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Quaternary Geology of the Grand and Battlement Mesas Area, Colorado

GEOLOGICAL SURVEY PROFESSIONAL PAPER 617

QUATERNARY GEOLOGY OF THE GRAND AND BATTLEMENT MESAS AREA, COLORADO

View southwest across Mesa Creek drainage toward west end of Grand Mesa

Quaternary Geology of the Grand and Battlement Mesas Area, Colorado

By WARREN E. YEEND

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Description, distribution, and geologic history of surficial deposits on and adjacent to Grand and Battlement Mesas, western Colorado

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1969

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

William T. Pecora, *Director*

Library of Congress catalog-card No. GS 68-329

For sale by the Superintendent of Documents, U.S. Government Printing Office
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QUARTERLY GEOLOGY OF THE GRAND AND BATTLEMENT MESAS AREA, COLORADO

By Warren E. Yeend

ABSTRACT

Grand and Battlement Mesas, erosional remnants of a large late Tertiary (early Pliocene) basalt plain, are the major topographic features in the area. Grand Mesa is about 20 miles east of the junction of the Gunnison and Colorado Rivers in the arid to semiarid lands of western Colorado. Both mesas rise above 10,000 feet, towering more than 5,000 feet above the adjacent Colorado River and Plateau Creek valleys. Grand Mesa, a basalt-capped plateau about 50 square miles in extent, occupies the southwestern part of the area.

Epeirogenic uplift in the late Tertiary caused streams to cut through the extensive, virtually flat-lying basalt flows into the underlying sedimentary rocks of the Green River, Wasatch, and Mesaverde Formations of early Tertiary to Late Cretaceous age. More than 5,000 feet of downcutting since the uplift began has produced long, steep slopes, oversteepened cliffs, and narrow canyons. Geologic processes operating throughout the area at any given moment in time were varied and often produced very different effects on the landscape because of the extremes in elevation, slope exposure, and range in bedrock types.

Two distinct levels of pediments capped with gravel are present on the north and west flanks of Battlement Mesa. The older and higher surface is about 1,300 feet above the Colorado River. The lower pediment, although extensively dissected, is present at numerous localities south of the Colorado River. Grass, Log, and Samson Mesas are local names given to some of these pediment remnants. Because of their high, isolated position above the modern Colorado River, the pediments are considered to be of early Quaternary age. Locally, however, they have been subsequently covered with mudflows and alluvial gravel of late Quaternary age.

Glaciers probably covered much of the high southern part of the area at least once in pre-Bull Lake(?) time. Chalk Mountain, in the southeastern part of the area, is capped with about 135 feet of till resting on striated sandstone bedrock. More than one period of pre-Bull Lake(?) glaciation may be represented in this till section; however, bona fide intertill soils were not found. Three pre-Bull Lake(?) alluvial terraces in the drainage of Plateau Creek lie 200–500 feet above the creek. Moderately thick well-developed buried soils on alluvial gravels indicate at least one pre-Bull Lake(?) terrace on the north-facing slopes of Battlement Mesa. Isolated occurrences of pre-Bull Lake(?) colluvium are present. A clearly recognizable relict (unburied) soil of pre-Bull Lake age was not found.

Late Pleistocene glaciations modified the topography of Grand Mesa. An icecap covered much of the upland and flowed into the surrounding valleys during both the Bull Lake(?) and Pinedale(?) Glaciations. Glacial, alluvial, and colluvial deposits associated with these two major glaciations are included in two newly named formations—the Lands End and Grand Mesa Formations.

During Bull Lake(?) time, ice covered the entire surface of Grand Mesa and flowed into the lowlands at least as low as 5,800 feet. In the stream valleys, till of this age and the soil formed on it (Lands End Formation) are buried by younger till. Terminal moraines are not present; consequently, a minimum elevation for the lower limit of this glaciation is difficult to determine. Outwash deposits of Bull Lake(?) age in Plateau Creek are buried by younger outwash gravels. Bull Lake(?) alluvial terrace and fan gravels are present along the Colorado River.

The ice that deposited the Grand Mesa Formation, which is locally separated by a well-developed soil formed on the older Lands End Formation, covered the highland and lowland parts of the area. Striations and a terminal moraine record the presence and movement of the ice on top of Grand Mesa as well as on a lower surrounding landslide bench. Glaciers of this age flowed down all the major stream valleys draining the north slopes of Grand Mesa and reached a probable minimum elevation of 5,400 feet. The individual ice tongues were able to extend to such a low elevation both because of the very extensive high-surface area (284 sq mi above 10,000 ft) available for snow accumulation and because of the deep valleys leading north from the mesa. Terminal moraines of the Grand Mesa Formation are not present in the valleys for here the till plains grade into outwash plains. Recessional moraines are present upvalley in some of the drainages; they record a partial halt in the ablation regimen of the ice. Two levels of outwash present along Plateau Creek further evidence this slight fluctuation in the climate during Pinedale(?) time.

Buried humic material in a terrace of the Grand Mesa Formation located along the Colorado River revealed a carbon-14 date of 19,730± 500 years B.P.

Ice of late Pinedale(?) age, in large part stagnant, left crevasse-fill deposits and fresh morainal topography on a landslide bench surrounding much of Grand Mesa. Glaciers of this age were absent from the top of Grand Mesa, existing only in the lower, more protected drainage heads.

The influences that landslides, slumps, and mudflows have had on the topography are even greater than those of the glaciers. Two of the prebasalt sedimentary rock units—the Wasatch Formation and an unnamed unit underlying the basalt flows—contain claystones that have been responsible for widespread mass wasting, particularly slumping. Extensive slumping of large blocks of basalt has greatly reduced the areal extent of Grand Mesa throughout the Quaternary. A wide, irregular surface characterized by disrupted drainages and hundreds of lakes and slump blocks has developed around the edge of the undisturbed surface of Grand Mesa. Such breakup of the basalt flows greatly facilitated rapid removal by glacial and colluvial processes of the high, originally much more extensive surface of Grand Mesa.

While glaciers were eroding and modifying Grand Mesa during the late Pleistocene, Battlement Mesa was being eroded by colluvial processes. Solifluction, slumping, frost breakup of basalt, and landslides moved debris from the high parts of the mesa onto the surrounding slopes and into the bordering stream valleys. Mudflows were common in the lower parts of the valleys and frequently poured out onto the older pediments and alluvial terraces bordering the Colorado River on the south.

No evidence of Recent glaciation was observed. Widespread talus deposits, rock glaciers(?), earthflows and solifluction debris are thought to correlate with the Recent glaciation of other parts of the Rocky Mountains.

Stream downcutting has been a dominant process since the disappearance of the last ice mass at the close of Pinedale(?) time. Wind-carried sand and silt have buried many of the bedrock structural terraces north of Plateau Creek on the south-facing slopes at the base of Battlement Mesa. Currently, arroyos are common on the hot dry barren slopes below Battlement Mesa, and most talus slopes are stable; however, small active slumps and earthflows are observed within the claystones of the Wasatch Formation and younger rocks. Measured stake displacements of incipient slump blocks adjacent to Grand Mesa, determined over a period of 2 years, indicate that certain large blocks are moving away from the mesa at rates of 0.05–0.5 foot per year.

Fabric analyses of tills and of landslide debris reveal a method of differentiating them. Elongate pebbles and cobbles in the tills are inclined upslope, but the opposite orientation (downslope plunge) was noted in the mass-wasted deposits.

Eight former levels of the Colorado River are based on terrace and reconstructed pediment levels—four of Bull Lake(?) and Pinedale(?) age, three of pre-Bull Lake(?) age, and one of possible Pliocene age. The profiles of the previous river levels are similar to the present river profile which has a slope of about 11 feet per mile.

On the basis of present climatic records, the sediment yield at low elevations in the area seems to be at a maximum; however, because of the high runoff coming from the uplands, stream aggradation along the throughgoing streams is not common. Discounting effects of mass wasting, it seems that almost any type of climatic change would initially result in continued downcutting, probably at a more rapid rate than at present.

INTRODUCTION

Grand and Battlement Mesas in western Colorado existed as nearly level highlands more than 10,000 feet in elevation throughout most of Pleistocene time. The region underwent epeirogenic uplift characteristic of much of the Colorado Plateaus province in the late Tertiary (Pliocene) or early Quaternary. An icecap covered most of the surface of Grand Mesa at least twice during the late Pleistocene and fed active glaciers in the surrounding deeply incised valleys. Battlement Mesa appears to have lacked an icecap during late Pleistocene time.

A primary reason for studying this area was to examine and evaluate the effects of Quaternary geologic processes in this unusual topographic situation. The effect that such a high flat surface as Grand Mesa would have on the accumulation and distribution of ice is of particular interest. The glacial history, however, is only one phase of the Quaternary history of this region. Of equal importance is the recognition and description of the widespread landslides, mudflows, and earthflows and their effects on the varied landscape. Should "Project Gasbuggy"[1] prove that nuclear explosions are feasible for the increased production of natural gas from tight sandstones, the Rulison gas field in the northern part of the mapped area will be a prime target for such a nuclear explosion. A knowledge of the location, internal characteristics, and susceptibility of movement of the mass-wasted deposits will aid in evaluating their effects on the landscape as a result of an underground nuclear explosion. Extensive pediments, alluvial terraces, and fan gravels flanking the north and west slopes of Battlement Mesa aid in understanding the history of a part of the Colorado River. These gravel deposits could be very important as construction aggregate to potential oil-shale industry and road building in the area.

Concurrently with this study of the Quaternary geology, the bedrock geology was studied by John R. Donnell, of the U.S. Geological Survey.

LOCATION AND SIZE OF AREA

Grand Mesa is east of the confluence of the Colorado and Gunnison Rivers in western Colorado (fig. 1). The mapped area covers approximately 973 square miles and lies between lat 39°00′ and 39°30′ N., and long 107°37′ 30″ and 108°15′ W. It is included on seventeen 7½-minute quadrangle maps: Grand Valley, Rulison, North Mamm Peak, South Mamm Peak, Hawxhurst Creek, Housetop Mountain, De Beque, Mesa, Molina, Collbran, The Meadows, Porter Mountain, Chalk Mountain, Leon Peak, Grand Mesa, Skyway, and Lands End.

METHODS OF STUDY

Field studies were made during the months of June–September 1963–65, and during June and July 1966. The surficial geology was mapped on aerial photographs (U.S. Geol. Survey, 1:20,000, taken in 1951) and on 7½-minute topographic quadrangle maps (1:24,000).

Supplemental subsurface data were obtained from hand-excavated test pits and soil-auger holes. Samples of soil, unweathered surficial materials, buried humic material, and fossil mollusks were collected for laboratory study. Microscopic examinations and hydrometer-size analysis studies were made of selected samples. Methods used in studying mass-movement rates and fabric determinations are discussed later in this report.

[1] Project Gasbuggy, the first joint industry-government nuclear explosion for peaceful purposes, is an attempt to liberate natural gas trapped in rock.

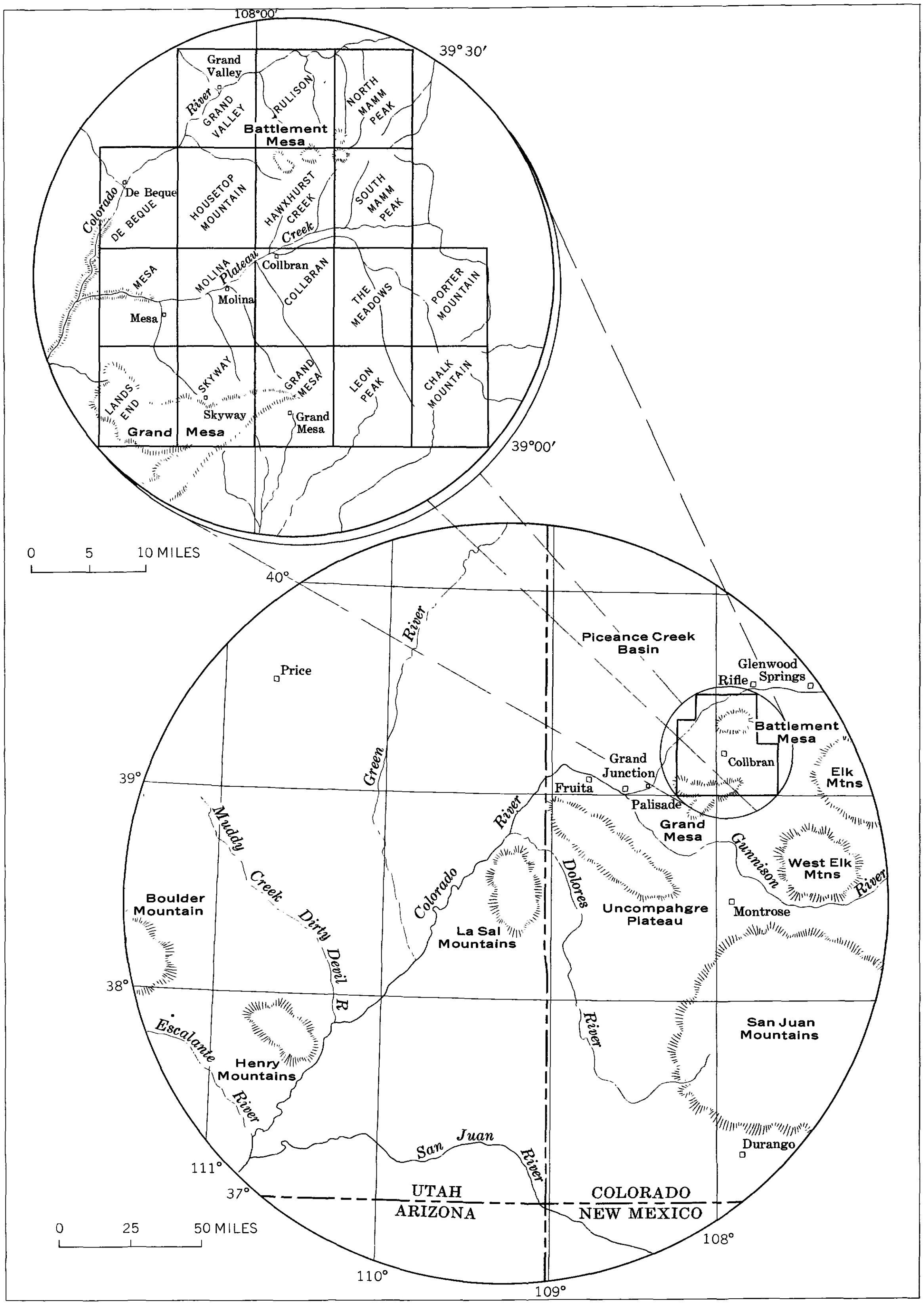

FIGURE 1.—Index map showing location of Grand and Battlement Mesas in western Colorado. Inset shows location of 7½-minute quadrangles in the area.

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PREVIOUS WORK

Reconnaissance mapping in the area was initially done by A. C. Peale as part of the work of the U.S. Geographical Survey of the Territories (Hayden, 1876). In his report on the Grand River and its tributaries, Peale described the topography, drainage, and general geology of the Grand and Battlement Mesas area.

Junius Henderson (1923), accompanied by John P. Byram and Erwine Stewart of Mesa, Colo., explored Grand Mesa by horseback; Henderson's report describes evidence of intense glaciation around the north and east sides and on a considerable part of the top of the mesa. Nygren (1935) found evidence supporting several episodes of glaciation of Grand Mesa. He mentioned that an icecap existed on Grand Mesa during the Pleistocene Epoch simultaneous with the development of small valley glaciers below the basalt rim. Nygren further noted the glacial modification of some slump blocks below the rim of Grand Mesa. Retzer (1954) recognized one pre-Wisconsin and two Wisconsin glaciations for Grand Mesa. His interpretation is based on location of moraines, topographic expression, and differences in degree of soil development. These reports were primarily concerned with the glaciation of either the mesa top or the immediately surrounding bench. Reference to glaciation or glacial effects at elevations below 9,000 feet has not been found in the literature.

The extensive pediments along the Colorado River north and west of Battlement Mesa have been noted by many.

ACKNOWLEDGMENTS

Special thanks are accorded John R. Donnell, of the U.S. Geological Survey, who acquainted me with the bedrock geology and geography of the area. Exchange of ideas with Mr. Donnell on many phases of the study proved extremely helpful.

Professor Robert F. Black, of the University of Wisconsin, visited the area during the summer of 1963 and offered suggestions useful in interpretation.

Helpful criticism was provided by Kenneth Pierce, of the U.S. Geological Survey. Dwight W. Taylor, of the U.S. Geological Survey, identified the mollusks. Suspected volcanic ash was examined by Ray Wilcox, of the U.S. Geological Survey. Rubin Meyer, of the U.S. Geological Survey, provided a valuable carbon-14 date on some humic material I collected from a low terrace.

PHYSIOGRAPHIC SETTING

Grand Mesa, a basalt-capped plateau remnant, is separated from the major mountain systems of western Colorado (fig. 1). From almost any direction the mesa commands one's immediate attention because of its topographic prominence (frontispiece). Rising to an elevation of 10,800 feet, it towers 5,400 feet above the irrigated Grand Valley of the Colorado River, west of the mesa. From the southwest edge of the mesa, one can view the Uncompahgre Plateau across the Gunnison River to the southwest, the San Juan Mountains far to the south, and the West Elk Mountains about 40 miles to the southeast. Looking north from Grand Mesa across Plateau Creek, one sees the small isolated basalt-flow remnants of Battlement Mesa. The tops of the 14,000-foot peaks of the Elk Mountains can be seen more than 60 miles to the east.

The surface of Grand Mesa is a nearly flat tableland sloping gently toward the west. It has been only slightly modified by glaciation. Striated knobs protrude through a thin veneer of till. Lakes and undrained depressions are common, and stream dissection has been slight. The top of Grand Mesa is underlain by continuous, undisturbed basalt flows and is about 50 square miles in extent. It has become a practice with local residents, however, to refer to Grand Mesa as including not only these high undisturbed basalt flows but the surrounding, somewhat lower, irregular bench as well. By including this bench, which is very widespread to the east, the areal extent of Grand Mesa is increased four to five times. Reference to Grand Mesa in this report will be restricted to the high, virtually flat tableland held up by the continuous, undisturbed basalt flows. A map view shows Grand Mesa to be Y-shaped with the top of the Y oriented toward the west. The east edge of the mesa, called Crag Crest, has been reduced to a knife-edged ridge by repeated slumping.

Steep cliffs, 100–500 feet high, surround the upland surface of Grand Mesa. Basalt talus and frost rubble have accumulated at the base of these cliffs. A very irregular surface produced by huge slumps and modified by glaciation extends outward from the base of the basalt cliffs. This landslide bench varies in width from several feet to several miles. The slump blocks are tilted back toward the undisturbed part of the mesa, forming long, narrow ridges that parallel the edge of the mesa for hundreds of feet. Many lakes have been formed as a result of this slumping and the subsequent glaciations.

East of Grand Mesa the landslide bench is extensive and shows the effects of late Pleistocene glaciation. The slump-block remnants rise conspicuously above the surrounding upland and form the drainage divides between such major streams as Plateau, Buzzard, Leon, and Park Creeks draining north, and Leroux, Hubbard, and West Muddy Creeks draining south into the North Fork of the Gunnison River.

