, and some movement might occur through melting and refreezing of such ice.

At least some of the rock glaciers postdate the Blind Lake drift. These probably represent the inception, expansion, and decay of numerous very small glaciers in Recent time and possibly are correlatives of ice bodies in the Sierra Nevada that may date from less than 4,000 years ago (Matthes, 1939, p. 519).

In places on the west slope of Boulder Mountain, small rock glaciers consist of two members, one overlying the proximal part of the other

(Kesseli, 1941, p. 222 and fig. 13). This relationship suggests two very minor pulses of glaciation. No basis for dating the two members was found but perhaps in this west-facing, little-protected position the lower member is of Blind Lake age, whereas the upper member is of the post-Blind Lake generation which is present more conspicuously on the north side of the plateau.

TALUS

Slide-rock in the form of apronlike talus occurs at the bases of rock cliffs along the Fremont River and elsewhere in the Teasdale-Torrey lowlands, but the deposits are too small to be shown on plate 6. The fragments are dominantly of sedimentary rock. Much of the slide-rock overlies a red flaggy colluvium (figs. 26, 27, and 28) believed to have accumulated during late Pleistocene (Donkey Creek and Blind Lake) time; the talus is now being dissected. Possibly it accumulated in part during an episode of cool climate that followed the Thermal Maximum (Flint and Deevey, 1951, p. 275).

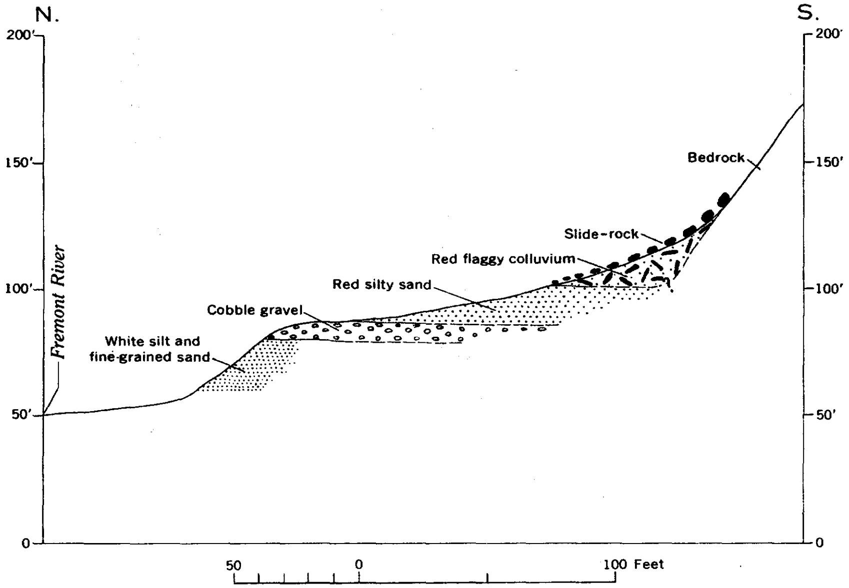

FIGURE 26.—Colluvium and river deposits exposed in gulches on south side of Fremont River just northwest of the Torrey-Grover road (pl. 6, loc. 5).

Talus aprons partly cloak the summit cliff and seem to consist of two groups. The older talus is the more extensive; it commonly masks more than the lower half, and in some places almost all, of the cliff. Most of this talus is stable and supports a sparse vegetation. It is confined to those parts of the cliff where the adjacent plateau top shows no evidence of glaciation, such as the Chokecherry Point and

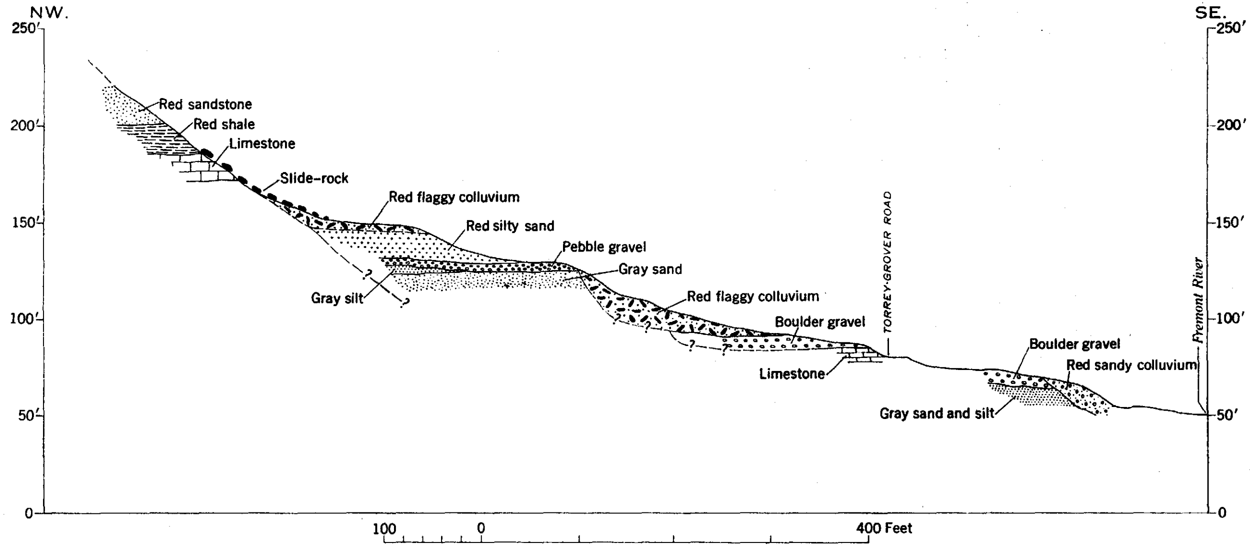

FIGURE 27.—Colluvium and river deposits exposed in tributary valley on north side of Fremont River along Torrey-Grover road (pl. 6, loc. 6). Vertical exaggeration 2 times.

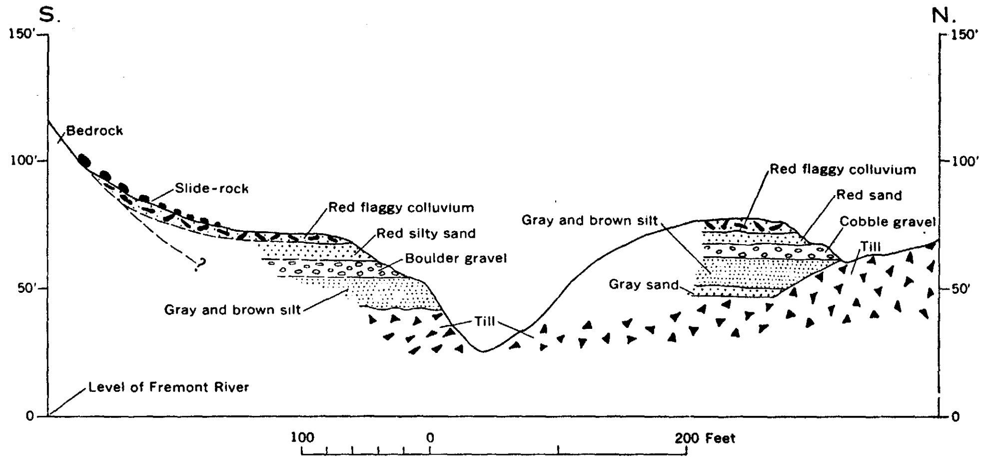

FIGURE 28.—Colluvium and river deposits overlying till. Exposure in gulch on south side of Fremont River between Fish and Carcass Creeks (pl. 6, loc. 8). Vertical exaggeration 2 times.