A steep slope produced by erosion of the Green River Formation is formed below the landslide bench. The contact between the Green River Formation and the underlying Wasatch Formation is generally marked by an abrupt change from a smooth, steep slope to gentle, irregular, commonly hummocky topography. The claystones and siltstones of the Wasatch Formation have failed repeatedly, and the surface is often broken and terraced as a result of earthflow, slump, and mudflows. A diagrammatic cross section from Grand Mesa on the south across Plateau Creek and Battlement Mesa to the Colorado River on the north, showing characteristic topography and underlying rock units, is shown in figure 2.

The glaciated valleys of Mesa, Bull, Cottonwood, Big, Leon, and Plateau Creeks head on the landslide bench, cross the steep slopes held up by the Green River Formation and the gentler slopes produced on the Wasatch Formation, and finally join Plateau Creek, the major tributary of the Colorado River in the area. Throughout most of the lower parts of the area, the Plateau Creek flood plain is about 1,500 feet wide and parallels old terraces and till plains. The lower 5 miles of Plateau Creek, however, is in an intrenched meandering narrow gorge more than 600 feet deep and about 400 feet wide, cut into the Mesaverde Formation. Terrace remnants are scarce in this canyon.

The topography north of Plateau Creek is characterized by steep canyons, arroyos, pediment surfaces adjacent to Battlement Mesa, and eolian silt-covered surfaces. The south-facing slopes receive little precipitation and are almost completely devoid of vegetation. Battlement Mesa consists of four small basalt-flow remnants more than 10,000 feet in elevation. These isolated flow remnants total less than a square mile in area and are surrounded by slump blocks broken into basalt-block rubble. The physiography and bedrock of Battlement Mesa (fig. 2) are similar to Grand Mesa, although Battlement Mesa is in a more advanced stage of degradation. Extensive pediments, commonly mantled by alluvial-fan gravel and mudflows, flank the north and west slopes of Battlement Mesa. These widespread surfaces slope steeply toward the Colorado River, which cuts across the northwest corner of the area. The Colorado River meanders on a gravel-floored valley at the foot of the oil-shale cliffs rising high above the river on the northwest. The extreme northwest corner of the area is dry and virtually vegetation free; surficial deposits are scarce. Steep bedrock slopes of the Green River Formation are flanked by isolated small dissected pediments.

CLIMATE

Climatic conditions vary widely within the area as a result of differences in elevation and exposure (north- versus south-facing slopes). Arid to subarid conditions prevail at the low elevations, particularly on the south-facing slopes. Humid to subhumid conditions exist on top of Grand and Battlement Mesas.

RAINFALL AND TEMPERATURE

Collbran (elev 6,000 ft) has an annual precipitation of about 13 inches with no well-defined wet season. Maximum precipitation occurs during March, April, and May, followed by a secondary maximum in August, September, and October. Rainfall during each of these months is generally between 1.0 and 1.5 inches. June and July are the driest months; less than 1.0 inch of

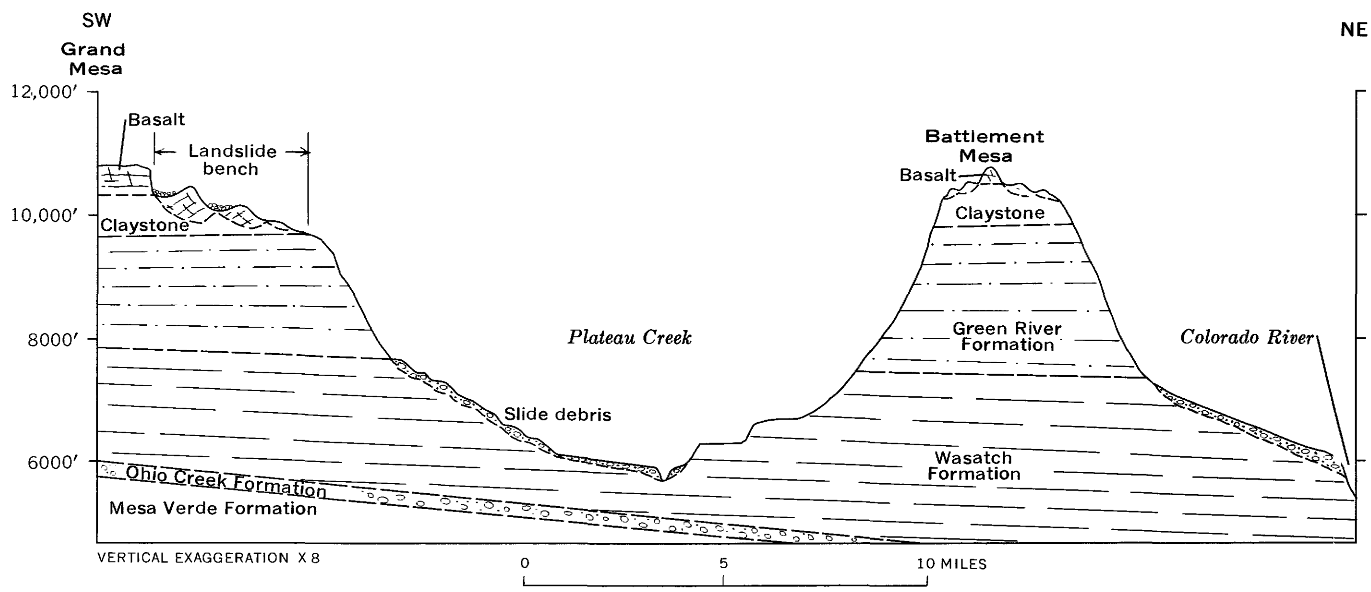

FIGURE 2.—Diagrammatic cross section from Grand Mesa through Battlement Mesa to the Colorado River.

rain falls during each month. Much of the rainfall during the summer falls as scattered thundershowers; consequently, precipitation amounts can be very variable throughout the area. There are no yearly climatic records for the top of Grand Mesa. The mean annual precipitation may be as high as 30 inches.

The average annual temperature at Collbran is about 48°F. December and January are the coldest months; the average monthly temperatures are 27°–28°F. July is the warmest month, and has an average monthly temperature of 71°F. During the summer, temperatures above 90°F. are common at low elevations. Freezing nighttime temperatures can occur any time throughout the year at elevations above 10,000 feet. Summer daytime temperatures on Grand and Battlement Mesas are very comfortable, rarely rising above 75°F.

The U.S. Weather Bureau maintains recording stations at Fruita, Palisade, Collbran, and Rifle (Berry, 1959). Collbran is the only station within the area of study. Monthly and annual temperatures, average annual precipitation, and snowfall for these four stations are given in table 1. Figure 1 shows the location of these stations. All four stations reflect a climatic warming and drying during the years following 1930. This trend is seen in the decreased average annual precipitation at all four stations and decreased average annual snowfall at three of the stations. Average annual temperatures increased more at the lower elevation (1.5°–2.5°) than at the higher elevations (0.6°–0.2°) in the years following 1930.

MOISTURE SOURCE REGIONS

The three major source regions for precipitation in the area are: (1) the cool Pacific Ocean, (2) the warm Pacific Ocean, and (3) the Gulf of Mexico (Crow, 1961; fig. 3). The cool-Pacific source region, designated as all the Pacific north of lat 34° N. (approximately the latitude of Los Angeles), supplies the major amount of moisture, which is concentrated in the winter and spring (Crow, 1961; fig. 4). The Gulf of Mexico is second in importance as a moisture source, delivering rainfall predominantly in the summer months. The warm Pacific, lying west and south of the south end of the high Sierra Nevada, is least important as a moisture source and supplies rainfall in the fall months.

SNOW SURVEY REPORTS

The following generalizations can be made from data collected during the years 1937–65 (28 yr) at four snow course stations (U.S. Soil Conserv. Service and Colorado State Univ., 1962) on the landslide bench below the top of Grand Mesa:

1. The greatest snowpack is commonly in April.
2. Snow depth and moisture content of the snowpack near the first of April averaged over the length of the surveys gives the following values:

	Snow depth (inches)	*Moisture content (inches)*
Trickle Divide	81. 9	27. 9
Park Reservoir	75. 8	25. 5
Alexander Lake	66. 9	23. 0
Mesa Lakes	56. 2	17. 9

TABLE 1.—*Monthly and annual temperatures and average annual precipitation and snowfall at Fruita, Palisade, Collbran, and Rifle, Colo.*

Station and elevation (feet)	Years of record	Average monthly and annual temperature (°F)													Average annual—	
		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Ann.	Precipitation (inches)	Snowfall (inches)
Fruita 4,500	Pre-1931 (28 yr)	21. 6	30. 8	42. 2	50. 4	58. 9	68. 2	74. 6	72. 6	63. 3	51. 0	37. 9	25. 0	49. 7	10. 49	(27-yr record) 22.4
	1931–60	26. 0	32. 2	41. 3	51. 6	61. 0	69. 4	75. 9	73. 3	64. 9	52. 7	37. 4	28. 5	51. 2	8. 31	(20-yr record) 19. 0
Palisade 4,700	Pre-1931 (18 yr)	24. 1	34. 1	42. 6	52. 7	61. 5	71. 2	76. 6	74. 2	65. 2	52. 4	40. 4	28. 8	52. 0	10. 90	(13-yr record) 22.9
	1931–50	28. 8	35. 0	43. 6	54. 1	63. 3	72. 3	79. 3	76. 6	69. 4	56. 9	42. 0	33. 1	54. 5	8. 76	(18-yr record) 17.3
Collbran 6,000	Pre-1931 (29 yr)	22. 0	28. 2	36. 4	45. 6	53. 6	62. 4	68. 4	66. 8	58. 9	47. 3	35. 8	23. 6	45. 8	16. 08	(33-yr record) 75.9
	1931–60	22. 8	27. 6	36. 1	46. 4	54. 8	63. 2	69. 4	67. 2	59. 4	48. 7	34. 4	26. 2	46. 4	13. 83	(21-yr record 63.0
Rifle 5,600	Pre-1931 (29 yr)	23. 0	29. 4	37. 6	47. 8	55. 6	65. 0	71. 0	69. 2	60. 8	49. 0	37. 3	25. 4	47. 6	11. 89	(10-yr record) 31.5
	1931–60	23. 2	29. 1	38. 3	48. 3	56. 7	64. 5	71. 0	68. 9	60. 6	49. 9	35. 9	26. 7	47. 8	10. 93	(20-yr record) 36.9

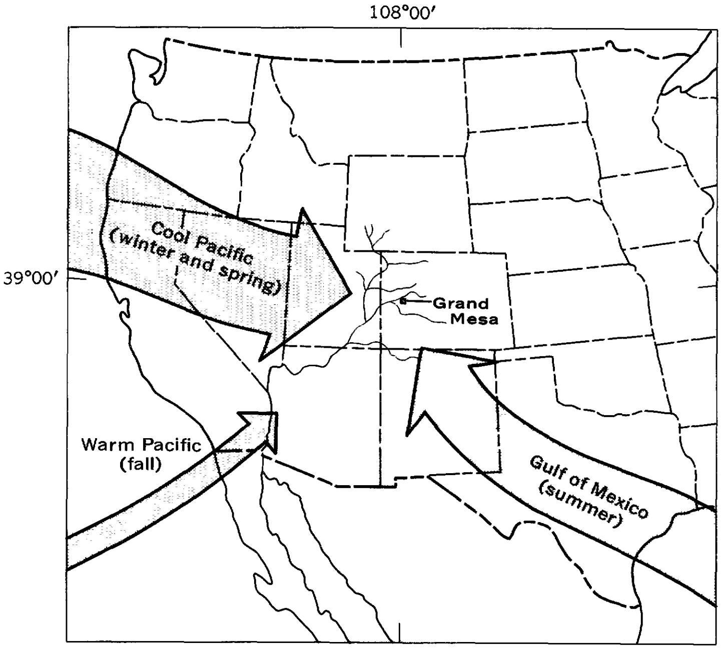

FIGURE 3.—Source regions for precipitation in the upper Colorado River Basin. Adapted from Crow, 1961.

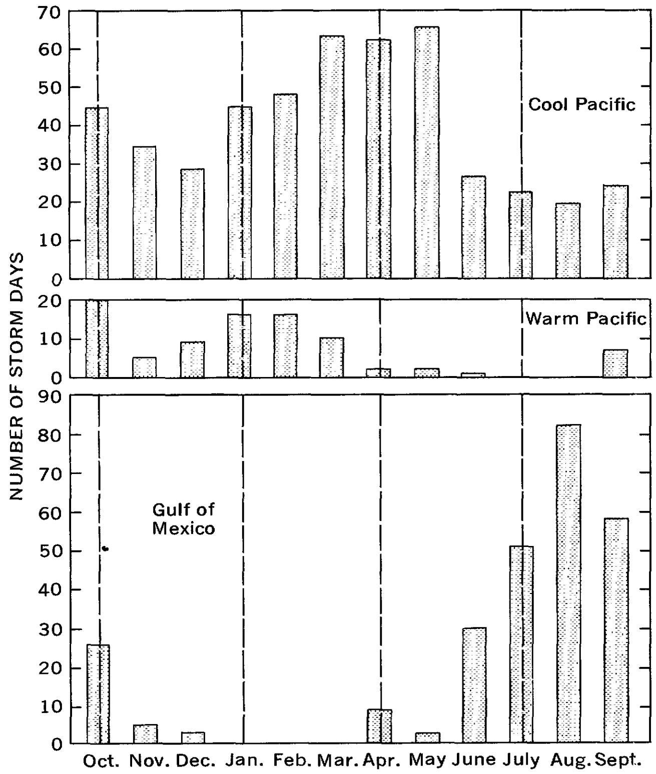

FIGURE 4.—Bar graphs showing frequency of storms from three moisture source regions from which significant daily precipitation was delivered at three or more stations in the upper Colorado River Basin. Tabulation is based on 40 years of daily records, 1911–51. Adapted from Crow, 1961.

The low-average snow depth and moisture content at the Mesa Lakes station as compared to the other stations may be due to the topographic position of the Mesa Lakes station. The major winter storms and prevailing winds come from the west. Alexander Lake, Park Reservoir, and Trickle Divide all lie to the lee of Grand Mesa and seem to be in a favorable position to receive thick deposits of snow, possibly because of a peculiar set of wind currents around the mesa and (or) the drifting of snow from the exposed top of the mesa.

3. The period 1940–50 was relatively wet at all four stations. The interval from 1951 to 1964 was generally drier than the preceding period.

Data have not been recorded for snow accumulation on the top of Grand Mesa. Local residents state that the surface is commonly covered with snow from late September to early June. Large drifts in heavily forested areas remain until mid-July or later. During the winter months no attempt is made to keep open the paved road over the top of the mesa.

VEGETATION ZONATION

Patches of Englemann spruce (*Picea engelmanni*) and alpine fir (*Abies lasiocarpa*) are scattered throughout large parks and open meadows of grass and wildflowers on the surfaces of Grand and Battlement Mesas. Spruce stands are widespread east of Grand Mesa and extend down to an elevation of about 8,700 feet on the north-facing slopes.

Aspen (*Populus tremuloides*) mixed with spruce flourish on the landslide bench below the steep cliffs of the high mesas. Aspen range in elevation from 10,200 to 8,100 feet. At the lower elevations aspen are restricted to the stream valleys.

Scrub oak (*Quercus gambelli*) thrives between 8,500 and 6,500 feet. Oak in dense thickets reaches 12 feet in height at the upper elevation limit. Mountain mahogany (*Cercocarpus* sp.) mixed with oak is common between 8,500 and 7,200 feet.

Juniper (*Juniper utahensis*), sagebrush (*Artemisia* sp.), and hardy desert grasses are scattered in the elevation range 7,200–5,000 feet. Cottonwood (*Populus fremontii*) are present within this elevation range along streams. Because of the arid conditions on the south-facing slope below Battlement Mesa, the zone of sagebrush and juniper extends much higher than on the north-facing slope below Grand Mesa.

The reason for the absence of ponderosa pine (*Pinus ponderosa*) from the area is not understood. Ponderosa pine is common at similar elevations to the south within the San Juan Mountains and to the west on the Uncompahgre Plateau, and within the La Sal Mountains. Several small piñon pine (*Pinus edulis*) are present.

but their scarcity is peculiar. Several bog samples from the top of Grand Mesa have revealed pine pollen in moderate amounts, but detailed work on this problem has not yet been done.

PRE-QUATERNARY GEOLOGY

STRATIGRAPHY

Sedimentary rocks ranging in age from Late Cretaceous to Pliocene(?) are exposed in the area (table 2). All are nonmarine except for the lower part of the Upper Cretaceous Mesaverde Formation. The total thickness may average 6,000 feet; it increases to the north toward the geographic center of the Piceance Creek basin. Basalt flows dated at 9.7±0.485 million years (potassium-argon method, J. R. Donnell, oral commun., 1965), considered to be Pliocene in age, cap Grand and Battlement Mesas. Fine-grained basic igneous dikes and sills, believed to be equivalent in age to the basalt flows, intrude the older sedimentary rocks in several places.

STRUCTURE

The area lies on the southern margin of the Piceance Creek basin, a broad structural and depositional basin trending northwest and formed during Late Cretaceous time. The sedimentary rocks dip gently (2°–5°) northward into the center of the basin. These low dips are responsible for gently sloping structural terraces held up by sandstones in the Wasatch Formation in the area north of Plateau Creek. A broad east-plunging anticlinal nose is present in the western part of the area. This fold, the Black Mountain anticline, was formed after the deposition of the Wasatch Formation of

TABLE 2.—*Pre-Quaternary stratigraphy of the Grand and Battlement Mesas area*

[Adapted from J. R. Donnell, unpub. data, 1965]

System	Series	Formation	Member	Thickness (feet)	Rock description
Tertiary	Pliocene	Intrusive and extrusive rocks		200–500	Basalt flows, dikes, and sills 9.7±0.485 million years (potassium argon).
		Unconformity			
	Pliocene(?)	Unnamed sedimentary rocks		50–900	Gravel and variegated claystones.
		Unconformity			
	Eocene	Green River Formation	Evacuation Creek	500	Light-brown and gray sandstone and gray marlstone and siltstone; in places, contains pelecypods, gastropods, ostracodes, and vertebrate fragments.
			Parachute Creek	600	Predominantly black, brown, and gray oil shale that in places forms cliffs; contains minor amounts of gray siltstone and gray and brown fine- to medium-grained sandstone; contains richest oil-shale beds.
			Lower	1, 000	Fine- to coarse-grained gray and brown sandstone, minor amounts of gray siltstone and marlstone, and a few thin tan low-grade oil-shale beds.
		Wasatch Formation	Upper	400–1, 600	Variegated shale and clay and some lenticular beds of sandstone, conglomerate, and limestone.
			Middle	0–400	Massive fine- to coarse-grained gray and brown sandstone, in part conglomeratic; conspicuous ledge former. Pinches out on west flank of Chalk Mountain.
			Lower	400–900	Variegated shale and clay and some lenticular beds of sandstone, conglomerate, and limestone.
		Unnamed rocks		(?)	Brown and somber-colored shale with thin coal seams.
	Paleocene	Ohio Creek Formation		10–150	Massive fine- to coarse-grained white to brown sandstone; in most places, contains pebbles and cobbles of quartz, quartzite, chert, and some limestone and granite pebbles.
Cretaceous	Upper Cretaceous	Mesaverde Formation		2, 000–3, 300	Fine- to medium-grained ledge-forming brown sandstone interbedded with gray shale, carbonaceous shale, and some thin coal beds.

Eocene age, as these rocks are involved in the folding. Several northwest-trending faults are present on the north side of Plateau Creek. They cut rocks as young as the upper Wasatch and possess throws of less than 150 feet. Small recent fractures in the basalt capping Grand Mesa are a result of landslide activity and do not extend far below the base of the basalt.