Bowns Point "peninsulas", Trail Point, and the southwest margin of Boulder Mountain. Such a distribution implies that this group of taluses antedates the Blind Lake glaciation.

The younger talus forms rather narrow sheets along the lower parts of the cliff and is less extensive than the older group. It is unstable and is virtually free of vegetation. It occurs along the foot of cliffs that fringe the distinctly glaciated parts of the plateau top, and where in contact with rock glaciers it overlies and hence postdates those features.

The younger talus in itself affords no evidence that it is not the product of continuous accumulation during the whole time since the rock glaciers were formed.

BOULDERY ACCUMULATIONS OF UNDETERMINED ORIGIN

Bouldery accumulations of undetermined origin (pl. 6) are masses of boulders with some finer material that cover large areas principally on the slopes of Boulder Mountain. Many of these accumulations mantle areas of conspicuous landsliding and slumping and are described in the following section. These accumulations are doubtless of both Pleistocene and Recent age, but their ultimate origin, whether drift, pediment gravel, or landslide debris, is largely unknown.

LANDSLIDES

The most extensive type of superficial deposit that mantles the sides of the plateau, far exceeding the total areal extent of drift or of exposed bedrock, is landslide debris. For the purpose of this paper a landslide is defined as any downward and outward movement of bedrock or mantle on slopes, at rates greater than that of creep.[4] In accordance with general usage the term is applied also to lobate bodies of debris resulting from distinct individual slides.

Three types of landslide deposits are present on the sides of the plateau. The simplest type is slump blocks, mostly at the base of the summit cliff; the second consists of lobate or tongue-like complex landslides; the third is a widespread mantle of landslide debris. The three types differ in character and in time of origin.

INDEPENDENT SLUMPS

Slump blocks that are not obviously integral parts of tonguelike complex landslides are here grouped under the term "independent

[4] Modified from Highway Research Board Landslide Committee (unpublished classification sheet). Landslide terms used in this paper are drawn from the same source.

slumps." They range from 100 feet to thousands of feet in length and generally are as much as 100 feet (in extreme examples 200 feet) in height. They occur at all altitudes on the plateau sides, in sedimentary bedrock, in lateral moraines and, most abundantly, in volcanic rocks at and below the summit cliff.

Some slumps have been rotated backward; less commonly, others have been rotated forward and have been displaced vertically by as much as 200 feet. Some have broken up into boulder rubble since their displacement but still preserve the general continuity of their layered rock. In the Fish Creek reentrant successive slumps, traced outward and downward from the summit cliff, show progressive differences in weathering that imply progressive increase in age. Some large eroded slumps, half a mile or more beyond the parent cliff and close to the altitude of the cliff toe, could hardly have moved to their position from the present locus of the cliff. The movement of such blocks may have occurred when the cliffs were adjacent to them. The cliffs have since retreated, probably because of glacial erosion and repeated slumping.

Some large slumps are covered with Donkey Creek drift and clearly have determined the local directions of flow of the Blind Lake glaciers. Others cut lateral moraines of the Donkey Creek drift. Still others are obviously very recent. Independent slumps have formed at various times, and it is quite possible that slumping has substantially reduced the area of the plateau top in post-Sangamon time (cf. Retzer, 1954).

TONGUELIKE COMPLEX LANDSLIDES

Six known lobate or tonguelike complex landslides on the slopes of Boulder Mountain are the Aquarius Ranger Station, Coleman, Bullberry, Hickman, Singletree, and Lion Mountain slides. Their locations are shown on figure 25 and their areal and vertical extent summarized below. These landslides are a combination of slumps, earthflows, and perhaps of debris-slides.

DISTRIBUTION

Four of the slides, Aquarius Ranger Station, Coleman, Hickman, and Singletree, originate at or near the summit cliff where they form peninsulas adjacent to segments of the plateau top that were not glaciated, at least during Donkey Creek and later times. The remaining two slides head in the lower slopes of Boulder Mountain and are relatively long and narrow.

Principal dimensions of tonguelike complex landslides around Boulder Mountain

Name of slide	Minimum length (feet)	Maximum width (feet)	Difference in altitude between head and toe (feet)
Aquarius Ranger Station	6, 000	5, 000	Unknown
Coleman	17, 000	8, 600	2, 800
Bullberry	11, 800	1, 000	840
Hickman	4, 600	1, 950	950
Singletree	16, 100	6, 700	2, 400
Lion Mtn	1, 800	450	280

TOPOGRAPHY

Each of the tonguelike complex landslides consists of an upstream portion marked by transverse steplike slump blocks separated by scarps and a longer downstream portion consisting of a lobate earthflow (fig. 29). The slump blocks resemble the independent slumps previously described. Individual blocks become progessively smaller and more broken up downstream. The landslides occuped preexisting valleys and forced the streams to assume positions along their lateral margins.

Simple and complex slumps have been observed elsewhere to possess undersurfaces of rupture and displacement on which the slump blocks have moved over the underlying material. In the downslope direction the surface of rupture is the continuation of the surface of the main or highest slump scarp. Ordinarily the surface is concave, both transversely and longitudinally. At some point downslope, at the foot (fig. 29), the surface of rupture intersects the ground surface, and may be visible there. In the complex landslides on Boulder Mountain, however, the foot is concealed beneath earthflow debris.

The transverse cracks, well developed in the downstream half of the Hickman slide, very likely represent tension in the surface of the earthflow as it passed over the foot of the surface of rupture (fig. 29). If so, they are analogous to the crevasses in a valley glacier developed where the ice flows over an abruptly steepened slope.

The Coleman slide is described in detail as typical of the tonguelike complex landslides on the slopes of Bounder Mountain: In this slide the slumped portion is confined to the head. Downslope there is an intermediate zone of boulders and finer debris arranged in discontinuous irregular ridges parallel with the margin of the slide. This has some characteristcs of a debris-slide. The terminal, lobate earthflow occupies a depression in the lower part of the plateau sideslope and has well defined lateral margins. The slump blocks evidently broke up within a short distance of travel. The stream along the west

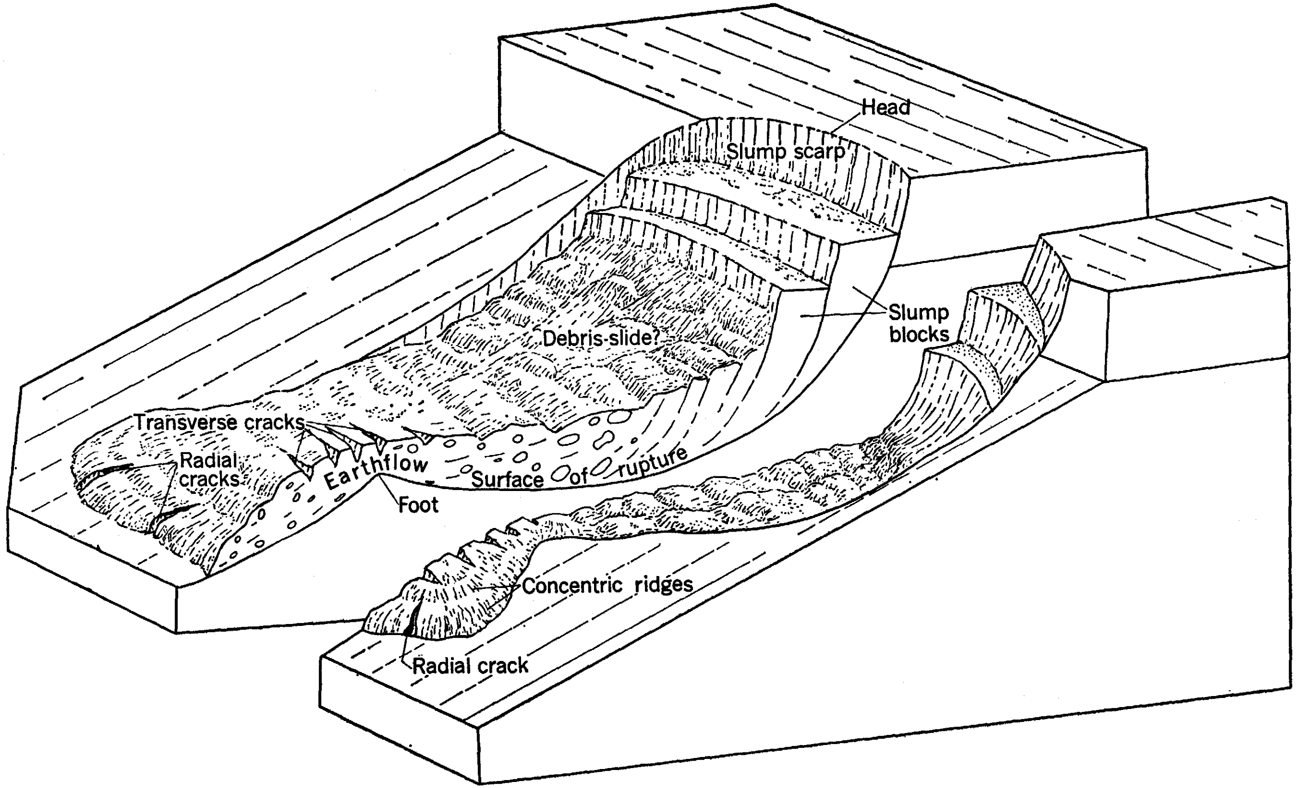

Figure 29.—Diagrammatic sketch of a complex landslide such as the Coleman slide and Singletree slide, showing component parts. (In part after Highway Research Board Landslide Committee, unpublished).

margin of the slide has incised itself slightly into the underlying bedrock.

In the downstream portion of the Coleman slide the features imply flowing movement rather than slumping and sliding. The toe of the slide, where not greatly altered by erosion, is convex downstream and has a frontal slope of about 40°. Upstream from and parallel with the toe are two or more arcuate ridges as much as 40 feet high. Farther upstream are irregular knolls, hummocks, and basins without apparent pattern and with a relief of about 30 to 40 feet. Relief is twice as great where there are long deep furrows transverse to the long axis of the slide. Some of these furrows contain lakelets.

The zone of transition from slumping to flowing is widest and most clearly defined in the Coleman slide, where the local topography suggests flowing movement around the sides of large stranded slump blocks. One of the stranded blocks, consisting largely of sedimentary rock, appears to have been cut at both ends by thin, slicelike slumps, parallel with the direction of flow. Some of these slumps were broken up and carried downstream. The main block is like a short loaf of bread cut by slices at both ends, with the outer slices merging into the surrounding earthflow. Basins between the slicelike slump blocks contain two long narrow lakelets.

COMPOSITION AND THICKNESS

In slump blocks at the heads of tonguelike complex landslides only volcanic rocks are exposed; in earthflow portions superficial exposures show volcanic fragments well mixed with material derived from sedimentary rocks such as silt, clay, and mashed and deformed masses of shale and siltstone. The landslides are usually mantled by rubble that consists of joint blocks and other angular fragments of volcanic rock of boulder size, generally more than 10 feet in diameter. Most exposures give an exaggerated impression of the number of volcanic boulders because they creep down as a mantle over the underlying material.

Much of the mass of debris is nonsorted and nonstratified. It resembles till except that it contains boulders and smaller fragments that have what appear to be nonabraded shapes. The intimate mixture of various rock types implies differential movement of component particles, but exceptions to such mixtures occur. Some large hummocks are completely mantled by boulders of a single kind of volcanic rock, evidently formed by breakup, through frost action, of one great mass of rock that had previously slumped or slid down from the summit cliff. In the Hickman slide, for example, all the debris on the downstream slope of the largest of the transverse furrows (600 feet long) consists of one kind of volcanic rock, whereas all that on the upstream side is of a different, agglomeratic type. This difference implies that two distinct blocks are at the surface on the two sides of the furrow.

The thicknesses of the Aquarius landslides are unknown. The topography near the toes of the Coleman and Singletree slides suggests that their earthflow portions may be as much as 200 feet thick.

ORIGIN

Boulder Mountain is strongly susceptible to landsliding. It consists of several hundred feet of flat-lying massive volcanic rocks underlain by several thousand feet of flat-lying sedimentary beds, mostly claystone and siltstone. Many complex landslides in other areas likewise are present where weak argillaceous rocks are overlain by competent caprocks.

Boulder Mountain would probably fail by landsliding under almost any climate. The weak sedimentary rocks, under confined pressure caused by the weight of the overlying volcanic rocks, would probably lose cohesion and sliding would result. During glacial ages, however, sliding in the Aquarius Plateau district was probably enhanced by large volumes of melt water that penetrated through the volcanic rocks to the underlying sediments.

Terzaghi (1950, p. 91–100), a keen student of landslides, expressed the opinion that the mere weight of water added to rock formerly dry is an unimportant causal factor, and that frost action is likewise unimportant because its effects are only skin deep. He stated, however, that failure could be caused by a new source of water entering material formerly relatively dry and dissolving a soluble binder or cement. Terzaghi gives another cause of failure (p. 101):

> Experience shows that the water, which seeps toward steep slopes during rainstorms, does not displace enough air to destroy the apparent cohesion of sand or silt. However, if water percolates through the ground toward the slope in large quantities and without any intermissions, the air is almost completely expelled, the apparent cohesion is eliminated, and the slope fails.

An additional cause, where clay rather than silt or sand is involved, is gradual swelling and softening of clay as it absorbs water, a process enhanced by the presence of minute cracks in clay beds that have been compressed by loading and expanded by unloading in the geologic past (Ward, 1945, p. 185).

These causes seem adequate to have brought about the Aquarius slides, given an extraordinarily large source of water, such as melt water from snow and glacier ice on the plateau top. The four large complex landslides, as well as some of the larger groups of slump blocks, are below cusplike peninsulas of the plateau top that apparently were not glaciated in Donkey Creek or later time. This distribution suggests a possible genetic relationship between landsliding and glaciation: the icecap acted as a protective blanket permitting little percolation of melt water down into the underlying rock. On the nonglaciated points, however, melt water from snow, most abundant during spring thaw, and summer melt water from the icecap itself percolated downward through vertical joints in the volcanic rocks, saturated, and reduced cohesion in the underlying claystones and siltstone so that rupture occurred.

A part of the downstream earthflow portion of the Singletree slide appears to be considerably dissected and perhaps is somewhat older than the remainder of the slide. The emplacement of the toe of the slide southeast of Lion Mountain may have been followed by an episode of dissection, which cut into the underlying bedrock, prior to the movement of the remainder of the Singletree slide.