QUATERNARY GEOLOGY

The presence of varied environments in the Grand Mesa area during the Quaternary Period necessitates the evaluation of numerous physical processes and a variety of resulting facies patterns. All the Quaternary deposits are grouped within three major facies: glacial, alluvial, and colluvial (pl. 1). To the glacial facies belongs the mostly unsorted debris that was deposited from glacial ice. Alluvial facies include the bedded, partially rounded pebbles, cobbles, and boulders set in a sandy matrix laid down by running water, including both outwash and nonglacial stream deposits. Colluvial facies include the varied types of deposits produced by mass wasting in which water, if present during movement of the material, probably amounted to less than 50 percent by volume.

A formation may include the three facies—glacial, alluvial, and colluvial—all of which would have been deposited during the same time interval. Different facies of the same formation are correlated by interfingering relationships, similar topographic form and position, soil development, and lithologic and textural similarities. Thus, the Lands End and Grand Mesa Formations are defined to include glacial, alluvial, and colluvial deposits of equivalent age. It does not seem desirable to introduce formation names for the pre-Bull Lake(?) deposits nor for postglacial and slump-block deposits. Most of these deposits are very local in extent, and the identification of deposits with particular intervals of time is difficult. These units are specified by morphologic and lithologic terms, such as "pediments," "slump blocks," "mudflows," "alluvial terraces," "earthflows," "talus," and "colluvium."

The soil profile descriptions are modified after methods recommended in the Soil Survey Manual of the U.S. Department of Agriculture (U.S. Bur. Plant Industry, Soils, and Agr. Eng., 1951). Color symbols are those of the Munsell System (Munsell Color Co., 1954).

PRE-BULL LAKE(?) DEPOSITS

PEDIMENT GRAVEL

Bordering the Colorado River on the south and southeast between Rifle and De Beque are extensive high-level pediments (fig. 5) mantled with coarse poorly sorted gravel of pre-Bull Lake(?) age. Grass, Log, High, and Samson Mesas are some of the local names given to these gravel-covered pediments. Morrisania and Holms Mesas are also covered by pre-Bull Lake(?) pediment gravels that are, however, overlain by younger deposits. A few pediments are preserved south of De Beque and on the north side of Plateau Creek. Kimbell Mesa and the south slopes of Black Mountain are two such remnants. Interestingly, all these pediments are peripheral to Battlement Mesa; none are recognized adjacent to Grand Mesa in the project area. In a few places the pediment remnants are traceable directly up to the mountain front, having been isolated by later stream erosion.

The pediment gravel is commonly 20–30 feet thick; however, it is locally thicker, especially near the Colorado River. The gravel is composed of subangular to subrounded pebbles, cobbles, and boulders. Locally derived basalt boulders as much as 8 feet in diameter are common near the steep slopes of Battlement Mesa. Boulders 1–3 feet in diameter are common at the downslope edge of the pediments. The gravel colors of gray green, gray brown, and yellowish white are due to the high content of oil shale, siltstone, sandstone, and claystone derived locally from the Wasatch and Green River Formations. Oil shale from the Green River Formation commonly occurs as slabs. Except in the present streambeds, weathered slabs of oil shale are common throughout all the terrace and pediment gravels in the area. From a distance, the gravel frequently appears yellowish white because it contains so much of the weathered shale. Bedding is rare and sorting poor in most of the pediment gravels. Crystalline-rock types derived from east of the area are abundant in the pediment gravel near the Colorado River.

Almost without exception the pediments are cut on very gently dipping sandstones, siltstones, and claystones of the Wasatch Formation. The basal contact of the pediment gravel is commonly covered with a thin veneer of talus and colluvium. The gravel surface is generally covered with a thin patchy layer of reddish-brown windblown sand and silt.

Two distinct levels of pediments are recognized. The older and higher is preserved in only three localities. Flatiron Mesa (North Mamm Peak quadrangle) and High Mesa (Grand Valley quadrangle) are the largest remnants of this surface. On Flatiron Mesa the pediment has a gradient of 280 feet per mile, and it projects to 1,300 feet above the Colorado River. Remnants of the lower gravel-mantled pediment are more widespread and have gradients of 230–1,200 feet per mile; the steeper gradients are near the mountain front. Gradients are commonly 300–400 feet per mile. These lower surfaces project to 440–600 feet elevation above the

FIGURE 5.—Pre-Bull Lake(?) pediments flanking the west side of Battlement Mesa. View from about 2 miles north of De Beque.

Colorado River and most commonly are about 500 feet above the river.

A deeply weathered residual soil was not found on the pediment gravels anywhere in the area. An adequate explanation for the lack of deep soil development on old gravel-covered surfaces is difficult. A Cca soil horizon 3–5 feet thick, often platy, is commonly present; however, a clay-rich B horizon is absent. Buried soils are truncated and show little more development than those on exposed surfaces. The reddish-brown (5*YR* 4/3) B horizon is seldom more than a foot thick on exposed surfaces. Eolian and alluvial activity may have complicated the normal soil-forming processes through the addition and (or) removal of fine-grained sediment. Precipitation is low in all areas where the pediments are preserved, which imposes a limitation on soil formation.

Less than half of the gravel surfaces are farmed, owing largely to the lack of available moisture and the difficulty of bringing irrigation water to the high surfaces. Sagebrush and scattered juniper trees are the common vegetation.

Discussion.—Remnants of pediments are correlated on the basis of their similar surface elevations and their elevated positions with respect to lower surfaces that are physically continuous. The pediments were formed by streams and mudflows issuing from the highlands of Battlement Mesa. These streams were graded to the Colorado River, which was flowing in a broad valley about 500 feet above its present valley. Differential amounts of downcutting by the Colorado since the development of these old pediments is suggested as the reason for the occurrence of the pediment remnants at different elevations above the Colorado River. Differential local uplift is ruled out because of the lack of warped bedrock surfaces.

The pediments are probably pre-Bull Lake(?) in age because of their high, isolated topographic position with respect to lower erosional and depositional surfaces of Bull Lake(?) age. The higher of the two pediments may be as old as Pliocene.

TILL

A thick section of unsorted basalt-rich material overlying a striated and grooved bedrock surface on Chalk Mountain (Chalk Mountain quadrangle) is the only recognized occurrence of pre-Bull Lake(?) age till in the project area. The till is shown on the geologic map (pl. 1) as a narrow band in the easternmost part of the mapped area where it is well exposed on the steep east-facing slopes of Chalk Mountain and is overlain by till of Pinedale(?) age. Section 1 is typical of the till sequence measured at this locality.

1. *Section of tills measured on Chalk Mountain, in the SE¼NW¼ sec. 10, T. 11 S., R. 92 W., Chalk Mountain quadrangle*

	Thickness (feet)
Topography: Steep (45°) slope.	
Elevation: 11,100 ft.	
Vegetation: Scattered spruce, fir.	
Grand Mesa Formation, till facies:	
No recognizable soil horizons:	
Till, gray-brown, very bouldery; less than 40 percent matrix; mostly angular basalt fragments; boundary abrupt	20
Pre-Bull Lake(?) tills and associated deposits:	
Sand and silt, red-orange	3
Sand and silt, gray-brown; subangular pebbles of basalt; white limestone fragments	18
Till, gray-brown matrix; abundant striated basalt boulders	30–50
Till, gray-brown matrix; abundant subangular basalt boulders and cobbles, moderately well indurated; stands as a cliff, white sandy lenses at base composed of quartz grains; slight color change at top of cliff from gray below to gray brown above; boundary sharp	6–10
Sand, red-orange, blocky	1–2
Till, gray-black; pebbly basaltic sand matrix, angular cobbles and boulders of basalt; boundary sharp	18
Sand, red-orange	2
Sand and silt, brown, moderately well indurated; boundary sharp	7
Till, gray-brown; 20–40 percent basalt fragments	5
Measured thickness	110–135
Unconformity.	
Green River Formation:	
Sandstone, glaciated pavement on surface; striations and grooves as much as ⅛ in. deep, S. 20° E., N. 20° W.	

East of the project area on Electric (T. 11 S., R. 91 W.) and Spruce Mountains (T. 10 S., R. 91 W.) are similar-looking thick sections of unsorted material containing abundant striated cobbles. It is reasonable to conclude that these high, isolated occurrences are also till and may, in part, be correlative with the till section on Chalk Mountain. More than 250 feet of till(?) was measured on Spruce Mountain, which is about 10 miles northeast of Chalk Mountain. Electric Mountain, about 6 miles southeast of Chalk Mountain, is capped by more than 200 feet of till(?). Several episodes of glaciation may be represented in these sections; however, buried soil horizons are not found in them. Variations in texture, color, and weathering characteristics are observed throughout all the sections.

Discussion.—It is difficult to determine the center of ice dispersal for this glaciation; but a southern source, in the vicinity of the isolated peaks of Crater Peak, Mount Hatten, and Mount Darline, seems possible. These high peaks are about 150–200 feet higher than Chalk Mountain and are probably the surviving remnants of the basalt flow that was at one time distributed over much of the area. A high, relatively flat surface similar to Grand Mesa could have accumulated ice that flowed north across a gently sloping surface that included Chalk, Spruce, and Electric Mountains. Ice-produced grooves and striations on Chalk Mountain, trending in a north-south direction, are compatible with a southern source. Except on the highest areas, extensive postglacial erosion has removed all evidence of the pre-Bull Lake(?) till sheet.

The tills are assigned a pre-Bull Lake(?) age because of their geographic occurrence capping remnant mountains isolated by valleys mantled with Bull Lake(?) and Pinedale(?) deposits.

TERRACE AND FAN GRAVEL

Three levels of old gravel-capped terraces are present on the north side of Grand Mesa. These terrace surfaces project 200–500 feet above Plateau Creek. Except for isolated occurrences along the lower stretches of Plateau Creek and a small fan exposed near the Colorado River along Spring Creek, Windger Flats (Mesa quadrangle) and Mormon Mesa (Molina quadrangle) are the only preserved exposures of the oldest and highest terrace gravels (fig. 6). In the northern part of the area, on the south side of the Colorado River, Taughenbaugh Mesa is capped by old alluvial gravel buried beneath younger alluvial and colluvial deposits that have poured out from Battlement Mesa onto the old gravel surface.

The gravel is composed of near-equal amounts of basalt and sedimentary rock fragments of locally derived sandstone, claystone, and marlstone. It contrasts markedly with younger gravel that contains 90–100 percent basalt fragments.

The basalt boulders and cobbles are mainly subrounded to well rounded, but a few are angular. The sedimentary rock fragments are commonly slabs. The matrix is generally light-greenish-gray silty sand. On the north side of Battlement Mesa near the Colorado River, the buried gravel is composed largely of par-

FIGURE 6.—Terraces of Kansas Mesa (Qam, middle pre-Bull Lake(?)) and Mormon Mesa (Qao, older pre-Bull Lake(?)). A low terrace (Qgam, middle Pinedale(?)) is visible near Plateau Creek.

tially rotted boulders and cobbles of plutonic igneous and metamorphic rocks derived from mountains east of the area.

The gravel commonly ranges in thickness from 10 to 60 feet, but more than 100 feet of gravel is present at the lower edges of some terraces along Plateau Creek and near the Colorado River. Gradients are generally between 150 and 400 feet per mile. The gravel surfaces are moderately smooth and locally mantled with reddish-brown windblown sand and silt.

Active slumps and mudflows are rapidly reducing the extent of Mormon Mesa. The gravel is ideally situated for slumping because it carries water to the underlying claystone of the Wasatch Formation. The gravel of Windger Flats lies on the Mesaverde Formation and is not subject to extensive slumping.

Soil profiles on the three terrace gravels are so similar that they afford no criteria for differentiating terrace levels on the basis of soil development. The B horizon ranges in the thickness from 1 to 3 feet, and the Cca horizon ranges in thickness from 3 to 4 feet. Section 2 is characteristic of the alluvial gravels in the Plateau Creek drainage.

2. *Section measured on the northwest edge of Mormon Mesa in the NE¼ sec. 18, T. 10 S., R. 95 W., Molina quadrangle*

Topography: Uniform north-sloping (2°) surface; about 900 ft. above Plateau Creek.
Elevation: 6,520 ft.
Vegetation: Cultivated surface, alfalfa; scattered juniper.

	Thickness (feet)
Pre-Bull Lake(?) alluvium:	
Pre-Bull Lake(?) soil:	
Soil horizons A and B:	
Dark-brown to brown (7.5*YR* 4/2) sandy silt; calcium carbonate aggregates scattered throughout:	
Structure: Very weak.	
Reaction: pH 8.0.	
Boundary: Abrupt	1.6
Soil horizon Cca:	
Very white, gravelly.	
Structure: Strong, platy.	
Cementation: Indurated.	
Reaction: pH 8.0.	
Boundary: Gradational	3.5

2. *Section measured on the northwest edge of Mormon Mesa in the NE¼ sec. 18, T. 10 S., R. 95 W., Molina quadrangle*—Con.

	Thickness (feet)
Pre-Bull Lake(?) alluvium—Continued	
Alluvial gravel:	
Sandy gravel, moderately well sorted:	
Coarse material: 70 percent, well-rounded basalt boulders and cobbles; sediment boulders and cobbles are in the form of slabs; crude bedding.	
Pebble count: 50 percent basalt (94 percent fresh, 6 percent weathered); 23 percent siltstone; 18 percent limestone; 5 percent sandstone; 4 percent tuff.	
Matrix: 30 percent; greenish-gray, dominantly sedimentary rock fragments; beds vary in texture and composition	60–100
Bottom of exposure.	

Discussion.—Although it is not possible to trace any of these gravels into identifiable glacial deposits, it seems probable that some of the gravels, particularly those on the north side of Grand Mesa, many represent outwash from an early glaciation—the evidence of such glaciation having been destroyed except in such places as Chalk, Electric, and Spruce Mountains. However, the low basalt content and high sedimentary rock content of the gravels would tend to support a theory of local, nonglacial origin for the gravels. The younger Pinedale(?) and Bull Lake(?) gravels at the low elevations, seemingly glacial in origin, contain a high percentage (more than 90 percent) of basalt, having been transported by the ice a significant distance from the high parts of Grand Mesa.

The gravel terraces are assigned a pre-Bull Lake(?) age because of their elevated position above the present streams and above more continuous terraces that are of Bull Lake(?) and Pinedale(?) age.

A buried soil developed on gravel of this age was found at Taughenbaugh Mesa just north of the area where the gravel road from Rifle ascends the mesa (NE¼SW¼ sec. 20, T. 6 S., R. 93 W.). The soil is developed on fine-grained alluvium resting on gravels rich in metamorphic and plutonic igneous rock fragments similar to those in the present flood plain of the Colorado River. A reddish-brown Bca horizon displays moderate to poor prismatic structure (fig. 7). The average preserved thickness of the buried soil is 4.0 feet. It is overlain by 20 feet of poorly sorted basalt-rich boulder- and cobble-gravel probably of Pinedale(?) age. Six feet below the surface is a buried reddish-brown B soil horizon, 1-foot-thick, displaying no discernible structure.

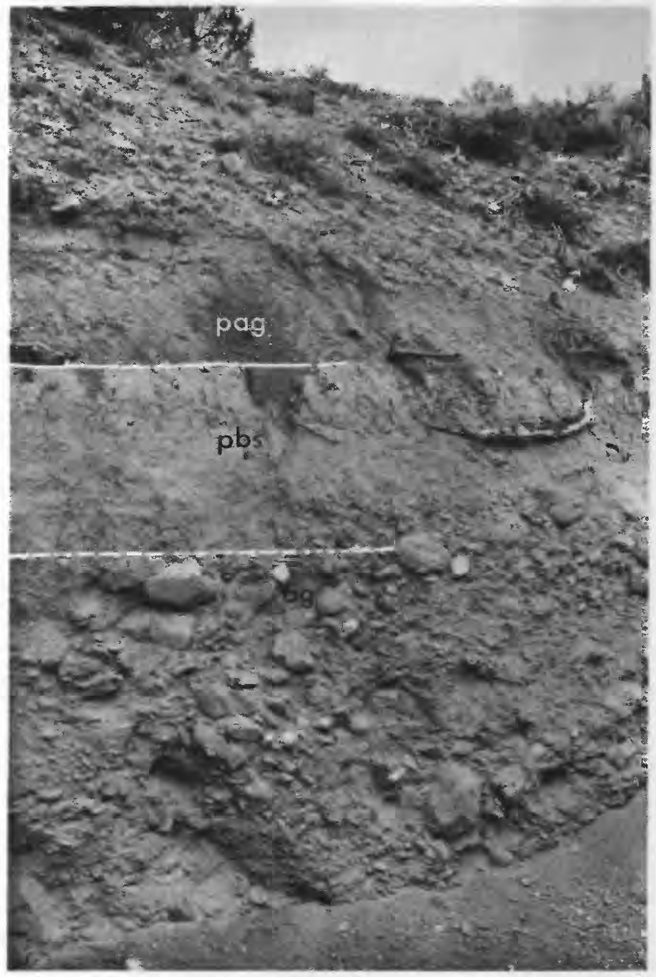

FIGURE 7.—Buried pre-Bull Lake(?) soil (pbs) developed on fine-grained alluvium overlying alluvial gravels (ag). The buried soil is overlain by Pinedale(?) alluvial gravel (pag). Exposed in roadcut on northeast side of Taughenbaugh Mesa (Rifle quadrangle, north of area).

COLLUVIUM

Two distinct units of colluvium were recognized and mapped, a younger colluvium and an older colluvium. The units could not be differentiated other than on the basis of relative topographic position. The older unit, recognized in only a few isolated localities, is about 200 feet above the younger. Much of both units has been removed through erosion, leaving thin caps on isolated hills. The summits of Beehive Mountain (Molina quadrangle) and Old Man Mountain (Collbran quadrangle) are two remnants of the older colluvium and are capped by 20–40 feet of angular unsorted blocky material. The deposits at many of the mapped localities are scarcely large enough to show at the scale of 1:24,000. The most extensive areas of the colluvium are in the Meadows and Collbran quadrangles.

The colluvium is composed of angular to subangular basalt boulders as much as 5 feet in diameter. Sandstone, marlstone, claystone, and siltstone slabs as much as 1 foot in diameter are common. The matrix is greenish-gray sandy silt.

Discussion.—Lithologically and texturally, except for the very large basalt boulders, this material resembles the alluvial gravel and till described above. Much of this colluvium may be remnant alluvial gravel or till that has been "let down" by erosion and weathering of the pediments, terraces, and till plains. Soils, where preserved, are similar to those developed on terrace gravel.

BULL LAKE(?) DEPOSITS

LANDS END FORMATION

The name Lands End Formation (Yeend, 1966) is applied to glacial and alluvial deposits on Grand and Battlement Mesas. It includes deposits of till and terrace and fan gravels. The formation is named for the widespread occurrence of till on the west end of Grand Mesa, known as Lands End. The type section (section 3) is exposed on Grand Mesa in a recessional moraine (SW¼ sec. 4, T. 12 S., R. 96 W.). The till rests unconformably on basalt of Pliocene age. One mile east of the type locality the till of the Lands End Formation is unconformably overlain by till of the Grand Mesa Formation.