On the other hand, recent movement is shown by a number of features. Leaning trees, including young trees, are common not only on many tonguelike complex landslides, but also on much of the slope of Boulder Mountain below the summit cliff. In one area several very large yellow pines (*Pinus ponderosa*), still growing, are conspicuously bent within 10 to 20 feet of the ground. A sawlog of the same kind of pine and of comparable size showed, in section, 320 growth rings. Hence the bends may record slumps dating from 250 to 300 years ago.

One hummock situated about halfway down the length of the Coleman slide exhibits a gaping rift 200 feet long. A large upright fir, whose long horizontal roots straddle the rift, has been split in two by pulling apart of the roots. When observed in 1952 the fir was not yet dead.

There is much evidence of minor present-day slumping of the lower slopes underlain by sedimentary rocks.

No direct evidence of any particular cause of sliding has been found, and the foregoing suggestion is merely a reasonable explanation. Mechanically it parallels the explanation given for the recently active Cedar Creek slide near Montrose, Colo. (Varnes, 1949). In that slide the trigger was a new and abundant supply of irrigation water percolating down into a firm caprock overlying a body of shale. The same author ascribed two other slides in western Colorado to large amounts of water added to shale overlain by a massive caprock. Another slide, in shale capped by sandstone, near Durango, Colo., probably was caused by the absorption of a sudden large increment of melt water (Vanderwilt, 1934).

It seems likely that on slopes of the Aquarius Plateau the development and movement of new slump blocks caused rupture of the volcanic rocks along joint surfaces, and that the resulting boulders moved downslope as debris-slides. Farther downslope the slump blocks were mixed with claystone and siltstone creating a transition from slumping to flowing movement. The resulting earthflow was composed of till-like material, although some blocks of volcanic rock and even large blocks of claystone and siltstone remain.

Movement of the Aquarius slides probably resembled that of some present-day slides. Vanderwilt (1934) described a complex slide 1,800 feet long near Durango, Colo., which started in 1932. Movement of slump blocks constituting the head of the slide produced talus consisting of joint blocks broken from sandstone caprock. Maximum measured rate of movement was 30 feet per day. Cracks opened and closed, trees were overturned and buried, and in the earthflow portion downstream, concentric ridges developed. Farther headward "low, rough ridges" developed parallel with the sides of the slide.

The Gros Ventre slide in western Wyoming (Blackwelder, 1912) began to move in 1908. Slumping at the head transmitted stresses down the slope to old landslide deposits, which "began to press forward, bulge, and crack" in slow flow "like that of a glacier". In 1909 the toe "bulged into low irregular domes fretted with open crevasses . . ." The rate of flow, however, was too slow "to be actually seen;" it was inferred from periodic observations. By 1911 movement had virtually ceased.

COMPARISON WITH LOBES OF GLACIAL DRIFT

Both in form and in component sediments the tonguelike complex landslides closely resemble the lobes of glacial drift. Atwood (1909, p. 63–65) found that both topographically and internally the two kinds of bodies, as they exist in the Uinta Mountains, are very difficult to separate. Blackwelder (1912, p. 491) concluded that "only the most painstaking and critical study will serve to discriminate the two types of deposits."

On the Aquarius Plateau the two groups are alike in that both may (1) originate at cliffs, (2) occupy valleys or other pre-existing depressions, (3) consist of nonsorted, nonstratified materials, and (4) possess tonguelike form, subparallel longitudinal ridges, and knolls and basins. The differences, therefore, are of detail rather than of general form and composition; not all are applicable to any one landslide or drift lobe. Some of the differences listed in the table below are depicted in figure 29.

Comparison of features of landslides and drift lobes around Boulder Mountain

Tonguelike complex landslides	Glacial drift lobes
External form and position	
May head in nonglaciated areas including those below peninsulas of the plateau top.	Head in reentrants and (or) glaciated areas or above former regional snowline.
Massive transverse ridges in headward part (slump blocks).	Sinuous transverse ridges in headward part (terminal moraines).
May have longitudinal ridges upstream.	Lack longitudinal ridges except at lateral margins (lateral moraines).
Concentric transverse ridges are confined to vicinity of toe and are not continuous with marginal ridges.	Concentric transverse ridges (terminal moraines) may be continuous with lateral ridges (moraines) and are not restricted to toe.
Possess nearly straight, transverse fractures and radial fractures at toe.	Lack fractures.
Lack outwash body beyond toe.	Commonly have small outwash body beyond toe.
Internal composition	
Material derived only from rocks present on the local slope.	Material may be derived from any or all rocks in glaciated area upstream.
Fragments include very large masses of weak bedrock and joint-faced boulders of strong rock.	Fragments are comminuted and mixed; include fragments with abraded surfaces.

Very few striations were seen on rock fragments in drift on the Aquarius Plateau, and none were seen on rock fragments in the landslides. During reconnaissance of the Wasatch Plateau, Flint observed abundant striations on limestone fragments in both drift and landslides; furthermore Vanderwilt (1934, p. 168), among others, noted striations on the surface of rupture beneath landslides. Striations, therefore, are not a means of discriminating between drift and landslides.

The features cited in the table are developed ideally and may give the impression that landslides are more easily discriminated from drift lobes than they actually are. The differences listed are often difficult to apply, as is indicated in these examples:

1. Slumping in the headward part of a drift lobe, as in the Donkey Creek lobe in the Fish Creek valley, may give the false impression that the lobe is a complex slide.

2. Exposures of the slides and drift lobes are so rare that their internal character generally must be inferred from the surface material.

3. Leading away from the toe of the Coleman slide is a nearly plane, inclined surface immediately underlain by alluvium. Deep exposures are lacking. Whether the underlying material was outwash could not be determined. The Coleman mass was identified as a slide on other evidence.

4. Slides may incorporate in their masses preslide glacial drift; hence the presence (for example, in the Singletree slide) of fragments having a glacially abraded appearance does not prove that the body of debris is glacial drift.

5. On a basis of the features listed in the table on p.144 the Miller Creek lobe (p.128) is identified as a drift lobe rather than a complex slide; however, the critical features are less well developed, and identification rests on less firm ground than that for the drift lobes on the north side of the plateau. Comparison of the Miller Creek lobe with the Coleman slide is made below.

Comparison of surface features of Miller Creek drift lobe and Coleman slide

Topographic features	Miller Creek lobe	Coleman slide
Hummocks and basins	Abundant, especially in south part of lobe.	Scarce except near terminus.
Lateral ridges	Well developed on flanks of canyon portion; compare favorably with those in Fish Creek lobe of Donkey Creek drift.	Rare; some present on northwest flank at head of Bullberry Creek.
Transverse, longitudinal, or radial cracks.	Absent.	Abundant.
Dissection	Slight.	Slight.

LANDSLIDE MANTLE

Bouldery deposits of undetermined origin (pl. 6) are chiefly a mantle of landslide debris that covers much of the area of the plateau slopes. The mantle has no distinct form. Its surface is a jumble of knolls and depressions (some of which are basins) having many sizes and shapes but with a preferred lineation paralleling the contour of the plateau slope. Some knolls reach 100 feet in height, and some basins have closures as great as 30 feet. The landslide mantle has reduced the relief of the Plateau slopes by partly filling or wholly obliterating small valleys. The positions of most of the small valleys have been determined by the relief of the landslide mantle itself.

The surface is covered generally with vegetation and exposures are scarce. Masses of sedimentary rock, in places much deformed, with a few fragments of volcanic rock are visible in the banks of small streams. Abraded cobbles, presumably glaciated, occur at a few localities, implying that the mantle postdates at least one glaciation.

TIME OF MOVEMENT

Information as to the time of movement of the landslides is scattered and inconclusive. At least a part of the landslide mantle antedates some of the tonguelike slides. Some groups of slumps along the summit cliff were formed in stages separated by intervals of stability. The slump blocks farthest away from the cliff are broken up, their boulders are exfoliated, and they are partly covered by soil and vegetation, whereas those near the cliff are intact and are not forest covered.

The toe of the Hickman slide (fig. 25) projects into the side of the Donkey Creek drift lobe showing that the slide postdates the moraine. Some large slump blocks in the vicinities of Blind Lake and Donkey Lake appear to antedate Blind Lake drift. Other slump docks in the Blind Lake area, situated as much as half a mile beyond the toe of the summit cliff but no lower in altitude, indicate substantial recession of the cliff since the slumping. The latter slump blocks imply a pre-Donkey Creek date of movement because post-Blind Lake recession has been slight.

Lack of continuity in most of the drift lobes, at and below the base of the summit cliff, suggests landsliding (chiefly slumping) since the lobes were deposited. Analogous discontinuity within drift bodies is present around the summit cliff of Grand Mesa, Colo., and has been explained in a similar way (Retzer, 1954).

The data above suggest intermittent sliding over a long time and repeated movement in the same slide. Except for very recent movement, however, they do not establish within close limits any major movement within any particular slide. The data are not inconsistent with the view that sliding was especially active during the times of glaciation. Some slumping along the sides of the large reentrants drained by Fish, Pleasant, and Boulder Creeks may have taken place when glaciers melted and exposed cliffs and slopes oversteepened by glacial erosion.

ALLUVIAL, COLLUVIAL, AND LACUSTRINE DEPOSITS

Alluvium occurs along the principal streams and was deposited by them. Colluvium occurs at the base of steep slopes and was derived from them by rills, minor streams, sheet runoff, and mass movements. The distinction between alluvium and colluvium is based largely on topography. Alluvium is mapped where the surface of the deposit slopes parallel with the main drainage. Colluvium is shown where the surface of the deposit slopes from the adjacent hills toward a main drainage line. Only the larger bodies of alluvium are shown on plate 6, and colluvium is mapped only in the Teasdale-Torrey lowlands, principally in small areas along the Fremont River between the outwash fans at the mouths of Carcass, Fish, and Donkey Creeks. Other bodies of colluvium are included with alluvium. Lacustrine deposits are scarce. None are shown on plate 6.

The alluvium is composed of different mixtures of gravel, sand, silt and clay. The material is derived chiefly from adjacent surficial deposits and sedimentary rocks, and in places contains varying amounts of volcanic debris. The fragments of rock range from a fraction of an inch to about 3 feet in diameter; the material is noticeably finer grained than outwash, terrace gravel, or pediment veneers. The matrix is sandy in areas of sandstone, and dominantly silty in areas of siltstone and shale. It is generally calcareous throughout and locally contains abundant gypsum. The material is not well sorted; the sands are commonly silty and the silts gritty. The gravels contain both angular and somewhat rounded fragments of rock. Where the local bedrock is thin bedded, the gravels contain numerous small flagstones.

Stratification of coarser grained alluvium is irregular, and channel fillings and disconformities are visible in many sections. Commonly the finer grained alluvium is evenly stratified, with 1- to 2-inch beds traceable along the strike for hundreds of feet (table below). The maximum observed or inferred thickness of alluvium is about 20 feet.

Section of alluvium exposed along Boulder Creek about 1 mile east of Teasdale (pl. 6, loc. 2)

	Feet	Inches
Top.		
Slumped	2	0
Sand, coarse-grained, and gravel, fine-grained, pinkish-gray, calcareous; bedded; layers from ½ to 2 inches thick; contain volcanic and sedimentary pebbles as much as ¼ inch in diameter, a few fragments of charcoal, a few lenses of silt, and 1 or 2 small lenses of crossbedded gravel as much as 6 inches across	5	6
Silt and fine-grained sand, gray and brown, mottled, massive, highly calcareous; contain carbonaceous material and numerous snail shells		4
Silt, gray to white, massive, calcareous; few carbonaceous seams; contains irregularly cemented masses, and black carbonaceous veinlets (roots?)	2	0
Silt, white, and fine-grained, gray sand, thin-bedded; contain irregularly cemented masses of silt, gray to black carbonaceous layers that range from ⅛ to 1 inch in thickness, carbonaceous veinlets (roots?), and a few thin lenses of very fine grained gravel	2	8
Silt, white, and fine-grained gray sand, thin-bedded to massive	4	0
Silt, white, and fine-grained gray sand, bedded; contain numerous thin lenses of carbonaceous material; base not exposed	3	0
Total	19	6
Base.		

In a few places the alluvium contains buried layers that are mixtures of organic and mineral matter, and that may be remnants of soil profiles. Bedded sand, which has lenses of gravel and includes the remnants of two possible buried soil profiles, is exposed along Bullberry Creek about 1 mile west of Teasdale (fig. 30). At the southeast end of the section, bedrock (Navajo sandstone) is overlain by bouldery gravel and sand. Gravel, sand, and silt lap over onto the northwest side of this bouldery material. The remnants of buried soil profiles shown were not exposed in the creek bank about 100 feet west of the northwest end of the area shown in figure 30. These buried layers are not continuous along the strike and are believed to record minor episodes of relative stability during alluvial deposition.

Almost no fossils or artifacts were found in alluvium. Snail shells were found in sandy alluvium exposed along Boulder Creek about 1 mile east of Teasdale (preceding table), and one artifact (a stone point) was found at a depth of 6 feet in pebbly gravel and sand exposed in the bank of a small arroyo near the Fremont River just south of the mouth of Donkey Creek.

It is impossible to assign any precise date to the alluvium. The fine-grained bedded sand and silt east of Teasdale (table above) are

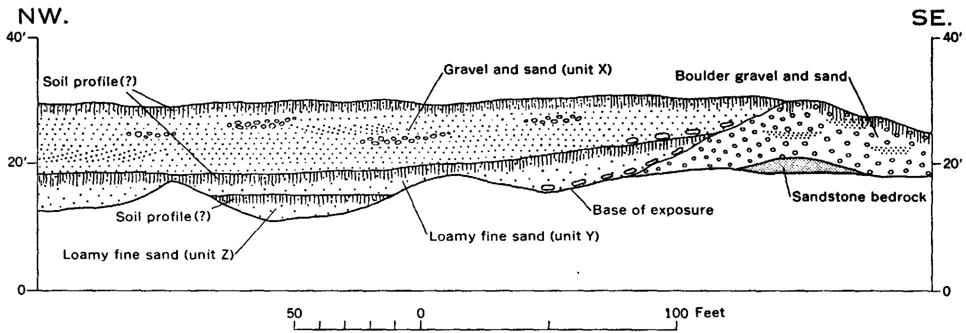

FIGURE 30.—Alluvium including two possible buried soil profiles exposed along Bullberry Creek about 1 mile west of Teasdale (pl. 6, loc. 1). Vertical exaggeration 2½ times.

certainly no older than the rock glaciers and probably record swampy conditions. The gravel and sand west of Teasdale (fig. 30) are also doubtless of recent date; perhaps unit *Z*, with its weakly developed horizon of lime and gypsum (soil profile), represents a relatively dry interval such as the Thermal Maximum, the overlying materials (units *X* and *Y*) being younger.