3. *Type section of the Lands End Formation; till exposed in a recessional moraine on the west end of Grand Mesa in the SW¼, sec. 4, T. 12 S., R. 96 W., Lands End quadrangle*

Topography: Slopes in recessional moraine and ground moraine 4° and less.
Elevation: 10,340 ft.
Vegetation: Scattered spruce stands and open grassy meadows.
Till of the Lands End Formation:

	Thickness (feet)
Soil horizon A:	
Brownish-black silt loam:	
Structure: Structureless.	
Consistency: Nonsticky.	
Reaction: pH 6.0.	
Boundary: Abrupt	0. 7
Soil horizon B:	
Dark-reddish-brown (5*YR* 3/4) silt loam.	
A few rotten basalt pebbles.	
Structure: Moderately platy parallel to ground surface.	
Consistency: Moderately sticky.	
Cementation: Poor.	
Reaction: pH 5.5.	
Boundary: Gradational	. 9

3. *Type section of the Lands End Formation; till exposed in a recessional moraine on the west end of Grand Mesa in the SW¼, sec. 4, T. 12 S., R. 96 W., Lands End quadrangle*—Continued

Till of the Lands End Formation—Continued	Thickness (feet)
Till:	
Dark-brown to brown (7*YR* 4/4) gravelly clay, unsorted:	
Coarse material: 30 percent.	
Pebble count: 100 percent basalt; 6 percent fresh; 48 percent slightly weathered; 36 percent moderately weathered; 10 percent very weathered.	
Matrix: 70 percent; quartz-rich sand, silt, clay.	
Consistency: Very sticky, compact.	
Reaction: pH 6.5.	
Bottom of exposure	3. 9

The lower contact with the basalt was not exposed in this section. Farther west, where the till cover is thin and spotty, several lower contacts were observed. The till rests both on fresh, unweathered basalt and on a rubble layer that grades down through weathered basalt to fresh basalt.

TILL

A thin veneer of till covers the west end of Grand Mesa. Eastward it is buried by the terminal and ground moraines of the Grand Mesa Formation and is not exposed at the surface on the mesa farther to the east. Test pits 2–6 feet deep, however, reveal the presence of this till beneath the till of the Grand Mesa Formation at various places farther east on the mesa. It is probable that the till sheet of the Lands End Formation covered the entire mesa. A reconnaissance of the Flowing Park lobe—the south branch of Grand Mesa, outside the mapped area—revealed that it is also covered by a thin veneer of this till.

Till of the Lands End Formation is not exposed below the top of Grand Mesa, except in vertical cuts where it is present beneath the younger Grand Mesa till. A moderately well developed buried soil zone is observed on the till in most of the major drainages leading north from the mesa. Because the till is either destroyed or buried at the lower elevations, any attempt to show the maximum extent of ice during this glaciation is most difficult.

The till surface on Grand Mesa slopes west, parallel to the basalt cap. It is gently rolling and poorly drained. Generally the surface is boulder free, but local boulder fields exist. The till cover varies from less than a foot in thickness near the extreme west edge of Grand Mesa to more than 10 feet farther east. Several low, wide, generally continuous ridges of till trend transversely across the mesa surface (fig. 8). These have been mapped as recessional moraines. Local outcrops of basalt protrude through the till cover. Although many of the isolated basalt inliers were examined, striations and grooving were not found.

Retzer (1954) reported an early (pre-Wisconsin) glaciation reaching as far west on the mesa as Deep Creek, where a terminal moraine was formed. This is about 1¼ miles farther west than the younger terminal moraine of till of the Grand Mesa Formation (fig. 8). After extensive work on the west end of Grand Mesa, where stratigraphy and samples in a number of test pits and auger holes were studied, it was concluded that the glaciation of Lands End time extended beyond Retzer's older terminal moraine to at least the present western limit of the mesa. Consequently, the moraine in the vicinity of Deep Creek is referred to as a recessional rather than a terminal moraine. No change was found in topography or internal character of the surficial material to indicate a west limit of the till on the mesa surface. Another recessional moraine, about 4 miles farther west than the one at Deep Creek, was also mapped. Just how far past the western limit of the mesa the glaciation extended is impossible to say because of extensive postglacial mass wasting.

The till of the Lands End Formation is quite uniform. In lithology and texture it is usually distinct from the till of the younger Grand Mesa Formation. Individual samples, however, show overlap (fig. 9), and lithology and texture by themselves may not be distinguishing features of the two tills. The coarse fraction of the unsorted till on the mesa is dominated by boulders, cobbles, and pebbles of basalt. The pebbles crush easily between the fingers, having been broken down by physical weathering and partly by chemical weathering. The till matrix contains a high percentage of quartz (60–80 percent). Mica, iron oxide, calcium

FIGURE 8.—View west toward Lands End, top of Grand Mesa. The terminal moraine (tm) of the till of the Grand Mesa Formation is in the foreground. The light-colored area on the moraine is a newly opened gravel pit. Two small ponds are present adjacent to the moraine (tm). A recessional moraine (rm) of till of the older Lands End Formation is to the west.

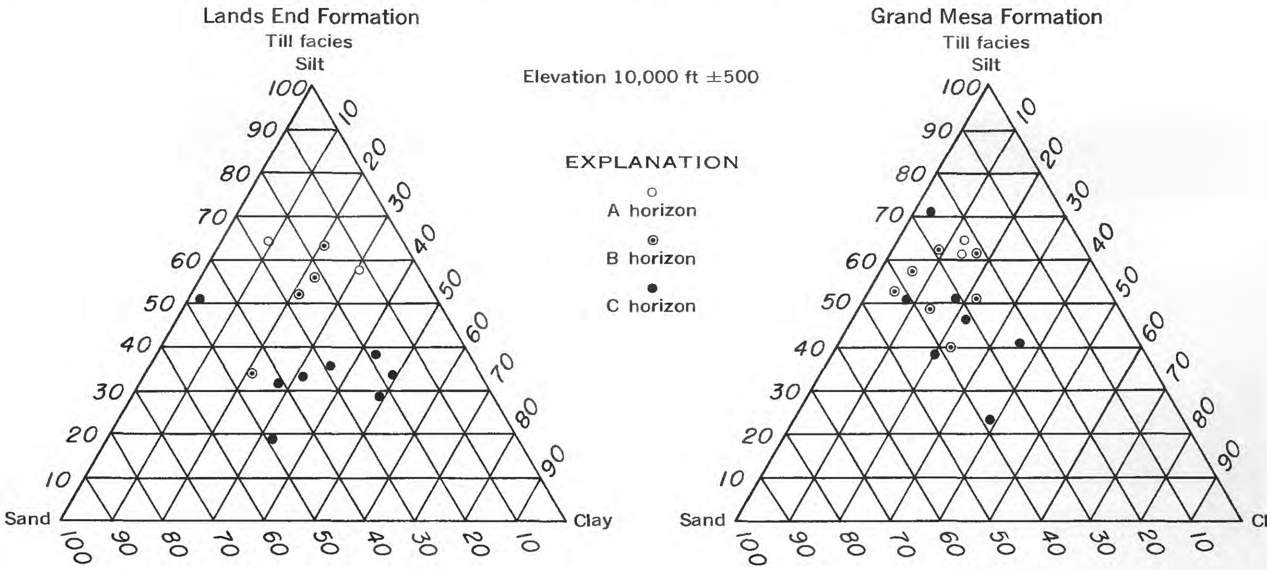

Figure 9.—Triangular diagrams showing percentages of sand, silt, and clay in the matrix of the tills of the Lands End and Grand Mesa Formations. Percentages are also shown for some of the soil horizons developed on the tills. Mechanical analyses were determined by hydrometer. Sand, silt, and clay were calculated as a percentage of the <2-mm fraction.

carbonate coatings, olivine with iddingsite rims, and magnetite are also present. The till is sticky when wet and contains "swelling" clays. Hydrometer-size analyses of the till matrix, as determined from 10 samples, give the following percentages: sand, 27.2 percent; silt, 35.5 percent; and clay, 37.3 percent (table 3). Colors include reddish brown, dark reddish brown, dark yellowish brown, brown, and dark brown, with the majority falling within the brown to dark-brown category. Above 9,000 feet little, if any, reaction to acid is noted. At lower elevations a Cca horizon is present.

Above 10,000 feet the soil developed on the till is weak, ranging in thickness from 1.2 to 3.3 feet. As will be subsequently discussed, the soil here is probably partially developed from loess. The A horizon is less than 2.0 feet thick, brown black in color, and grades abruptly into the underlying B horizon. The B horizon ranges in thickness from 0.2 to 1.3 feet and is commonly reddish brown to dark reddish brown. A horizontal platy structure within the B horizon is frequently noted. This material is much less sticky than the underlying till and shows a size breakdown of sand, 27.7 percent; silt, 51.6 percent; and clay, 20.9 percent (fig. 9; table 3). The matrix is 80–95 percent quartz, both frosted and clear. The B horizon also differs from the underlying till in containing five to six times as many weathered basalt fragments relative to fresh basalt fragments.

The buried till in the stream valleys is distinguishable from the overlying till of the Grand Mesa Formation in only those localities where an interglacial soil is preserved between them. Fortunately, this buried soil has been preserved in numerous localities. The best exposures are found in the drainage of Cottonwood and Big Creeks. The lowest observed occurrence of the buried soil of the till is in Cottonwood Creek at an elevation of 5,800 feet. The two tills exposed in Cottonwood Creek (fig. 10) are described in section 4.

4. *Till of the Grand Mesa Formation overlying till of the Lands End Formation exposed in a roadcut along Cottonwood Creek southeast of Molina, Colo., in the SW¼NE¼ sec. 19, T. 10 S., R. 95 W., Molina quadrangle*

Topography: Till plain sloping 4° north.
Elevation: 6,220 ft.
Vegetation: Cultivated to hay; sagebrush, juniper.

	Thickness (feet)
Grand Mesa Formation, till facies:	
Soil horizon A:	
Brown, humic silt; plant remains.	
Reaction: pH 8.0.	
Boundary: Gradational	0.2
Soil horizon B:	
Dark-reddish-gray (5*YR* 4/2) gravelly silt:	
Structure: Weak, fine granular.	
Consistency: Very slightly sticky.	
Cementation: Weak.	
Reaction: pH 7.5.	
Boundary: Abrupt	1.5
Soil horizon Cca:	
Gray-white.	
Structure: Weak medium crumb.	
Cementation: Poor.	
Boundary: Gradational	1.5

4. *Till of the Grand Mesa Formation overlying till of the Lands End Formation exposed in a roadcut along Cottonwood Creek southeast of Molina, Colo., in the SW¼NE¼ sec. 19, T. 10 S., R. 95 W., Molina quadrangle*—Continued

	Thickness (feet)
Grand Mesa Formation, till facies—Continued	
Fresh till:	
Light-gray-brown, gravelly, sand, silt loam, unsorted.	
Coarse material: 40 percent, angular to subangular.	
Pebble count: 95 percent basalt, 98 percent of which is fresh and 2 percent slightly weathered; 2 percent siltstone, 2 percent claystone; 1 percent limestone.	
Matrix: 60 percent, light-gray-brown (10*YR* 6/2) sandy silt loam.	
Boundary: Abrupt	5. 0
Lands End Formation, loess and till facies:	
Soil horizon B: (weathered loess).	
Reddish-brown (2.5*YR* 5/4) silty clay loam:	
Structure: Moderate, blocky semiprismatic.	
Consistency: Slightly sticky.	
Cementation: Well indurated.	
Reaction: pH 8.5, carbonate.	
Boundary: Gradational	1. 5
Soil horizon Bca: (weathered loess, and till).	
Reddish-brown (2.5*YR* 4/4) silty clay loam:	
Similar to B horizon but darker in color with abundant $CaCO_3$ stringers.	
Structure: Moderate prismatic.	
Cementation: Indurated and layered at base	
Boundary: Gradational	5. 0
Fresh till:	
Similar to Grand Mesa till with the addition of some andesite fragments derived from the post-Green River sedimentary rocks.	
Coarse material: 40 percent.	
Pebble count: 94 percent basalt; 2 percent siltstone; 2 percent claystone; 2 percent limestone.	
Matrix: 60 percent.	
Boundary: Abrupt	7. 0

At a locality in the Big Creek drainage, where part of the buried B horizon has been stripped, a well-developed platy Cca horizon 4 feet thick is present (fig. 11). This is generally the greatest thickness noted for the Cca on till of the Lands End Formation at low elevations. The till is commonly less than 40 feet thick, but is locally more than 200 feet thick in the narrow, restricted drainages, such as Cottonwood Creek, Leon Creek, and the upstream part of Big Creek. The tills have been eroded to depths of about 200 feet in some of these major drainages, and, in many places, bedrock has not yet been exposed.

Discussion.—The moderately high clay content of the till of the Lands End Formation can be explained in several ways. The first explanation presupposes that the glacial episode during which the till was deposited was the earliest glaciation to affect the area. A thick clay-rich soil was probably developed on the basalts throughout much of late Tertiary time and would have provided an ample source of clay for the till. It seems more likely, on the other hand, that Grand Mesa was subjected to earlier Pleistocene glaciations, of which no evidence was found. In such a case, it is very likely that a clay-enriched soil would have been developed during pre-Bull Lake(?) time on an earlier till sheet and that it could have been subsequently incorporated in the till of the Lands End Formation.

FIGURE 10.—Till of the Grand Mesa Formation (Qgt) overlying weathered loess (wl) on till of the Lands End Formation. Exposed in roadcut on west side of Cottonwood Creek, elevation 6,220 feet. Notice the blocky, semiprismatic structure in the weathered loess.

More difficult to explain, however, is the increased silt content and decreased clay content of the B horizon of the soil compared to that of the parent till. In normal soil development the B horizon is the zone of clay enrichment by virtue of the breakdown of unstable minerals and illuviation from above. In this case it must be appreciated that the parent material is already very rich in clay. Although no quartz-bearing bedrock is present on Grand Mesa, the till contains much quartz, and the silty B horizon is even richer in quartz. If the surface of Grand Mesa was the site of an early major drainageway from quartz-bearing terrain, as will be subsequently discussed, the high quartz content of the till can be explained. A certain amount of silt and sand

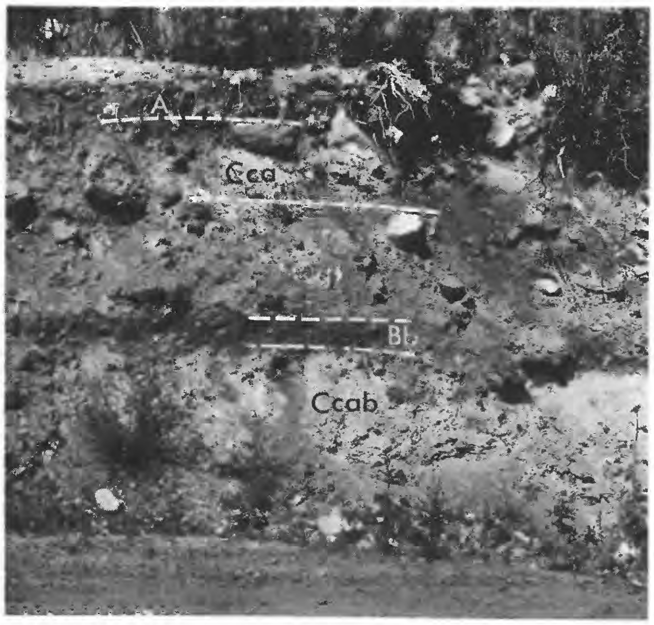

FIGURE 11.—Exposure of till of the Grand Mesa (Qgt) Formation and buried soil (Bb and Ccab) on till of the Lands End Formation in the drainage of Big Creek. Roadcut on Kansas Mesa about half a mile north of the Pleasant View School.

would have been brought into the area by this drainage system as well as by winds blowing across the wide, virtually featureless expanse of the then-extensive basalt surface. The quartz part of this earlier cover is evidently still present, having been mixed with the weathered products of the basalt by the processes of glacial erosion, transportation, and deposition. However, the excess amount of silt-sized quartz grains in the A and B horizons is still unexplained. Perhaps these quartz particles were blown into the area during and following glaciation. The B horizon may then reflect eolian activity more than illuviation. Many of the quartz grains are unfrosted, but this does not rule out an eolian origin. The majority of the grains are fine sand to silt size (0.25–0.002 mm) and fall below the critical threshold for frosting by mechanical means (Kuenen and Perdok, 1962). Both frosting and unfrosting of detrital quartz grains has been shown to occur in place owing mainly to chemical action (Kuenen and Perdok, 1962). Consequently, the presence or absence of abundant frosted quartz grains is not a valid criterion for concluding the presence or absence of eolian sand.

Preferential sorting by frost action in the near-surface materials might produce the concentration of silt-sized particles above the sticky till (Corte, 1963). Whether frost action could be responsible for the entire thickness of the silt-rich zone (1–1.5 ft) is open to question.

Correlation of the till of the Lands End Formation is in doubt. It is difficult to date the period of glaciation through comparisons with other described and dated glacial sequences in the Rocky Mountains because of differences in lithologic content of tills, elevation, exposure, latitude, physiography, and climate. Although Retzer (1954) labeled the till as "doubtless of pre-Wisconsin" age because of its most westerly position on the mesa, the subdued topography of the till surface, and the advanced subsoil development, I doubt that the till is that old. The high-clay content of the till cannot be taken as evidence for an old age of this deposit, for much of the clay was probably inherited from an earlier soil. The till surface is poorly drained; streams have breached the moraines in places, but undrained depressions are common. Accounting for the effects of local factors, the loess mantle and the soil development are similar to those on till of the Placer Creek Formation in the La Sal Mountains, inferred to be of Bull Lake age (Richmond, 1962, 1960, 1948).

Aberrant quartz-rich cobbles and pebbles on Grand Mesa

On the west end of the mesa within and on the glacial deposits of the Lands End Formation are a few well-rounded quartz-rich cobbles and pebbles resembling remnant-stream gravels. Locations where the gravels are in greatest concentration are shown on the geologic map of the Lands End quadrangle. Quartzite, quartz, chert, granite, arkose, and petrified wood occur in this suite of aberrant rock types. The pebbles and cobbles are well rounded and frequently occur as "broken rounds." The chert fragments are commonly angular and show some polish and solution texture. The cobbles are commonly 1–2 inches in diameter, but some as much as 5 inches are found. The cobbles and pebbles seem to be concentrated along a northeast-trending preglacial stream valley extending completely across the present surface of Grand Mesa several miles south of the FAA station. The small valley, 200–300 feet wide and 30–60 feet deep, is cut in the basalt and contains a thin veneer of till. Whitewater Creek currently heads in this old stream valley. The close association of the isolated gravels with the shallow preglacial stream valley suggests that they are related. Glaciation has not appreciably disturbed the old river cobbles and pebbles. Ice did pick up a few of the rocks and moved them farther to the northwest on the mesa surface.

The lithologies of the gravels suggest that a preglacial river, possibly an ancestor of the Colorado or a tributary to it, brought the cobbles from the White River Uplift or the Elk Mountains 50–80 miles to the east. These high-level gravels may then represent remnants of old Colorado River alluvium deposited when the Colorado was flowing on a gently sloping basalt plateau that was much more extensive than the remnants on Grand and Battlement Mesas. The Colorado River is now about 5,000 feet below the surface of Grand Mesa. It cuts across many major structures and resistant beds, which indicates that the position of much of the Colorado River valley is a result of superposition. If, in fact, the Colorado at one time flowed across the Uncompahgre Plateau through Unaweep Canyon (Lohman, 1961), then the Colorado was even more discordant with the underlying structure than it is now, as it flows in the soft Mancos Shale around the north end of the Uncompahgre Uplift. The preglacial drainageway on Grand Mesa, along which the high-level gravels are concentrated, lines up closely with the trend of Unaweep Canyon. This fact seems to lend support to the hypotheses that the Colorado River may have flowed through Unaweep Canyon, and that it was superposed upon the Uncompahgre structure from a capping of virtually flat-lying basalts (Hunt, 1956).

The channel preserved on Grand Mesa was probably abandoned soon after downcutting began in favor of a position farther to the northwest. The time of uplift has been suggested as Pliocene or early Pleistocene (Lohman, 1961). The gravels might have been originally deposited on the mesa in the Pliocene. All that can be said with assurance is that the gravels were originally deposited after the eruption of the basalt (early Pliocene) and before the deposition of till of the Lands End Formation (Bull Lake? time).

TERRACE AND FAN GRAVEL

Alluvial deposits of the Lands End Formation are divisible into four categories: (1) thin poorly sorted fan gravel with some probable mudflow debris that mantles the extensive pre-Bull Lake(?) terraces and fans such as Holms and Morrisania Mesas north and northwest of Battlement Mesa; (2) thick alluvial fan gravel at the mouths of several Colorado River tributaries in the western part of the area; (3) remnants of Colorado River terrace gravel rich in crystalline rocks northeast and southwest of the town of De Beque; and (4) outwash gravel in Plateau Creek buried by younger till and outwash of the Grand Mesa Formation.

The gravels capping Holms and Morrisania Mesas are about 20–40 feet thick and display poor sorting and crude bedding. Subangular to subrounded boulders of basalt and locally derived sedimentary rocks are common. The matrix is mostly grayish-brown coarse sand. These gravels are probably of both alluvial fan and mudflow origin.

The remnant terraces preserved along the Colorado River in the De Beque quadrangle are rich in nonlocally derived crystalline rocks and lesser amounts of basalt and locally derived sedimentary rocks. The terrace deposits commonly contain well-rounded cobbles, 2–5 inches in diameter, in a coarse sand matrix. The terraces vary from 140 to 300 feet above the Colorado River. The thickness is variable, but 50–100 feet of gravel is not uncommon.

No outwash terraces are mapped along Plateau Creek, as they have been buried by subsequent till and outwash of the Grand Mesa Formation. A poorly preserved buried soil on gravel representing probable outwash of the Lands End Formation was noted at only one locality. Some of the outwash gravel that has been mapped as terrace gravel of the Grand Mesa Formation may actually be outwash of the Lands End Formation. Lithologically and texturally the two deposits are indistinguishable. Soil development, generally greater on the deposits of the Lands End Formation, has been complicated and modified by extensive irrigation. Hay is grown extensively on these terraces along Plateau Creek. Much of the fill of outwash, which attains a thickness in excess of 200 feet within Plateau Creek valley, is probably related to the Lands End Formation. Buried soils, although common within the till sequence in the major tributaries of Plateau Creek, have been removed from the outwash gravel deposits, apparently by the subsequent glacial melt waters.

In general, soils developed on the gravels of the Lands End Formation resemble those developed on the till at the lower elevations (section 4); cultivation and eolian activity, however, have altered the soils in places.

Discussion.—Gravels of the Lands End Formation were deposited on older surfaces above the Colorado River valley, and in like manner, younger mudflows and fan gravels of the Grand Mesa Formation have been deposited on benches above the main drainage. On Taughenbaugh Mesa, they completely bury the older gravels. Although it appears that there has been a great deal of downcutting (600 ft) since the deposition of the gravel of the Lands End Formation on Holms, Morrisania, and Taughenbaugh Mesas, it must be realized that the surfaces of these mesas were perched above the Colorado River base level during deposition of the fan gravel. Streams that deposited the fan gravel of the Lands End Formation flowed on the mesa surfaces and inherited the older gradients. The fan gravel of Lands End age that spilled into the Colorado River valley and onto its flood plain has been destroyed by subsequent river erosion and mass wasting. The younger fan and mudflow debris of the Grand Mesa Formation, on the other hand, can be observed in numerous localities (Grand Valley and Rulison quadrangles) where it transects the Lands End Formation—overlying it on the mesa surfaces, cutting through it at the mesa margins, and lying below it in the Colorado River valley.

It is doubtful that any of the gravel derived from Battlement Mesa is glacial outwash. Till of the Lands End Formation was not found on Battlement Mesa, which indicates that the mesa did not support glaciers during Lands End time. The wetter conditions associated with the glaciation documented on Grand Mesa provided sufficient runoff for the development of mudflows and fan debris peripheral to Battlement Mesa but insufficient for appreciable downcutting.

These gravels are probably of Bull Lake(?) age because of their topographic position with respect to the present streams and younger gravel terraces. The soil development, where preserved, is similar to that on other Bull Lake gravels in the Rocky Mountains.

PINEDALE(?) DEPOSITS

GRAND MESA FORMATION

The name Grand Mesa Formation (Yeend, 1966) is applied to glacial, alluvial, and colluvial deposits on the prominent lava-capped plateau called Grand Mesa. The formation includes two tills, three levels of terrace gravel, pediment gravel, mudflow deposits, and fan gravel. The type section is exposed where the Lands End road cuts through the terminal moraine of the lower till member on the top of Grand Mesa. The till rests on basalt of Pliocene age, and east of Grand Mesa it is locally overlain by the upper till member of the Grand Mesa Formation. A description of the type section follows.

5. *Type section of the Grand Mesa Formation; till facies exposed in roadcut through terminal moraine on the surface of Grand Mesa, in the SW¼ sec. 3, T. 12 S., R. 96 W., Skyway quadrangle*

Topography: Hummocky surface with many undrained depressions; slopes as much as 22°.
Elevation: 10,440 ft.
Vegetation: Scattered spruce and open grassy meadows.

Lower till member:	*Thickness (feet)*
Soil horizon A:	
Brown to dark-brown (7.5*YR* 4/2) gravelly silt loam:	
Structure: Weak, granular.	
Reaction: pH 6.5–7.0.	
Boundary: Gradational	1. 2
Soil horizon B:	
Moderate-yellowish-brown (10*YR* 4/4) gravelly silt loam:	
Coarse material: 30 percent.	
Matrix: 70 percent.	
Structure: Weak, granular.	
Consistency: Nonsticky.	
Cementation: Poor.	
Reaction: pH 6.0–6.5.	
Boundary: Sharp	1. 6

5. *Type section of the Grand Mesa Formation; till facies exposed in roadcut through terminal moraine on the surface of Grand Mesa, in the SW¼ sec. 3, T. 12 S., R. 96 W., Skyway quadrangle*—Continued

Lower till member—Continued	*Thickness (feet)*
Fresh till:	
Moderate-brown to olive-gray (5*YR* 3.5/4–5*YR* 3/1) gravelly silt loam, unsorted, unweathered.	
Coarse material: 50 percent.	
Matrix: 50 percent.	
Fabric: See fabric plots, p. 41.	
Bottom of roadcut	3. 2

Remarks: The A and B horizons and parent material (till) are often mixed and difficult to differentiate.

LOWER TILL MEMBER

In the southern half of the area, one of the most widespread Quaternary deposits is the lower till member of the Grand Mesa Formation. It is present on the east half of Grand Mesa, on the landslide bench to the north, east, and south of the mesa, and within most of the larger stream valleys draining the north slope of Grand Mesa. In the extreme eastern part of the area, this lower till member is concealed by the upper till member.

The till surface on Grand Mesa is hummocky and stoss and lee topography is common. Boulders showing little weathering are strewn on the till and the glaciated bedrock surface. Small drainageways have been choked with till and postglacial peat deposits. Striated and grooved basalt surfaces protrude through the thin veneer of till. Although the original glacial polish has been almost completely removed, the deep ice-produced grooves in the basalt are evident at many localities.

A prominent hummocky terminal moraine of the lower till member, containing many undrained depressions, extends in a north-south direction across the middle of Grand Mesa (fig. 8). The moraine is 20–40 feet high and 500–1,000 feet wide. It is traceable down off the basalt surface into Kahnah Creek and then back up on the surface again onto the Flowing Park lobe of Grand Mesa (fig. 12). The moraine is about 150 feet high where Kahnah Creek cuts across it. North of Grand Mesa this terminal moraine is not traceable across the landslide bench or south of the Flowing Park lobe. In the Kahnah Creek embayment a remnant of a recessional moraine of the lower till member is several hundred feet behind the terminal moraine.

The fact that the terminal moraine on the mesa can be traced into Kahnah Creek and again up on the mesa negates the possibility of eroding more than half a mile of the Kahnah Creek embayment after glaciation, as was previously thought (Retzer, 1954). Had the terminal moraine been truncated at the edges of the basalt

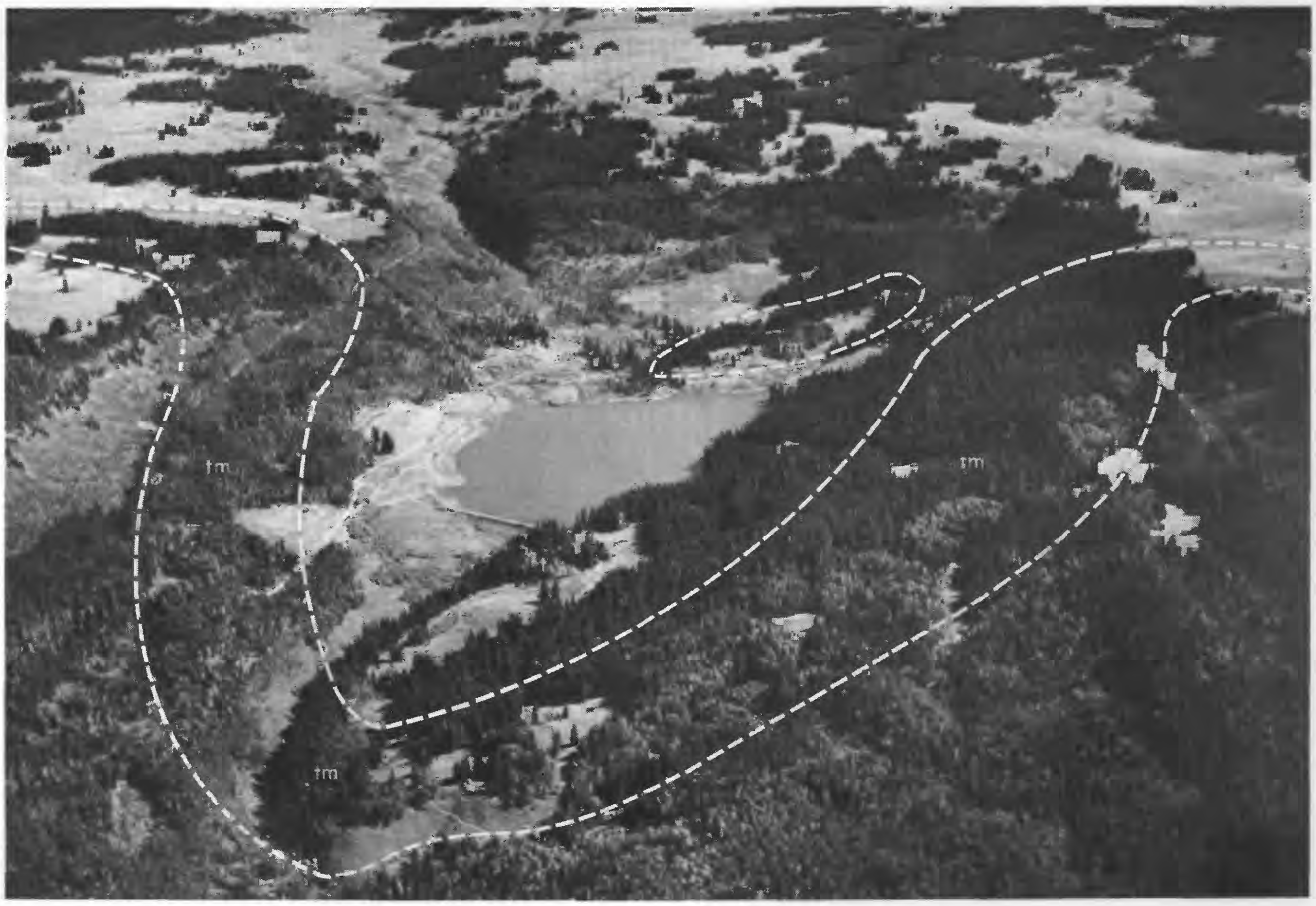

FIGURE 12.—Aerial view northeast over the Kahnah Creek embayment and Carson Reservoir. The terminal moraine (tm) left by the Grand Mesa ice can be traced from the main part of Grand Mesa on the left down into the embayment and up onto the Flowing Park Lobe of the mesa on the right. A recessional moriane (rm) produced by a withdrawal of the ice sheet in Grand Mesa time is behind Carson Reservoir.

cliff, it would have been necessary to postulate the postglacial erosion of the terminal moraine and the mesa in the intervening area as well as a significant part of the mesa east of the moraine now occupied by the embayment. The ice was able to move farther west in the embayment because of the increased gradient of the ground surface and the increased supply of ice channeled into the Kahnah Creek valley.

The topography of the glaciated landslide bench is dominated by a multitude of lakes, manmade reservoirs, and ridges and valleys produced by the older slump blocks. Till of the Grand Mesa Formation is restricted to the troughs between the slumps. Ice moving at right angles to the long dimensions of the slumps scraped over the tops of the blocks and produced grooves and striations in the hard basalt. A few of these striated surfaces are still present on the crests of the large blocks near Grand Mesa.

Between the major drainages north of this rugged slumped topography are wide, open, rolling slopes carved on the Green River Formation. These fairly level surfaces were glaciated and are mantled by a layer of till. The outer margin of the till on these divides is difficult to map because terminal moraines were not found.

Most of the cap ice was channeled into the major north-flowing drainages (Mesa, Bull, Cottonwood, Big, Grove, and Leon Creeks). A few end moraines were formed in some of the narrow stream valleys, but most of the till plains in the lower parts of the valleys grade into the outwash plains without a topographic break (frontispiece). The wide valleys of Mesa, Bull, and Big Creeks, from 1 to 2 miles wide in their lower reaches, allowed the ice to spread out laterally, and debris at the ice margin was wasted away, leaving behind no semblance of moraines (fig. 13). Remnants of

FIGURE 13.—View south over the till plain (tp) in the Mesa Creek drainage. Grand Mesa is on the skyline. Arrows show direction of ice movement as it flowed off the landslide bench into the Mesa Creek valley. Outwash deposits (od) are marginal to the till plain on the west.

lateral moraines are in Bull Creek above 7,500 feet, and recessional and lateral moraines are in Cottonwood Creek as low as 6,600 feet. Remnants of a recessional moraine are northeast of the town of Collbran near Buzzard Creek. This moraine is at an elevation of 6,300 feet. It is difficult to map the boundary of the till and the associated outwash deposits because no terminal moraines are present in any of the drainages. This boundary was generally placed between the lowest downvalley exposure of unsorted angular basalt-rich unconsolidated material and the highest upvalley exposure of sorted rounded basalt-rich gravel. Most of the till plains do not extend all the way to Plateau Creek. The till in Cottonwood Creek is an exception, however (fig. 14). Long, narrow finger ridges of till are present on the till plain in the Mesa and Bull Creek drainages. These ridges may be till deposits that have moved downslope under the influence of gravity subsequent to their original deposition from the ice.

The surfaces of the smooth sloping till plains are bouldery in most of the drainages at the lower elevations except where they are cultivated. The till is thin, generally less than 20 feet, and commonly rests on older till of the Lands End Formation (section 4, p. 16). Gradients of 200–400 feet per mile characterize the till surfaces at the lower elevations. Streams have incised the superposed tills to depths of 100–200 feet. Till is found at a minimum elevation of 5,400 feet in a gravel pit on the north side of Plateau Creek near Jerry Gulch. This till is overlain and underlain by outwash deposits. The lack of a buried soil zone at this locality makes it difficult to distinguish whether this till belongs to the Grand Mesa or to the Lands End Formation.

On the basis of composition and textural characteristics, the Grand Mesa till seems to differ from the older till of the Lands End Formation in the following ways:

1. The till of the Grand Mesa Formation does not feel sticky and only rarely swells on the addition of water, because expandable clay minerals are scarce.

FIGURE 14.—Till plain (tp) at the mouth of Cottonwood Creek. View southwest over Plateau Creek.

2. The till of the Grand Mesa Formation contains a higher percentage of unweathered basalt detritus.
3. The matrix of the Grand Mesa till appears to be more variable in grain size than the Lands End till. Size analyses of 12 samples reveals the following ranges:

	Range, in percent
Sand	26–41
Silt	22–70
Clay	3–39

4. The triangular diagrams (fig. 9), which show the sand, silt, and clay ratios for selected samples of the two tills, indicate that the till of the Grand Mesa Formation is siltier and sandier, and contains less clay than does the till of the Lands End Formation. The average values of silt, sand, and clay for all the samples collected, tabulated in table 3 below, support this assertion.

TABLE 3.—*Average values, in percent, of samples of sand, silt, and clay-sized particles in the C and B horizons of tills of the Grand Mesa and Lands End Formations*

[All samples were collected above 9,500 ft]

Till	Grand Mesa Formation (12 samples)		Lands End Formation (10 samples)	
	C horizon	B horizon	C horizon	B horizon
Sand	35. 5	36. 0	27. 2	27. 7
Silt	45. 6	50. 0	35. 5	51. 6
Clay	18. 7	14. 0	37. 3	20. 9

From the preceding table it is apparent that there is little difference in the size breakdown of the C and B horizons of the till of the Grand Mesa Formation. This may mean that there has been little physical or chemical weathering of the till or that little loess and sand has been deposited on the Grand Mesa till. The Cca development is completely absent at the high elevations.

The till in the valleys is similar to that at high elevations except for the weathering profile and the proportion of sedimentary rock detritus to basalt detritus. The presence of sedimentary rocks as a source for the till at the lower elevation has caused the matrix of the till to be very rich in sand- and silt-sized particles, most of which are quartz. The till is light gray, much lighter than the till on the mesa surface, which evidently reflects the presence of light-colored sediments as well as increased calcium carbonate concentration. The coarse material in the low-altitude till is more than 90 percent basalt fragments, mostly unweathered.

Fabric studies of the till of the Grand Mesa Formation and younger landslide deposits were made at 10 localities. Results and conclusions of these studies will be presented in a subsequent chapter.

Discussion.—The recognition of widespread till deposits at low elevations (below 7,000 ft) within the Grand Mesa area might be justly questioned, realizing that such low-level occurrences of till are rare in this part of the Rocky Mountains (table 4). This is especially true for the Pinedale Glaciation as recognized elsewhere. Evidence supporting the assertion that these low-level, unsorted surficial deposits in the Grand Mesa area are in fact till is summarized:

1. Deposits are characterized by complete lack of sorting with abundant angular to subangular, coarse detritus—internal characteristics which are typical of tills.
2. The abundance of large basalt boulders (>10 ft in diameter) 10 miles or more from a basalt source implies a very competent transporting agent such as ice.
3. Grooves and striations are present on a few large basalt boulders.
4. Topographic features resembling glacial moraines are as low as 6,300 feet in elevation.
5. Some modern glaciers lack end moraines, for at the margin of some of the present Alaskan glaciers on the south side of the Alaska Range (for example, Capps and Kahiltna Glaciers) the wide flat moderately steep surfaces grade into water-washed (outwash) plains.
6. The unsorted material at the low elevation is physically continuous with what is undoubtedly till above 10,000 feet on the landslide bench surrounding Grand Mesa.
7. Finally, and perhaps most conclusively, the fabric of the deposits shows a majority of linear fragments inclined uphill (up-ice), similar to known till fabrics and distinctly different from the predominant downhill dip of the fragments in mudflows and other landslide deposits (see p. 41).