Alluvial, colluvial, and some lacustrine deposits are exposed along the Fremont River from the mouth of Donkey Creek, eastward to Carcass Creek. The colluvium is red and gray silty sand, in places containing lenses of flaggy or pebbly gravel. It underlies slopes that rise steeply toward the adjacent bedrock wall of the valley (fig. 26). In places the content of gravel is greater near the valley wall than toward the center of the valley; elsewhere the deposit is almost free of gravel within a few tens of feet of the adjacent bedrock slope. In many places colluvium is overlain by slide-rock.

A small mass of colluvium along the south side of the Fremont River between Fish and Carcass Creeks is shown on plate 6. This colluvium is as much as 30 feet thick and is underlain by silt, sand, and gravel that rest in places on Carcass Creek(?) till (fig. 28). The reddish silty sand and flaggy colluvium apparently were derived from the adjacent slopes, whereas the underlying gray silt, sand, and gravel are fluvial and probably lacustrine deposits, perhaps of glacial origin. The colluvium showing in figure 28 and observed in other exposures in the vicinity demonstrate that valleys at least 30 feet deep were excavated in the till before deposition of the overlying beds. Other exposures show that before deposition of the red silty sand and flaggy colluvium there was an erosion interval during which the underlying fluvial and lacustrine deposits were dissected to depths of at least 20 feet.

Similar lithologic units arranged in a more complex fashion are exposed (fig. 27) in the small tributary valley that joins the Fremont River from the north and that is followed by the Torrey-Grover road. The northwestern half of this section contains a sequence of beds similar to those shown in figure 26 except that the sequence occurs at altitudes about 50 feet higher relative to the Fremont River than do those sequences to the south. The flaggy colluvium is near the same height above the Fremont River as the outwash of Carcass Creek age about half a mile southeast. The southeastern half of the section (fig. 27) shows similar beds (gravel overlain by colluvium) deposited after at least part of the sequence to the northwest had been dissected.

The sandy reddish flaggy colluvial deposits along the Fremont River between Donkey and Carcass Creeks may have been derived from the adjacent slopes and deposited on the eroded top of the underlying glacial(?) deposits. The colluvium is perhaps in part reworked eolian sand blown from the Teasdale-Torrey lowlands during Donkey Creek or later times and deposited on the sides of the Fremont valley, whence it was moved downslope by mass-wasting to its present position. Doubtless much eolian sand was deposited on the Fremont River flood plain and was carried on downstream. This hypothesis explains the occurrence of loamy sand close to steep bedrock slopes where coarser colluvium would be expected if the material had been derived directly from adjacent bedrock. The fact that a buried soil with caliche was not found in the reddish silty sand favors the hypothesis that this deposit postdates the Carcass Creek drift. The slide-rock that overlies the reddish colluvium is perhaps no older than the rock glaciers (post-Thermal Maximum of Flint and Deevey, 1951). The slide-rock records a time interval when the adjacent cliffs yielded considerable fragments of rock and finer material, perhaps as the result of more vigorous frost action than takes place at present. All these deposits are now being dissected.

Silt and sand, probably of lacustrine origin, are exposed in a few places along the Fremont River (figs. 26 and 28). Stream gravel, perhaps outwash, and lake deposits, exposed in the first arroyo east of the mouth of Fish Creek, about half a mile south of Fremont River, are described below. These well-bedded silts and sands were probably deposited in standing bodies of water, dammed perhaps by drift or by ice at the mouth of Carcass Creek.

Section of surficial deposits exposed along first arroyo east of mouth of Fish Creek, about half a mile south of Fremont River (pl. 6, loc. 7)

Top.	Feet
Gravel, pebbly and cobbly, sandy matrix, gray, dominantly of volcanic rock; pebbles and cobbles are subangular (outwash?)	6
Sand, fine-grained, pinkish-gray; silty in upper part (outwash?)	15
Gravel, pebbly, gray, contains well-rounded pebbles of volcanic rock and of quartzite (outwash?)	3
Silt, white, thin-bedded; contains a few thin seams of clay (lacustrine?)	40
Gravel, pebbly and cobbly, dominantly of volcanic rock; base not exposed	2
Total	66

Base (bottom of arroyo, 112 feet above mouth of arroyo along Fremont River).

The fluvial and lacustrine deposits along the Fremont River probably were laid down in slack or ponded water formed by drift dams at the mouths of Fish and Carcass Creeks; they are rather well sorted and may include considerable outwash. The bedded silt and fine sand may be lacustrine deposits in temporary ponds on the flood plain or outwash plain of the Fremont River.

We do not know to what substage or substages the Fremont River deposits belong. Apparently those south of the river and west of the Torrey-Grover road (fig. 26) record a gradeline of the Fremont River about 40 to 50 feet above that of today, whereas the Grover lobe outwash at the mouth of Fish Creek is graded to an altitude about 100 feet above the river. This discrepancy in height suggests that some Fremont River deposits perhaps belong to Donkey Creek or Blind Lake times. Two intervals of alluviation separated by erosion are suggested by the relations shown in figure 27. Soils with caliche similar to those developed on drift of the Fish Creek-Grover lobe were not seen on top of, or buried by, these alluvial, colluvial, and lacustrine deposits along the Fremont River. If we assume that the soils with caliche on the Carcass Creek drift were formed prior to deposition of the Donkey Creek drift, it would be logical to conclude that their absence suggests that these deposits date from post-Carcass Creek time (table, p.158). We might suppose that the interval between the times of deposition of Carcass Creek and Donkey Creek drifts was a time of erosion by the Fremont River and that an indefinite amount of Carcass Creek drift could have been removed during the interval. In summary, the deposits along the Fremont River suggest at least two episodes of alluviation separated by an erosion interval, they are probably no older than the Carcass Creek drift and no younger than the Thermal Maximum (Flint and Deevey, 1951, p. 275).

EOLIAN FEATURES

Sand, believed to be eolian, together with ventifacts and lag concentrates of pebbles left after the removal of fines by the wind are found in the Teasdale-Torrey lowlands. No eolian deposits are shown on plate 6. Coarse-grained loose sand, in places silty, occurs as a widespread mantle and as isolated patches. The sand is generally pink but ranges from white to red. No stratification is visible, and the sand is fresh. A few inches of brownish oxidized(?) material may be present just beneath the organic surface horizon, but no horizon of caliche was noted. The maximum observed thickness of sand is about 3 feet, but at some localities thicknesses as great as 10 feet can be reasonably inferred. The sand has no distinct topographic expression of its own; no ancient or modern dunes were observed. Most of the sand appears to be stabilized at present, although some wind movement probably takes place on flood plains and on patches of bare ground on pediment surfaces in the Teasdale-Torrey lowlands. The sand occurs on pediment veneers at altitudes of as much as several hundred feet above the present drainage and overlies soils with caliche developed on drift of the Fish Creek-Grover lobe. The sand is, therefore, younger than Carcass Creek time and is assumed to postdate the Carcass Creek-Donkey Creek interval. We suspect that the eolian(?) sand is partly of late Pleistocene and partly of Recent age.