The absence of terminal moraines in the valley bottoms is understandable (as mentioned in No. 5) when it is realized that gradients in all the valleys, even in their lower extents, are steep. The author has seen numerous large debris-chocked glaciers on the south slope of the Alaska Range with no terminal moraines. Active glaciers in New Zealand that are not depositing terminal moraines have also been reported (Speight, 1940). Abundant melt water on the associated steep gradients probably washed away rock debris from the ice as rapidly as it was released.

Once established that these are probably low-level tills, the question immediately asked is: Why is there such a low-level occurrence of till in the Grand Mesa area, and what conditions allowed the movement of ice to these very low elevations? Several factors probably contributed, but perhaps the most significant is the unusual topographic situation of Grand Mesa and the surrounding uplands as compared to the other mountain areas in the Southern Rockies. Grand Mesa and the surrounding landslide bench offered a tremendous collecting area for snow and ice buildup during times of glacial activity. The following table gives comparative land areas above 10,000 feet for Grand Mesa and several surrounding isolated glaciated mountain ranges. The average elevation that the ice termini reached during the various glacial stages in the individual areas is also given (table 4).

TABLE 4.—*Minimum elevations of Quaternary ice lobes and measured land area above 10,000 feet for selected mountain localities in Colorado and Utah*

Location and latitude	Minimum ice lobe elevations as based on the lower limit of till (feet)			Approximate land area above 10,000 feet (square miles)
Little Cottonwood and Bells Canyons, Wasatch Mountains, Utah (Richmond, 1964a); 40°35′ N.	Bull Lake Glaciation, 4,920–5,100	Pinedale Glaciation		42
		Lower till, 5,680–6,600	Upper till, 6,560–9,640	
Grand Mesa area; 39°05′ N.	Till of the Lands End Formation, 5,700(?)	Grand Mesa Formation		284
		Lower till member, 5,400	Upper till member, 8,500	
Boulder Mountain, Utah (Flint and Denny, 1958); 38°07′ N.	Carcass Creek Drift, 6,600	Donkey Creek Drift, 8,000	Blind Lake Drift, 9,400	120
La Sal Mountains, Utah (Richmond, 1962); 38°30′ N.	Till of the Placer Creek Formation, 9,230–9,670	Beaver Basin Formation		40
		Lower till, 10,270	Upper till, 10,630	
Battlement Mesa; 39°23′ N.	No evidence of glaciation			34

The Wasatch Mountains north and west of the other mountain systems is in a position to receive significantly greater amounts of precipitation from the Pacific Ocean winter storms and suffer less ablation during the summer. Therefore, despite the relatively small, high accumulating area (42 sq mi above 10,000 ft) of the Wasatch mountains, glaciers were able to extend down as low as 5,000 feet during the late Pleistocene.

The evidence from these few areas, except for the Wasatch Mountains, seems to indicate a relation between the size of the land area above 10,000 feet and the lowest elevation to which ice lobes descended. Although both the La Sal Mountains and Boulder Mountain would experience greater amounts of ablation than Grand Mesa because they are farther south, they are also farther west and would receive more winter precipitation from the west. It is interesting to note that no evidences of glaciation have been found on Battlement Mesa, roughly 30 miles north of Grand Mesa. Its small areal extent above 10,000 feet (34 sq mi) would seem to have been below the critical size necessary for the initiation of glaciation at this particular latitude.

Perhaps as important as the mere areal size is the topography of the accumulation zone. Grand Mesa and the surrounding landslide bench are not characterized by typical mountain topography with individual separated drainage basins and high-level cirques. Rather, almost all of the area above 10,000 feet in the Grand Mesa region is either of plateau- or modified plateau-type topography with no part greatly separated in elevation from any other part. Consequently, instead of experiencing the typical mountain-type glaciation, where ice collects in cirques and valleys and each cirque supplies the individual drainage with ice, Grand Mesa possessed an icecap. Probably, permanent snow first accumulated around the base of the mesa in the protected areas between the slump blocks on the landslide bench, as snowbanks do now. The buildup of ice on the landslide bench eventually covered the slump blocks and the mesa as well, covering the surface to a minimum depth of 150 feet. The presence of striations on the mesa surface implies a minimum of 150 feet of ice to start glacier movement (Demorest, 1938). With this tremendous collecting ground feeding all the peripheral valleys, a favorable situation was created for the development of long ice tongues flowing far out into the surrounding lowlands. The steep gradients of the valleys aided the rapid flowage of ice from the highlands to the lowlands. Even then the valleys could not handle all the ice supplied from the icecap, and the glaciers rode out on the stream divides leading away from the landslide bench. Within the valleys that were deep and narrow, as were Cottonwood, Leon, and Buzzard Creeks, the ice was better channeled and extended farther than it did in the wide valleys of Mesa and Bull Creeks.

The lower till of the Grand Mesa Formation is believed to be correlative with the type lower and middle Pinedale tills, on the basis of following criteria:

1. Glacial topography on the mesa surface is very fresh with abundant undrained depressions and steep slopes within the terminal moraine.
2. Grooves and striations on the basalt are evident in many places on the mesa surface, indicating little weathering and erosion since the melting of the ice sheet that formed them.
3. Soil profiles are weak and immature.
4. Dissection of the till plains in the lower valleys has been slight.
5. Basalt detritus in the till at all elevations shows little weathering.

UPPER TILL MEMBER

The type locality of the upper till member of the Grand Mesa Formation is the open, parklike area west of Trickle Park Lake (fig. 15). Here, the till is characterized by very hummocky topography with undrained depressions and steep bouldery slopes. The till rests on the lower till member of the Grand Mesa Formation and is locally overlain by colluvium and alluvium. Abundant grayish-green and red siltstones and sandstones, exposed by virtue of the earlier landslide and glacial activity, dominate the lithology of the till. Fresh basalt boulders and cobbles are common throughout the deposit. Size analyses of the till matrix (five samples) give the following percentages: 46 percent sand, 45 percent silt, and 9 percent clay. Soil formation on the till is restricted to an organic-rich A horizon and a very subdued color B horizon.

The upper till member is exposed in most of the major drainages northeast and south of Grand Mesa. Although several low, arcuate, recessional moraines were observed, there are no terminal moraines. The lowest occurrence of this till is at an elevation of 8,500 feet.

Ridges of bouldery till are common on the divide between Leon Creek and West Leroux Creek and in Trickle Park (fig. 15). Slopes of 35° occur on these short, locally sinuous ridges. The mapping of the ridge complex on the divide between Mesa and Bull Creeks revealed no particular pattern in relation to topography, bedrock, or inferred ice margins. These narrow steep-sided bouldery ridges are interpreted as crevasse-fill deposits associated with ice stagnation. This interpretation best explains the irregular pattern of the

FIGURE 15.—Crevasse-fill deposits of the upper till member of the Grand Mesa Formation west of Trickle Park Lake. Elevation 10,000 feet.

ridge complexes. They cannot be adequately explained as moraines related to some position of the ice margin, because they lack any pattern that would suggest such a relation. Similarly, they cannot be explained as eskers, because they lack length and interconnection and the particles making up the ridges are not sorted or rounded.

Because the till is restricted to the landslide bench where bedrock exposures are rare, no striated and grooved bedrock surfaces were found. Striated basalt boulders, however, are common. The thickness of the till may range from 10 to 100 feet.

Ice of this glaciation probably represented little more than the final gasp, or ice-stagnation phase during Grand Mesa time. For this reason it was deemed desirable to map the till as a separate member of the Grand Mesa Formation. The till and crevasse fills are generally distinguishable from older, more widespread till on the basis of topographic sharpness. Lithologically, it is impossible to differentiate the two tills, and the weakly developed soils present on both tills are not a distinguishing feature.

ICE EXTENT DURING GRAND MESA TIME

Striation directions were measured on much of the present surface of Grand Mesa and surrounding landslide bench. The data were plotted to show ice movements and accumulation centers (pl. 1). The ice-movement indicators suggest that the ice flowed away from a center roughly equivalent to the highest part of the mesa. This is a low rise less than half a mile south of the paved road that goes over the top of the mesa ($S\frac{1}{2}$ sec. 8, T. 12 S., R. 95 W.). Despite the absence of glacially produced grooves and striations on the landslide

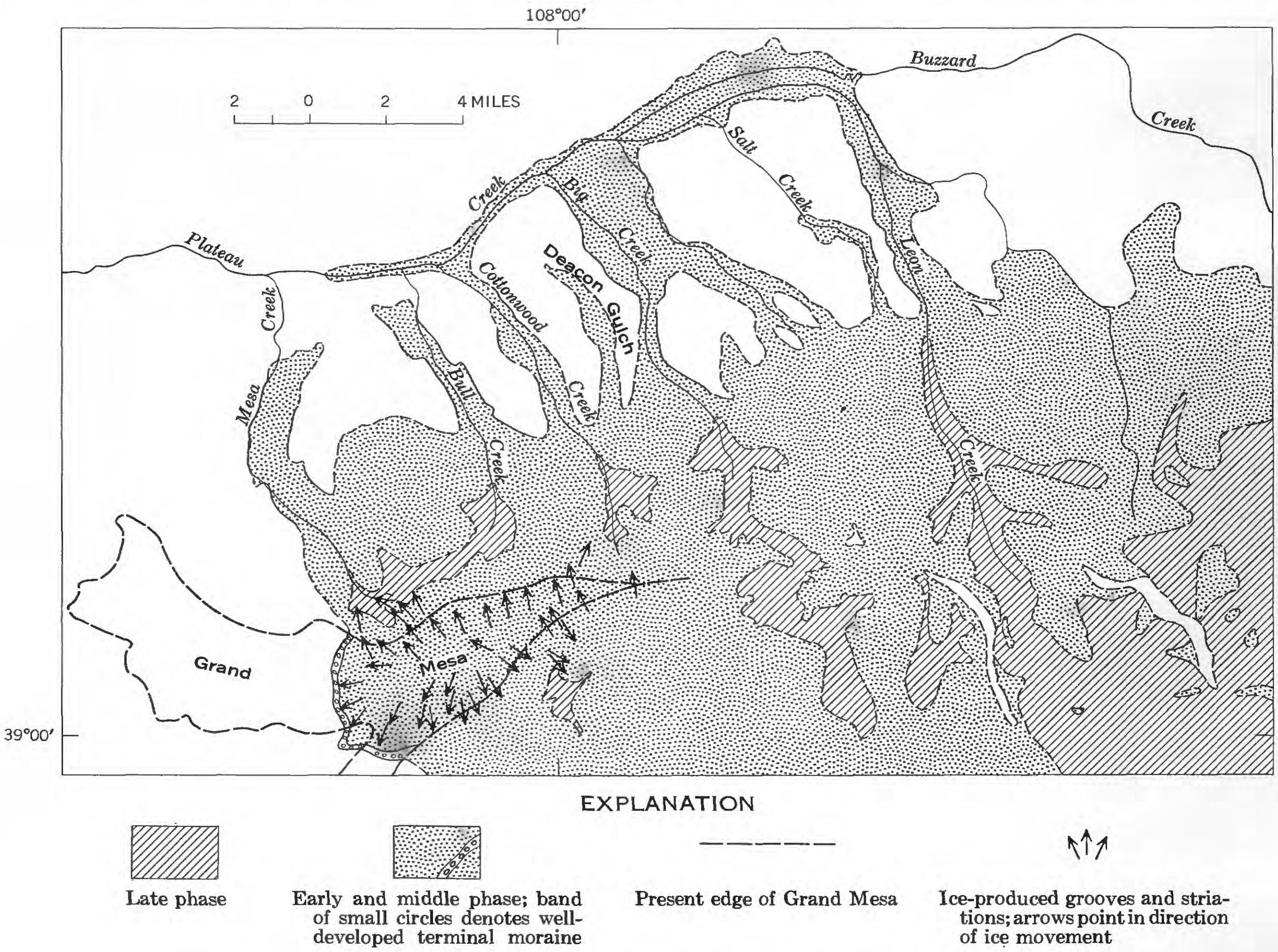

FIGURE 16.—Map showing postulated maximum ice cover during Grand Mesa time.

bench east of Grand Mesa, it is probable that this area was the site of ice accumulation. The high, virtually flat areas of Sheep Flats and the Flat Tops, as well as the drainage heads of Leon, Willow, Cow, Leroux, and Marcott Creeks, appear to have been accumulation centers. Almost this entire upland east of Grand Mesa was covered with ice during deposition of the Grand Mesa Formation. A few of the high bedrock and slump-block ridges may have risen above the surface of the ice. Figure 16 shows the postulated maximum extent of the Grand Mesa ice sheet during Grand Mesa time.

A somewhat anomalous situation exists in the northwest corner of the Chalk Mountain quadrangle. In this otherwise extensively glaciated area, more than 10,000 feet in elevation, there exists a gently sloping, stream-dissected bedrock surface about 6 square miles in extent showing no effects of glaciation. Consequent northwest-flowing drainage has developed on this surface, and as much as 200 feet of dissection was noted. Evidences of glaciation are everywhere around this bedrock "inlier." Certainly, this "driftless area" must have been covered with ice during Grand Mesa time. It could be reasoned that this area is the position of the true ice center from which ice flowed radially outward. Consequently, a drift-free zone would remain upon melting of the ice.

The ice lobe in Leon Creek must have been the longest in the area. It dammed up Plateau and Buzzard Creeks and produced a fairly large lake extending up the Plateau Creek drainage, now the site of the Vega Reservoir, made a right-angle turn at the junction of Buzzard Creek, and met the thin sheet of ice coming down the wide Big Creek drainage in the vicinity of Collbran and Plateau City. It continued on down Plateau Creek, joined the fairly large ice tongue issuing from Cottonwood Creek, and finally stopped short of the Mesa Creek drainage. The total length of this tongue of ice was close to 20 miles.

The ice in Mesa and Bull Creeks did not quite reach Plateau Creek. In both drainages the ice was not confined, but was allowed to spread out over the wide valley floors. Also, the ice reached a lower warmer environment much sooner than did the ice in the drainages farther east; consequently, ablation was a limiting factor in the length of these ice tongues. The ice in the Big Creek drainage reached Plateau Creek, even though the ice tongue was more than 2 miles wide in its lower reaches. This was probably due to the fact that it had two major valleys contributing ice to it. However, ice flowing in this valley probably did not contribute much ice to the Plateau Creek ice tongue that was being fed from Leon Creek. The ice in Deacon Gulch did not reach far into the lowlands, as it was without any through drainage connection with the highland. Rather, it received ice from the divided between Cottonwood Creek and Mosquito Creek.

Although the mapping did not extend far beyond the landslide bench on the south, a cursory reconnaissance indicated that ice did not extend as far into the lowlands on the south as it did on the north. This is expected because of the increased amount of insolation on the south-facing slopes.

During late Pinedale(?) time the large ice sheet that had covered much of Grand Mesa melted back until only patches remained in the protected drainage heads high on the landslide bench. Much of the till was probably deposited from stagnant ice, although a slight readvance may have occurred. The lowest occurrence of the ice in late Pinedale(?) time was 8,500 feet. Ice was generally restricted to the drainages, although several drainages were connected by ice across divides. The divide separating Mesa and Bull Creeks, Big Creek and Trickle Park, Willow and Dike Creeks, and Leon and Leroux Creeks contained ice during this time. The most extensive ice cover during late Pinedale(?) time was in the eastern part of the area in the drainages of Leon, Leroux, Hubbard, and Cow Creeks (Leon Peak and Chalk Mountain quadrangles).

The Pinedale glaciers in most areas in the southern Rocky Mountains did not extend into the lowlands as far as did the Bull Lake glaciers (Richmond, 1962, 1965b; Flint and Denny, 1958). In the Grand Mesa area, although it appears from the geologic map that the Pinedale(?) Glaciation was more widespread than the Bull Lake(?) Glaciation and extended to a lower elevation, this may not be a valid conclusion. Buried till at the lower elevations lacking weathering profiles may be mistakenly mapped as Pinedale(?) till. Bull Lake(?) till perhaps originally extended farther down the Plateau Creek drainage than did the Pinedale(?) till. The Bull Lake(?) till would have occupied an increasingly narrow canyon, and it is doubtful that it would have survived heavy runoff and canyon widening and deepening during the melting of the later Pinedale glaciers.

OLDER AND MIDDLE TERRACE GRAVEL

Outwash terraces of the Grand Mesa Formation border much of the south side of State Highway 330 along Plateau Creek. They range in elevation above Plateau Creek from 50 feet in the downstream part of the creek to 200 feet in the vicinity of Collbran. The narrow isolated terrace northeast of Collbran, called the "Peninsula," is composed of these outwash gravels. Nonglacial gravel terraces are present in several drainages descending the south slope of Battlement Mesa. Isolated terrace remnants of the Grand Mesa Formation, averaging 100 feet above the Colorado River, are composed predominantly of crystalline rocks derived from outside the area. The floors of Wallace Creek, Spring Creek, and Pete and Bill Creek on the northwest side of Battlement Mesa are mantled with alluvial gravel of this age. Alluvial fans have been deposited at the mouths of these and other nearby streams. A buried black organic zone, 1–3 inches thick, with associated air-breathing snails, was found in a roadbank of one of these fans. The buried organic material gave a radiocarbon age of 19,730±500 years B.P. (U.S. Geol. Survey lab. No. W–2143). The land snails, identified by Dwight Taylor of the U.S. Geological Survey include:

Gastrocopta holzingeri (Sterki)
Pupilla blandi Morse
Vallonia gracilicosta Reinhardt
Discus cronkhitei (Newcomb)
Euconulus ?
Zonitoides arboreus (Say)
Oreohelix cf. *O. subrudis* Pfeiffer

Section 6 is a description of the terrace gravels at this locality.

6. *Section of alluvial fan gravel exposed in a roadcut on the east side of the Colorado River about 600 feet west of the mouth of Wallace Creek in the NW¼SW¼ sec. 34, T. 7 S., R. 96 W., Grand Valley 7½-minute quadrangle*

Topography: Northwest-sloping surface (2°).
Elevation: 5,060 ft.
Vegetation: Uncultivated; juniper, grass.

	Thickness (feet)
Grand Mesa Formation, fan gravel facies:	
Soil horizons A and B, weakly developed	1.0
Boulder-rich gravel, poorly sorted; well-rounded boulders of basalt common; mostly locally derived rock types present	10.0
Silt and sand, brown and grayish-green	3.0
Pebbles and cobbles, rounded; basalt and locally derived sedimentary rocks; few nonlocally derived crystalline rocks	3.0
Silt, red-brown with brownish-black organic zone in middle; this unit is not continuous on the outcrop, having been eroded out in places; fragments of altered wood moderately common; snails	0.1–0.6
Pebbly silt and clay; abundant snails	2.0

6. *Section of alluvial fan gravel exposed in a roadcut on the east side of the Colorado River about 600 feet west of the mouth of Wallace Creek in the NW¼SW¼ sec. 34, T. 7 S., R. 96 W., Grand Valley 7½-minute quadrangle*—Continued

	Thickness (feet)
Grand Mesa Formation—Continued	
Sandy silt alternating with pebbly layers; some snails in silty beds	2.0
Pebbly sand; pebbles predominantly sedimentary rocks	3.0
Clay-rich silt, brown and grayish-green; some snails	1.0
Cover	25.0
Colorado River.	
Average measured thickness	50.3

The outwash plains in Plateau Creek resemble the till plains and intertongue with the till deposits in numerous localities. As stated previously, it is difficult to map the precise contact between outwash and till. The terrace gradients are 50–100 feet per mile, similar to the present streams. The gravels are 100–200 feet thick near Plateau Creek, the site of the major outwash drainage channel during and following the last major glaciation. In the vicinity of the Colorado River the gravels commonly exceed 100 feet in thickness and are frequently mantled with 5–10 feet of reddish-brown fine sand and silt. The gravels are thin in and around the town of Mesa. The resistant bedrock below the gravels, conglomerate of the Ohio Creek Formation, acted as a barrier to earlier alluvial downcutting. Small inliers of the conglomerate are scattered throughout the thin gravel veneer.

Generally, the gravels are well sorted, except in the alluvial fans and where they grade into till in the Plateau Creek drainage. Rounded basalt boulders as much as 4 feet in diameter are common. Cut-and-fill structure is prevalent near Plateau Creek and is especially noticeable along paved Highway 65 where it ascends the terrace from the Plateau Creek flood plain. The roadcut shows a coarse boulder-rich gravel channeling into a fine-grained pebbly sand composed mostly of sedimentary rock fragments. Imbricate structure is common, and cobbles and boulders dip eastward (upstream) in the exposures near Plateau Creek. Basalt, commonly coated with calcium carbonate, is the dominant rock type in the gravels; however, sedimentary rocks, especially oil shale from the Green River Formation, are well represented. The matrix is sandy and generally makes up less than 30 percent of the deposit.

Weathering profiles vary from 1–3 feet thick, depending on extent of cultivation and irrigation of the terraces. Generally, the soils resemble those developed on the till of the Grand Mesa Formation at the lower elevations.

Two levels of terrace gravels, of which the older and higher is by far the more widespread, are included within this unit. The lower gravels, often well indurated by ground water, are commonly found along Plateau Creek as isolated exposures plastered on the valley sides. A few terraces, 30–60 feet below the higher terraces, flank the south side of Plateau Creek valley downstream from the town of Collbran. The lower gravels may record an intermediate stand of the ice marked by recessional moraines in some of the valleys.

The higher outwash gravels along Plateau Creek and its southern tributaries are clearly correlative with the till of the Grand Mesa Formation because the units are physically continuous. Streams draining the unglaciated slopes of Battlement Mesa contributed a smaller amount of gravel during Grand Mesa time.

YOUNGER TERRACE AND FAN GRAVEL

Outwash gravels and nonglacial alluvium deposited during or soon after the final melting of the ice máss in Grand Mesa time are present in the valleys of the major streams flowing north into Plateau Creek. This poorly sorted alluvial material is restricted to the narrow channels cut into the lower till member of the Grand Mesa Formation and into the alluvial plains. The gravel fill in the old channels is generally less than 150 feet wide and probably not more than 100 feet thick. The present streams have cut narrow valleys (10–50 ft deep) into these alluvial-fill and fan deposits. Poorly sorted alluvial-fan deposits are along the sides of Plateau Creek and the Colorado River were small tributaries empty into these major drainageways.

The most extensive occurrence of gravels of this age is along the Colorado River where low terraces locally merge with the Colorado River flood plain. The wide valleys occupied by Roan Creek northwest of De Beque and Parachute Creek northwest of Grand Valley are also partly filled with gravels of this age.

The gravels along the Colorado River are rich in well-rounded and well-sorted nonlocally derived crystalline rocks, whereas those in the tributary streams generally exhibit poor to moderate sorting, subrounded to rounded boulders and cobbles of locally derived basalt, and sedimentary rock detritus. As with the older gravels, these gravels are commonly covered with 5–10 feet of reddish-brown fine sand and silt. This fine-grained mantle may represent overbank flood-plain deposits.

The poorly sorted gravels in the Plateau Creek drainage, in large part outwash, contain basalt boulders as much as 4 feet in diameter. The matrix is light-brownish-gray to gray-brown silty sand. Coarse material makes up more than 50 percent of the deposit.

Soils are weak, characterized by a structureless horizon of loose sand generally less than a foot thick. The Cca horizon, when present, is less than a foot thick and often characterized by thin carbonate films on stones.

Discussion.—The final melting of the ice sheet in Grand Mesa time contributed considerable water for runoff throughout this area of the Rocky Mountains. The Colorado River flowed in a moderately wide valley, mantling its channel liberally with gravel. On the high north-facing slopes below Grand Mesa, melt-water streams with steep gradients eroded deep gorges in the older glacial deposits and underlying bedrock. Down-valley where the gradients decreased, much of the coarse load was deposited along the narrow stream channels and as fans where the streams emptied into the Plateau Creek Valley. Owing to a mudflow that diverted Big Creek above Plateau City, part of one of the old melt-water channels is preserved dry and virtually unchanged.

The alluvial deposits of this age represent the last period of major filling in the lower stream valleys. Since deglaciation, stream erosion seems to have been more dominant than stream deposition.

PEDIMENT GRAVEL

Low-level dissected pediment surfaces are common on the arid sparsely vegetated south-facing slopes. They occur in the northwest corner of the area at the base of the Roan Cliffs and at the foot of the south-facing slopes of Battlement Mesa. The pediments flanking Battlement Mesa extend more than 3 miles north from Plateau Creek before ending abruptly against the steep Wasatch slopes of Battlement Mesa (fig. 17). The surfaces have been dissected by recent gullying and possess steep banks supporting little vegetation. The pediments are capped with 5–40 feet of gravel and have gradients ranging from 150 to 200 feet per mile. Near Plateau Creek the thin pediment gravels, rich in sedimentary rocks, overlie and intertongue with the basalt-rich outwash gravels derived from Grand Mesa. As seen from several miles away, the pediment-gravel veneer shows as a thin cream-colored layer contrasting markedly with the underlying truncated Wasatch Formation.

The gravels are composed of angular to subrounded slabby pebbles and cobbles of sandstone, siltstone, and marlstone derived from the Wasatch and Green River Formations. Near the mountain front a few large boulders of basalt are on the pediment surfaces, but basalt detritus is generally rare. The soil is very immature and is often obscured by a layer of reddish-brown eolian silt.

In a single locality north of the town of Grand Valley, two pediment levels are mapped. The lower and more widespread pediment is 100–200 feet above the streams. The higher surface is about 300 feet above streams.

FIGURE 17.—Low-level pediments north of Plateau Creek adjacent to Battlement Mesa. View is northwest from till plain in Big Creek across Plateau Creek. Pediments are graded to the outwash terraces in Plateau Creek.

Discussion.—The pediments were probably formed during and immediately following the ice advance in Grand Mesa time. This is evidenced by the fact that the pediment gravels in the vicinity of Plateau Creek interfinger with and lie on the outwash gravels of the Grand Mesa Formation.

The contrasts in climate that exist in the area today probably existed during glacial times, although to a slightly lesser degree. During Grand Mesa time the area of pediment development, although probably not so arid as today, was relatively dry and certainly received less moisture than the glaciated areas.

MUDFLOW AND FAN GRAVEL

Mantling much of the high surfaces of Holms, Morrisania, and Taughenbaugh Mesas north of Battlement Mesa are poorly sorted basalt-rich gravels of the Grand Mesa Formation. These gravels were derived from Battlement Mesa, having been delivered to their present position as successive mudflows and by debris-clogged streams issuing from Battlement, Cache, Spruce, Porcupine, and Beaver Valleys. These gravels were deposited on older alluvial gravel of the Lands End Formation and on older pediment gravels. Buried soils are present beneath the mudflow deposits. The ends of some of the mudflows in the vicinity of Holms Mesa have been outlined on the map (Rulison quadrangle) to indicate successive flows overriding and eroding earlier flows. In most of the localities the gravels can be traced down to the edge of the present Colorado River flood plain.

Several pediments north of the Colorado River opposite Morrisania Mesa (Grand Valley and Rulison quadrangles) are mantled with this mudflow and fan debris. Sedimentary rocks predominate in these gravels.

The source for much of the gravels south of the Colorado River was solifluction deposits that cover most of the high portions of Battlement Mesa and extend into the major drainages. In both Battlement Creek and Cache Creek the mudflow debris merges upvalley with the solifluction mantle.

The gravels are extremely variable in thickness; the deposits range from several tens to several hundreds of feet thick. Angular to subangular basalt boulders are commonly less than 2 feet in diameter; however, boulders as much as 8 feet in diameter are present. The matrix is a light-gray silty sand. Natural levees occur along the lower stretches of Battlement and Cache Creeks. Soil development, as characteristic of deposits of the Grand Mesa Formation at the low elevations, is weak.

Discussion.—The probable wetter conditions associated with Grand Mesa time were most likely responsible for the development of these mudflows and fan deposits peripheral to Battlement Mesa. Glacial conditions did not exist on Battlement Mesa during Grand Mesa time, but there must have been abundant annual runoff, particularly on the north-facing slopes where evaporation was at a minimum.

SLUMP BLOCKS, TALUS, AND SOLIFLUCTION DEPOSITS, UNDIFFERENTIATED AS TO FORMATION

One of the most prominent topographic elements in the area is the landslide benches surrounding Battlement Mesa and most of Grand Mesa (fig. 18). This irregular chaotic surface of ridges and depressions varies in width from several hundred feet near the west end of Grand Mesa to more than 5 miles east of Grand Mesa. The topography is a result of a series of slump blocks, or "Toreva-blocks," (Reiche, 1937) rock and debris falls, rockslides, and solifluction movements that have occurred throughout the Pleistocene and are still continuing. Parallel to the present margins of the undisturbed basalt flows on Grand and Battlement Mesas are long, linear Toreva ridges and, at the base of the ridges, associated talus-block rubble. Figure 19 is a map of Grand and Battlement Mesas showing the associated landslide benches and the traces of the prominent slump ridges. Some unbroken blocks are more than 2 miles in length and are 500 feet high. The large basalt blocks have rotated as a unit and now dip as much as 50° back toward the mesas. The amount of rotation tends to increase with the distance from the mesa rims. The topographic prominence of the slumps, however, decreases outward from the mesas. They have experienced longer periods of weathering and erosion and, hence, show less topographic relief than those blocks near the mesas.

Crag Crest, the eastern knife-edged extension of Grand Mesa, is a mesa remnant left after extensive Toreva-block slumps on both the north and south sides of the mesa (fig. 20). Battlement Mesa has been almost completely destroyed by similar types of mass wasting and subsequent frost breakup of the blocks. It provides a clue to the probable fate of Grand Mesa (fig. 21), a few million years from now (based upon the 9-million-year age of the original basalt plateau).

Much of the material included in this mapped unit is made up of slump blocks. Much of the mass-wasted debris, however, has not undergone backward rotation and is more correctly termed "solifluction mantle" and "block rubble" or "talus." The solifluction deposits include soil, basalt boulders, and unconsolidated earth materials that moved downslope under the influence of gravity. Most of the slopes surrounding the areally restricted landslide bench on Battlement Mesa are covered with this solifluction mantle. It seems probable that contemporaneous with glaciation on Grand Mesa, solifluction activity was the dominant degradation agent on Battlement Mesa. These solifluction deposits extended down the steeper parts of the major drainage basins heading on Battlement Mesa (Rulison, Hawxhurst Creek, North Mamm Peak, and South Mamm Peak quadrangles).

The landslide bench produced by the Toreva-blocks surrounds most of the east, north, and south sides of Grand Mesa (fig. 19). The geologic map, however, shows the slump block and solifluction debris mapped in only a few localities surrounding the mesa. These few localities represent the slide areas not modified by subsequent glaciation. Generally, glacial modification has been slight and the landslide-ridge-and-depression topography, still dominant, shows itself vividly beneath the thin patchy veneer of till. Glacial striations were found on a few of the slump-block surfaces. Late glacial and postglacial frost action, however, has been responsible for the breakup of most of the original basalt surfaces of the blocks, and striations are difficult to find. Many of the lakes in the region just below the basalt surface of Grand Mesa are due to the disruption of the drainage by both the Toreva-block slumping and the subsequent glaciation.

CAUSES AND AGE OF SLIDES

The bedrock conditions responsible for the extensive development of these slides are moderately well understood. Underlying the basalt flows holding up Grand

FIGURE 18.—View west over the landslide bench (outlined) adjacent to Grand Mesa. Mesa Lakes are in the center of the picture on the landslide bench.

Mesa and possibly Battlement Mesa and overlying the Green River Formation is a sequence of claystone, conglomerate, and sandstone that is extremely variable in both thickness and lithology. A formal formation name has not as yet been assigned these rocks. A complete section has not been found, but a composite section can be constructed. Failure of the weak claystone underlying the basalt has caused nearly all the slumping and mass movement involving the overlying basalt flows. Recent roadcuts along the road to Mesa Lakes show that the claystone is highly deformed as a result of the mass movements. The claystone is currently sliding and flowing because of the removal of lateral support in the recent road excavations. The Green River Formation has not been observed in any of the massive slumps, which would seem to indicate that the Green River Formation has not been responsible for the slumps. The steep bedrock slopes surrounding the landslide bench are held up by the Green River Formation, and these slopes have not undergone much slumping. Figure 2 shows the bedrock and the topographic relations.

The causes for the widespread slumping and solifluction are compound. Certainly the stratigraphic situation of massive jointed basalt flows overlying weaker clayey beds is ideal for the development of slides. That the presence of the claystones underlying the basalt is instrumental in promoting the slides is indicated by the correlation of the increased slide development with the suspected increased thickness of the claystone section from west to east. The claystone section at the extreme west end of Grand Mesa is thin (<50 ft) and the landslide bench is correspondingly narrow (<200 ft). To the east the width of the landslide bench increases, as does the thickness of the claystone section. East of Crag Crest the original basalt surface has been almost completely destroyed, and there remains only a wide zone of slumped material including basalt rubble and disturbed outcrops of the claystone-rich section. It seems evident that the probable greater thickness of the

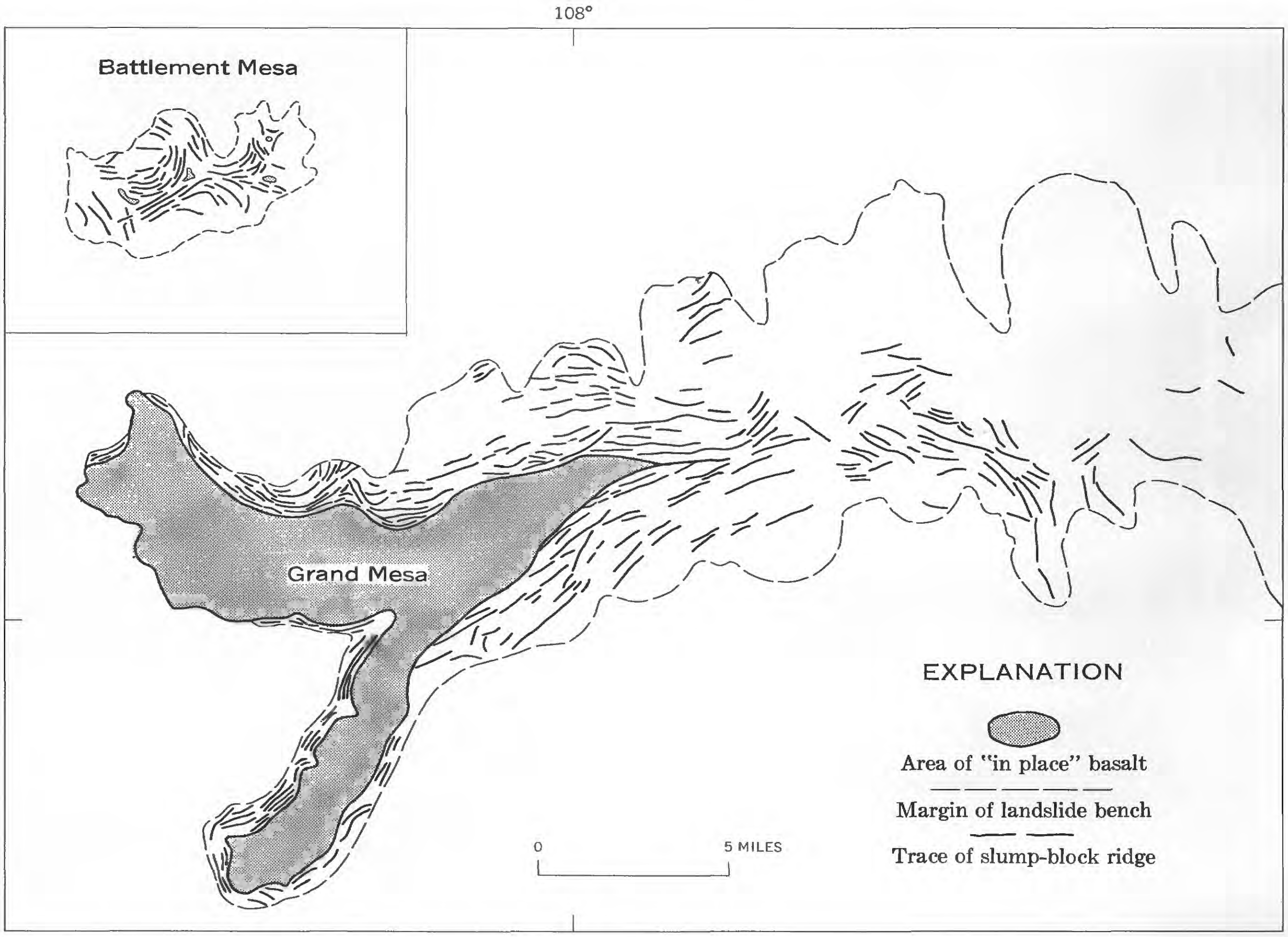

FIGURE 19.—Map showing landslide bench and trace of slump-block ridges on Grand and Battlement Mesas.

claystones in this region has been responsible for the early destruction of the east end of the basalt-capped mesa surface.

The jointed basalt, the presence of abundant water together with freezing temperatures, and lack of lateral support are other conditions prompting the development of the slumps. The joints developed within the basalt are ideal collecting areas for rainwater and snow. Subsequent freezing and thawing promote wedging and deepening of the joint fractures. Lubrication of bedding planes and the rise of pore-water pressure (Terzaghi, 1950) through the addition of large supplies of melt water would greatly weaken the internal shearing resistance of the claystone and result in eventual failure. The slump, by trapping water in its created depression, will often become self-perpetuating. Ice sapping and subsequent removal of ice support at the mesa sides following deglaciation would have caused an increase in the shearing stress and would have been an external cause in promoting the development of the slumps. Successive slumping would maintain the steep cliffs. The interaction of all these factors would seem to have contributed to resulting failure and extensive slumping.

The slumps probably move slowly at rates dependent upon supply of ground water and freezing temperatures. Tight, complex, small-amplitude folds in the claystones underlying the basalt suggest a fairly slow rate of deformation. Fracturing of the claystones would be expected if movement rates were rapid.