In the Teasdale-Torrey lowlands many boulders of volcanic rock on the ground surface have been grooved or polished by sandblasting. Grooves or flutings are best developed on vesicular volcanic rocks, probably because the wind-driven sand enlarged the vesicles. However, grooves occur on volcanic rock that is not vesicular. Some sandblasted surfaces are partly covered by crustose lichens and have been slightly weathered since sandblasting. Many ventifacts have been partly exfoliated or have been broken into smaller fragments. In some places, such as the lowlands north of Torrey, ventifacts are free of lichens and have the glistening coating of black oxides called desert varnish. The freshness of such ventifacts suggests that they may be ancient forms now being reworked by sandblasting. The partial destruction of the vegetative cover exposes patches of bare sand that is being picked up and transported by present-day winds.

Sandblasted boulders of volcanic rock are found on Carcass Creek drift (till and outwash), on terraces along Fremont River, and on pediment veneers. They occur on surfaces several hundred feet above present drainage lines, such as the mesa about 2 miles east of Teasdale. The degree of weathering and exfoliation of ventifacts and their association with eolian(?) sand suggest that they are no older than the Donkey Creek drift. The ventifacts on top of the mesa east of Teasdale probably were cut by wind-driven sand blown from the lowlands to the southwest, up over an escarpment about 150 feet high.

All the larger ventifacts in the Teasdale-Torrey lowlands are boulders apparently not rotated since sandblasting. The orientations of these suggest that the sand-laden winds came from the adjacent highlands. Thus the grooves and the orientation of the pitting of the larger ventifacts south of the Fremont River indicate southwest winds from Boulder Mountain, whereas the ventifacts north of Torrey suggest northwest winds from Thousand Lake Mountain.

Pediment sand and gravel in the Teasdale-Torrey lowlands are covered by a lag concentrate of volcanic boulders and pebble-sized fragments of rock. The fragments are of quartzite and chert, highly polished, together with spalls from adjacent boulders of volcanic rock. The underlying materials contain only a relatively small percentage of pebbles. The veneer of fragments is believed to have resulted from removal of fine sediment by wind.

PEDIMENTS AND TERRACES

Pediments, now greatly dissected, slope radially outward from Boulder Mountain on its northern, eastern, and southern slopes (pl. 6). To the west, pediments are absent, and a pronounced scarp separates the mountain from the Awapa Plateau and Rabbit Valley. The pediments are rock-cut surfaces veneered with sand and gravel; they form long, gently sloping surfaces (1°–4°) indented by broad, shallow swales as much as 30 feet deep and as much as several hundred feet in diameter, trending down the regional slope. The pediments are dissected and lie from 50 to several hundred feet above the adjacent streams. Pediments in the Teasdale-Torrey lowlands are distinctly fan shaped.

The gravel and sand that comprise the pediment veneers are composed predominantly of fragments of volcanic rock together with varying proportions of diverse sedimentary rocks (see table below). The fragments are mostly unweathered, but a few are stained throughout or crumble between the fingers. The matrix ranges in texture from silt to sand and generally is highly calcareous. Thin seams of clay were observed in some exposures. The rock fragments are subangular to slightly rounded, and range in size from pebbles to boulders as much as 15 feet in diameter. There is a slight decrease in maximum size of the boulders from the apex of a pediment downslope toward the main drainage line.

Pediment veneers range from strongly bedded to nonstratified bodies. Texture changes vertically and horizontally over short distances. Crossbedding and channelling are visible in many sections. Where the base of the gravel is exposed along the Bicknell-Torrey road about 1½ miles north of Teasdale the maximum observed thickness is about 30 feet. Exposed thicknesses of 10 feet are numerous. The maximum inferred thickness is about 70 feet.

Section of pediment veneer capping mesa about 2 miles east of Teasdale (pl. 6, loc. 3)

	Thickness (feet)	*Depth (feet)*
Top.		
Slumped, surface covered with boulders of volcanic rock	10	0–10
Gravel, pebbly, calcareous, contains pebbles of volcanic rock, limestone, and sandstone; upper 3 feet is highly calcareous, white	6	10–16
Sand, reddish, stratified, cemented, calcareous; contains few small pebbles and a few seams of gray sand, silt, and clay	10	16–26
Gravel, pebbly and bouldery; contains fragments of volcanic rock, conglomerate (Shinarump), and sandstone (Moenkopi); base of pediment veneer not exposed	3	26–29
Total	29	
Base.		

On the basis of their internal characteristics the pediment veneers are indistinguishable from outwash. Pediment gravel and sand are shown on plate 6 where the material mantles a rock-cut surface but lacks drift near its apex. Small bedrock mesas that rise several hundred feet above present-day arroyos are capped by sand and gravel. The caps are mapped as pediment veneers but may be outwash derived from glaciers whose drift sheets have not been recognized. The pediment veneers near Teasdale are perhaps outwash of the Carcass Creek glaciation, the associated till being unrecognizable because of subsequent landsliding, such as that represented by the Coleman slide.

In the Pleasant Creek drainage, pediment remnants lie about a mile north and a mile south of the terminal segment of the Pleasant Creek drift lobe. Both remnants have thin veneers of bouldery sediment, and both stand high above present drainage and appear to antedate the drift lobe. Pediment remnants having an apparently similar relation to the Boulder Creek drift lobe occur in the vicinity of Boulder (fig. 24).

The pediment remnants slope with the main drainage lines. Although minor drainage adjustments have occurred during and following pediment formation, the principal streams probably occupied about their present positions at the time the highest pediment was formed. The establishment of the course of the Fremont River through the north end of Miners Mountain and Capitol Reef appears to antedate any existing pediment remnants. Most of Miners Mountain drains eastward toward Capitol Reef, the drainage divide lying close to the west base of the mountain. The northern part of Miners Mountain has no surficial mantle. It is a broad anticlinal ridge of bare rock without the scattered fragments of volcanic rock that are widespread on the slopes of Boulder Mountain. The distribution of boulders of volcanic rock suggests that streams which cut a pediment on Lion Mountain flowed either northward to the Fremont River or southward into Sulphur Creek, and that the drainage divide along Miners Mountain was present then although doubtless somewhat east of its present location. An unlikely alternative is that erosion has stripped off any surficial covering on Miners Mountain related to streams that cut the Lion Mountain pediment. However, it is probable that the volcanic rocks that cap Boulder and Thousand Lake Mountains originally were one body of rock that extended at least as far eastward as Miners Mountain, and probably much farther. It is likely that Miners Mountain at one time had a surficial mantle of volcanic debris that has since been completely removed. Such stripping is almost certainly pre-Carcass Creek and probably is older than Sangamon time (Hunt, 1953, p. 204).

The range in altitude of pediment remnants above present streams suggests that several episodes of planation occurred in Pleistocene time, probably both before and following the Carcass Creek glaciation. The soils developed on the pediment veneers are not markedly different from those developed on Carcass Creek drift. Elsewhere in the Western United States surficial deposits and land surfaces believed to be of pre-Wisconsin (Sangamon and older) date have weathering and soil profiles very different from those on younger deposits or land surfaces (Hunt and Sokoloff, 1950; Richmond, in preparation). The pre-Wisconsin soils have marked similarities over a wide range of altitudes and parent materials. However, none was seen in the Aquarius Plateau district, although Huff (oral communication) found what may be such a profile on till(?) about 2 miles east of the Wildcat Ranger Station (p. 124).

Thus the ages of the several pediment remnants are largely unknown. The lowest remnants (Qpg_3, pl. 6) grade to a line not more than 40 feet above the Fremont River and, therefore, may be no older than Carcass Creek drift. The higher pediment remnants (Qpg_2 and Qpg_1) are tentatively assigned to Sangamon and older times.

Small remnants of terraces occur in some places but have been mapped (pl. 6) only along the Fremont River. Gravel and sand that underlie terraces are similar to pediment veneers except that terrace gravels are dominantly pebbly whereas pediment veneers may contain numerous cobbles and boulders. The terraces range in height from about 50 to 80 feet above the Fremont River. Near the power plant south of Torrey a soil with caliche is developed on bouldery gravel that forms a terrace about 80 feet above the Fremont River and about 20 feet below the base of the outwash to the south. These facts suggest that the terraces along the Fremont River are not older than Carcass Creek time and probably are considerably younger.

CORRELATION WITH THOUSAND LAKE MOUNTAIN

Thousand Lake Mountain lies north of Boulder Mountain, between the Canyon Lands on the east and Rabbit Valley and the Fish Lake Plateau on the west (fig. 24). In topography and geology the mountain closely resembles Boulder Mountain. A cap of volcanic rock overlies a thick sequence of Tertiary(?) and Mesozoic sedimentary rocks. The volcanic rocks on each mountain may originally have been a continuous sheet. The cap rock forms a steep, even precipitous, escarpment from which great masses of rock have slumped and moved downward and outward in all directions. A shelf or gently sloping bench extends outward from the base of the escarpment for nearly a mile, beyond which the slopes descend more steeply to the adjacent lowlands. Pediment remnants at several altitudes are present on the lower slopes.

The principal difference between the two mountains is the area of the cap of volcanic rock. The summit of Thousand Lake Mountain has a total area of only about 2 square miles compared with an area of about 70 square miles for the summit of Boulder Mountain. An examination of aerial photographs of Thousand Lake Mountain and a reconnaissance trip to its summit did not reveal evidence of late Pleistocene glaciation similar to that on Boulder Mountain. We believe that the ice tongues on the sides of Boulder Mountain were probably offshoots of its icecap; the apparent absence of such ice tongues on Thousand Lake Mountain indicates that the area of the latter's summit was too small to nourish an icecap, at least in late Pleistocene (Donkey Creek or Blind Lake) time.

The base of the escarpment is mantled with slide-rock but no rock glaciers were found close to it. The surface of the adjacent bench is covered in many places by ancient boulder fields, and it is surprising that remnants of rock glaciers were not found on Thousand Lake Mountain. Perhaps they existed formerly, and were destroyed by subsequent mass movements.

QUATERNARY HISTORY

The late Quaternary history of the northeastern part of the Aquarius Plateau is summarized in the table below. The facts do not permit firm correlation with the Quaternary features of other areas in the Western United States. The deposits suggest that a warm episode and two cold episodes followed the deposition of Blind Lake drift; the three episodes are presumably of Recent date. The warm episode is doubtless the Thermal Maximum, but proof that it antedates the formation of the rock glaciers is lacking.

In terms of glaciation the Aquarius Plateau, like other highlands in the Cordilleran region, is probably a marginal area. Glaciers could have flourished on it only when temperatures were lower and when summer-season ablation, perhaps owing to greater cloudiness, was less than at present. Such glacial conditions can be expected to have existed at times of increased frontal activity associated with low-index (Willett, 1944) atmospheric circulation. A slight change from higher toward lower index circulation might have had only a small effect on the melting Laurentide Ice Sheet in and north of the Great Lakes region, while exerting at the same time a marked influence at the top of the Aquarius Plateau. Very likely this is the reason why the relative distances between the borders of the successive drift sheets are greater in the Aquarius Plateau district than in the region of ice-sheet glaciation.

Quaternary history of Boulder Mountain, Utah

Epoch	Events in Boulder Mountain region		Possible correlation with events in Rocky Mountain region (Holmes and Moss, 1955)
Recent	Formation of slide-rock at base of cliffs surrounding Boulder Mountain; slight dissection; slight reworking of eolian deposits and of ventifacts; local landsliding; deposition of alluvium.		Little Ice Age (Matthes, 1939).
	Formation of rock glaciers, from accumulations of snow along base of cliff around plateau top, at altitudes of about 10,500 to 10,700 feet; local landsliding; continued eolian activity; probable deposition of slide-rock along Fremont River.		Temple Lake stage (Howard and Hack, 1943).
	Glaciers absent from Boulder Mountain; probable continued eolian activity.		Thermal Maximum (Flint and Deevey, 1951, p. 275).
	Deposition of Blind Lake drift close to base of cliff around top of plateau by glacier ice from plateau top; glaciers descend to altitudes as low as 9,900 feet; possible deposition of outwash in valley of Fremont River; movement of Hickman slide southwest of Fish Creek and probable sliding elsewhere. Erosion(?)	Probable deposition of red sandy and flaggy colluvium along Fremont River and of	Pinedale stage.

Pleistocene	Deposition of Donkey Creek drift on upper slopes of Boulder Mountain by glacier ice from plateau top. Glaciers descend to altitudes as low as 8,200 feet; possible deposition of outwash in valley of Fremont River; possible movement of large slump blocks near Blind and Donkey Lakes and probable landsliding elsewhere.	eolian(?) sand in Teasdale-Torrey lowlands; abrasion of ventifacts.	
	Glaciers of Boulder Mountain are small or absent; assumed time of formation of soils with caliche; widespread dissection.		
	Deposition of Carcass Creek drift by glacier ice from the plateau top; along Fremont River includes outwash and perhaps lake beds; glaciers descend to altitudes as low as 6,600 feet; landsliding including probable movement of the tonguelike complex landslides.		Bull Lake stage.
	Formation of pediments and bouldery accumulations of undetermined origin; possible deposition of drift near mouths of Fish and Carcass Creeks and in valley of Pleasant Creek by glaciers from the plateau top.		Buffalo and pre-Buffalo stages (Sangamon? and older).

The summit of the neighboring Fish Lake Plateau is more than 11,000 feet high and is glaciated; plateaus at lower altitudes were not glaciated (Hardy and Muessig, 1952). Thousand Lake Mountain, altitude 11,000 feet, is the only exception. The difference implies that during glaciation the regional snowline lay somewhat below 11,000 feet.

Sharp (1942, p. 500) approximated the altitude of the late Wisconsin orographic snowline (the regional snowline as modified by local topography) on San Francisco Mountains, Ariz., by comparing the altitudes of glaciated and nonglaciated peaks. The value, 11,000 to 11,300 feet, he compared with the value of 10,000 feet derived by Atwood for the comparable feature in the Uinta Mountains. The gradient between the two points gives a value for the Aquarius Plateau, 190 miles north of San Francisco Mountains on a direct line to the Uintas, of 10,400 to 10,700 feet. That value is consistent with the distribution of the Donkey Creek and Blind Lake drifts of the Aquarius Plateau slopes.

The existing snowline cannot be far above the highest point on the plateau, because during the summer of 1952 snowbanks were observed as late as August 10 on the open little-protected plateau top. Although snowfall during the preceding winter had been unusually heavy, it is believed that lowering of the snowline by only a few hundred feet would be sufficient to restore glacier ice to the Aquarius Plateau.

No direct evidence was found as to whether the icecap disappeared entirely from the plateau during the intervals between successive glaciations. However, because of its small size and areal position the icecap probably disappeared during the Carcass Creek-Donkey Creek interval and very likely disappeared also during the interval between the Donkey Creek and Blind Lake glaciations. During the subsequent cold episode, when most of the rock glaciers accumulated against the summit cliff, snowbanks or even small glaciers may have developed on the plateau top, but no evidence of their existence has been found.

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