The age of many of the slumps is clearly older than the last glaciation of Grand Mesa. Fresh grooves and striations characteristic of the last glacial episode are found near the crests of some of the slump blocks. These striations, trending for the most part perpendicular to the axes of the slumps, are present on both sides of the blocks, indicating that ice moved up and over the block subsequent to, and possibly during, the slumping of the block to its present position. If striations were present on only one side of the slump block (the top as restored

FIGURE 20.—View west over Crag Crest and the surface of Grand Mesa. Slumped and glaciated topography borders the mesa on both the north and south. Talus is common at the base of the basalt cliffs.

to its original position), it could be interpreted, quite logically, that the striations had been developed when the block was still a permanent part of the mesa. The slumps would, of course, be postglacial features if this had been the case. The presence of undisturbed till of the Grand Mesa Formation in the valleys between the slump blocks further substantiates a preglacial age for the slumps. The advanced stage of decay of some of the slump blocks far removed from Grand Mesa indicates that they are older than the Lands End Formation. Much of the solifluction activity on Battlement Mesa probably occurred during and following the last glaciation. It is reasonable to suspect that slumping and solifluction activity associated with the removal of the once-widespread basalt flows has occurred throughout the Pleistocene. Consequently, this unit is indicated as having a wide range in age (pl. 1).

The modification of Grand Mesa by mass wasting has not ceased. Slumps in all stages of development are common along the edge of the mesa. A discussion of these recently developed features and estimated rates of movement will be subsequently presented in this report.

NATURE OF THE SLIP SURFACE

A concave-upward surface of movement with an axis of rotation parallel to the long dimension of the slump block, as in figure 22, is necessary to explain the rotation of the slumps. This surface is probably seldom a circular arc of uniform curvature because of the influence of bedding planes, flow contacts, joints, changes in lithology, and local structures. The fracture surface extends through the basalt into the underlying claystones, but it does not affect the underlying Green River Formation. Based on an average thickness of the basalt and claystones and the fact that the fractures in the basalt seem to be vertical near the surface, a radius of curvature of the slip surface could be as great as 600 feet. Where the combined thicknesses of the basalt and the claystones are greater than 600 feet, as they seem to be in the eastern part of the area, the radius of curvature of the slip surface would be correspondingly increased.

FIGURE 21.—The isolated basalt remnant of North Mamm Peak on Battlement Mesa. Toreva-block slides and frost breakup of the basalt have all but destroyed the original basalt surface.

POST-PINEDALE(?) DEPOSITS

ALLUVIAL, EOLIAN, AND LAKE FACIES

ALLUVIAL, EOLIAN, AND LAKE SAND, SILT, AND CLAY

Undrained depressions and blocked drainages on the surface of Grand Mesa are being filled with organic matter, alluvial silt and clay, and eolian sand and silt (fig. 23). The relief of these undrained areas is generally less than 30 feet.

North of Plateau Creek on the bedrock-defended slopes bordering Battlement Mesa on the south and west, alluvial and eolian fine sand and silt have accumulated to depths ranging from a foot to several tens of feet. Intermittent streams are cutting gullies into the fine-grained fills in many localities (fig. 24). It appears that the bedrock is being buried by its own weathering products. Vegetation is not abundant here because of the high evaporation and low water retention by the sand and silt. The soil is constantly being moved by both wind and water.

In the eastern part of the area numerous minor tributaries to Buzzard Creek are floored with fine sand and silt. These deposits have been locally incised by flash floods.

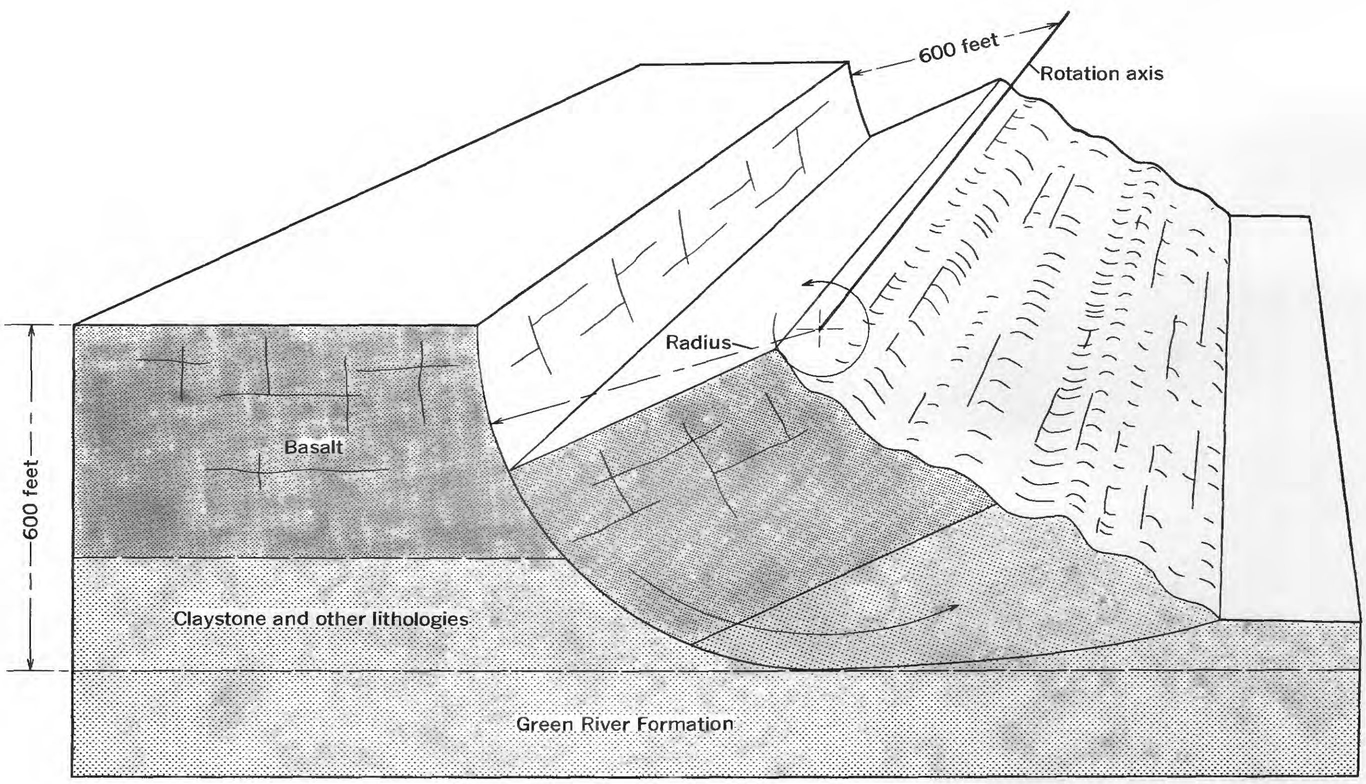

FIGURE 22.—Diagrammatic sketch of a typical slump block showing relation of slip surface to bedrock.

FIGURE 23.—Preglacial drainage of Kahnah Creek on surface of Grand Mesa. Drainage is now being filled with peat and fine-grained sediment. View east from paved road that goes over the top of the mesa.

Isolated depressions throughout the area contain fine sand to clay which are included within this unit.

In general, the material is well sorted and composed chiefly of sand- and silt-sized quartz. It is commonly reddish brown to yellowish brown. Soil development is rare. The material occasionally weathers to miniature badland topography.

Discussion.—The sand and silt probably began accumulating soon after the melting of the ice, and eolian processes became prominent in the transport and removal of loose sediment. The present conditions are conducive to removal, transport, and deposition of a certain amount of material. Wind is probably still accountable for much of the present movement of this fine detritus, especially in the more arid parts of the area. Intermittent streams are also responsible for the transportation and deposition of this fine material in the small drainages.

FIGURE 24.—View northeast from the De Beque Cutoff Road across a fill of eolian and alluvial sand and silt. Recent gully in foreground is cut into the fill.

LOW-TERRACE AND FLOOD-PLAIN DEPOSITS

The present flood plains of the Colorado River and its major tributary in the area, Plateau Creek, are composed of well-rounded and moderately well sorted gravel. Along the Colorado River this flood plain is in places as wide as and only very seldom wider than the meander belt of the river. It reaches a maximum width of 1 mile south of De Beque and narrows to 300 feet several miles above De Beque. Below De Beque the river flood plain merges with the older and slightly higher terrace of the Grand Mesa Formation. Where this occurs, it was not possible to map the contact between the two gravels (De Beque quadrangle).

The gradient of the Colorado River in the project area is about 11 feet per mile. The gravels are commonly composed of more than 50 percent nonlocally derived crystalline rocks. Where tributary streams empty into the river, locally derived basalt, sandstone, marlstone, oil shale, siltstone, and claystone are common in the floodplain gravels. A braided river pattern exists on the flood plain, and during times of high water, generally in the spring and early summer, channel changes are common.

Plateau Creek and a few of its major tributary streams possess narrow flood plains. Plateau Creek has entrenched its flood plain 5–10 feet in places. Above Windger Flats the flood plain averages 1,000 feet in width. Below Windger Flats entrenched meanders characterize Plateau Creek as it flows through the thick Mesaverde Formation. The flood plain there is less than 200 feet wide. The average gradient of Plateau Creek is about 40 feet per mile.

The gravels are composed of well-sorted and well-rounded basalt boulders and cobbles. The boulders rarely exceed 1 foot in diameter and are commonly 6 inches or less in diameter. About 10–20 percent of the boulders and cobbles are sedimentary rocks—sandstone, siltstone, and marlstone. The sandy matrix of the gravels is pinkish gray. A thin organic-rich silt, not everywhere present, is the only evidence of a soil zone on the flood plain.

During the summer months when cloudbursts are common, Plateau Creek transports abundant silt and sand and small pebbles and cobbles. Occasionally, the creek overflows its low banks and spills out on the flood plain, depositing a thin layer of mud and fine gravel.

COLLUVIAL FACIES

FROST RUBBLE, TALUS, AND ROCK GLACIERS (?)

Talus aprons surround the base of the basalt cliffs marking the present edge of Grand Mesa (fig. 19) and the isolated basalt remnants on Battlement Mesa (fig. 20). Angular to subangular blocks, 1–4 feet in diameter, are common in the deposits, and some blocks are as large as 20 feet across. Arcuate ridges of rubble resembling the ridges and furrows on rock glaciers characterize the topography of some of the deposits. The slope of the talus cones is commonly 30°–40° and in places 50°.

Many deposits of sliderock adjacent to slump blocks of basalt are too small in areal extent to be mapped at existing scales and are included in the slump-block deposits.

Discussion.—Frost wedging is thought to be the primary agent responsible for the development of these large blocks making up the talus and rubble. The well-jointed basalt, combined with the abundant moisture and numerous hard freezes and thaws as would have been prevalent during and following the last glaciation, would seem to have provided an ideal situation for the formation of the unconsolidated deposits.

Although many of the blocks are covered with moss and lichen and do not appear to have moved recently, some deposits show mounded rumpled soil at the leading downslope edges and give the impression of having moved recently (fig. 25). In other places, spruce trees growing on the talus indicate present stability of the deposits.

FIGURE 25.—Talus creep(?) near divide between Leroux Creek and Leon Creek drainages. Note disrupted soil at leading edge of talus field.

EARTHFLOW AND SOIL CREEP

Earth movements younger than the previously described slump blocks are widespread on the north- and west-facing slopes below Grand and Battlement Mesas. The earth movements are a combination of earthflow and soil creep that are almost exclusively restricted to areas underlain by the claystone-rich members of the Wasatch Formation. The abrupt slope change at the Green River-Wasatch contact generally marks the upper limit of the deposits.

The average slope on the earthflows is about 600 feet per mile. The surfaces are irregular and often crudely terraced with lobes, swales, and undrained depressions. Much of the area involved in the slides bordering Grand Mesa was initially covered with till. Contained in the earthflows are till, old soils, and the Wasatch Formation. The excavation for the South Side Irrigation Canal has opened many cuts across the earthflows. These cuts commonly show deformed bedding in the variegated claystones of the Wasatch Formation. A fabric is often discernible to the naked eye, showing that flat cobbles and pebbles dip gently downslope. A fabric study was made in a cut of the South Side Irrigation Canal. It shows (fig. 33, location 21) a preferred orientation with the pebbles dipping downslope. Basalt boulders as much as 5 feet in diameter, derived from till, and slabs of sandstone and siltstone 1 or 2 feet across are scattered on the surface. The matrix, although variable in color and grain size, is generally light green and is made up dominantly of claystone from the Wasatch Formation. Local water-washed sandy and silty deposits, in places crossbedded, are found. In some places the material resembles an unconsolidated flat-pebble conglomerate.

Material derived from old soils are involved in the mass movements. Soils developed on the earthflows are immature and are often absent where the slopes have undergone recent movement.

Discussion.—The terraced and crudely lobate topographic character of the deposit, together with the deformed bedding, suggests that the deposits were formed by slow earthflow and soil creep. Movement of these extensive slopes underlain by the weak Wasatch claystone has ceased, except for local occurrences of very recent slumps and mudflows that have been mapped separately. Most of the movement probably occurred when the climate was wetter than now and pore-water pressures within the shale and clay were high enough to decrease markedly the internal shearing resistence of the bedrock. During and following deposition of Grand Mesa Formation, when the talus and frost rubble were accumulating at higher elevations, the slopes underlain by the Wasatch Formation at the lower elevations were probably failing repeatedly by slow flowage of the water-saturated surface materials.

MUDFLOWS

The term "mudflow" as used here pertains to a rapid downslope movement, generally restricted to a channel, of rock, soil, and vegetation. The water content, perhaps as high as 50 percent, allows for the rapid flowage of material. A high clay content (40–50 percent) of the surficial material is not absolutely necessary for the initiation of a mudflow (Blackwelder, 1928). Most of the mudflows that have occurred in this area have involved materials composed of more than 60 percent sand and silt.

Five locations of mudflows have been mapped in the area, all on the south side of Plateau Creek. The mudflow on Big Creek (Collbran quadrangle) is developed on a till (ground moraine) of the Grand Mesa Formation. The other flows originated on weak claystones of the Wasatch Formation. Topographically, the flows are distinct from the solifluction and slump deposits. Irregular surfaces, lobate flow ridges, small ponds and lakes, modified scars, streamlike form and, rarely, natural levees, are all characteristic of mudflows. The aerial photographs are useful in mapping the flows, as both the flow ridges and streamlike character of the deposits are easily distinguished.

The flow on Big Creek appears to have been associated with the last glaciation in that it partly fills a late-glacial melt-water channel (fig. 26). It not only filled the channel, but actually reversed the topography by piling up material several tens of feet above the surrounding till plain. This pile of debris diverted Big Creek, which now flows around the mudflow to the west. The source of the material in this flow is not known. There appears to be no scar or other nearby feature from which this material was derived. The debris may have been derived well upvalley (5 miles or more) near the retreating front of the Grand Mesa glacier. If the flow came this distance, it seems strange that there is no evidence of it in the channel of Big Creek. It appears that the mass moved as a unit, leaving little material behind, until it finally came to rest at its present position as the channel gradient lessened.

The slopes on which the mudflows occurred commonly have gradients ranging from 400 to 600 feet per mile. The flows on the north side of Mormon Mesa (Molina quadrangle) have much steeper gradients where they have flowed down the steep sides of Plateau Creek and piled up on the flood plain. These mudflows are younger and display much fresher topography than the others in the area (fig. 27). During times of heavy rainfall, small flows are observed within the channels made by the earlier flows.

The extensive mudflow north of Chalk Mountain in the Mesa quadrangle is older than most of the flows, as streams have cut valleys 150 feet deep through the mudflow into the underlying bedrock.

The mudflows lack sorting and contain sedimentary rock fragments, basalt boulders and cobbles (both rounded and angular), and some pieces of wood and charcoal. Fabric studies (fig. 33, locations 19, 22) show a preferred downslope dip orientation of the elongate cobbles and pebbles. The matrix is silt and sand with scattered clay pods. The matrix often resembles dried chunky mud and contains an abundance of small sedimentary rock fragments. The color is extremely variable. Dark reddish brown, yellowish green, brown, and

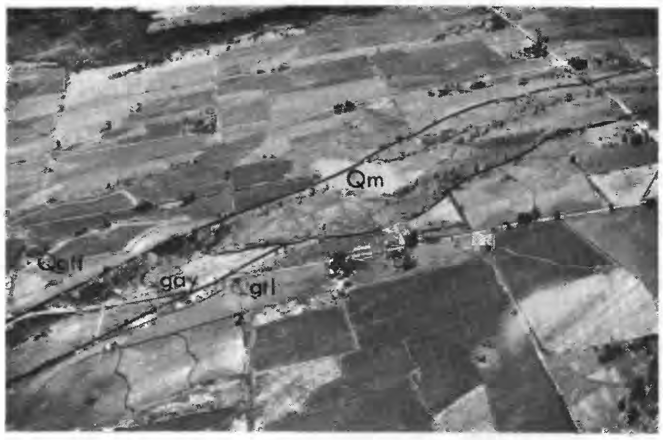

FIGURE 26.—Downslope edge of the mudflow (Qm) filling the old Big Creek outwash channel (Qgay). The channel was cut into till of the Grand Mesa Formation (Qgtl) in late Pinedale(?) time.

FIGURE 27.—Recent mudflows originating on the upper member of the Wasatch Formation. They flow down the steep side slopes of Plateau Creek across the sandstones in the middle member of the Wasatch Formation and pile up on the flood plain of Plateau Creek.

grayish brown are typical matrix colors. Soil zones either are not present or are characterized by a thin A organic layer. Size analysis of the matrix of the mudflow in Big Creek gives the following percentages: sand, 26 percent; silt, 60 percent; and clay, 14 percent.

Except for very recent flows, vegetation has been established on the mudflows and does not differ from the surrounding vegetation.

ACTIVE (?) EARTHFLOW, SLUMP, AND LANDSLIDE DEPOSITS

Deposits resulting from small very fresh isolated earth movements are grouped into this general map unit. Most of these movements either are going on today or have taken place in the very recent past. Similar to most of the mass wasting previously described, the features are concentrated in areas underlain by claystones of the Wasatch Formation and the post-Green River prebasalt unnamed unit. The slopes bounding Mormon Mesa with its thick porous gravel cap are especially vulnerable to these recent slides. Recent slides are also present, but less common, in the till of the Grand Mesa Formation.

These slides leave a fresh scar. Small slumps are the most common type of failure. The slumps generally grade downslope into a hummocky earthflow with flow ridges. In the most recent slides the vegetation is uprooted and tilted at varying angles. During the road relocation up to Mesa Lakes, removal of lateral support from accumulations of till and the older Toreva-block slides has resulted in repeated failure of the slopes adjacent to the new road (figs. 28, 29). Slumping and earthflow have been and will continue to be a major problem in the maintenance of this road.

Fractures in the basalt that are of recent origin have been mapped near the present edge of Grand Mesa (Grand Mesa, Skyway, Lands End quadrangles). The following section describes movement rates of some large blocks that are breaking loose from the mesa.

FIGURE 28.—Recent slump in till along new road to Mesa Lakes.

FIGURE 29.—Recent slides on new road to Mesa Lakes. Developed in till and claystones of the post-Green River unnamed unit.

RECENT MOVEMENT OF LANDSLIDE BLOCKS ADJACENT TO GRAND MESA

Grand Mesa is being reduced by continual slumping of elongate blocks of basalt. Slumps in all stages of development can be found bordering the edge of the present steep basalt cliff surrounding the mesa. The incipient slumps are evidenced on the mesa by long, deep fractures in the basalt and by basalt rubble along scarps at the head of fractures (figs. 30, 31). Backward rotation of the blocks is observed, as is forward rotation and toppling that results in rockfall. Many of the incipient slump fractures contain snow and ice the year around.

FIGURE 30.—Incipient slump blocks on the northeast side of Grand Mesa. Slump is on the left.

FIGURE 31.—Recent opening of fracture in basalt on west end of Grand Mesa. Slump is on the right.

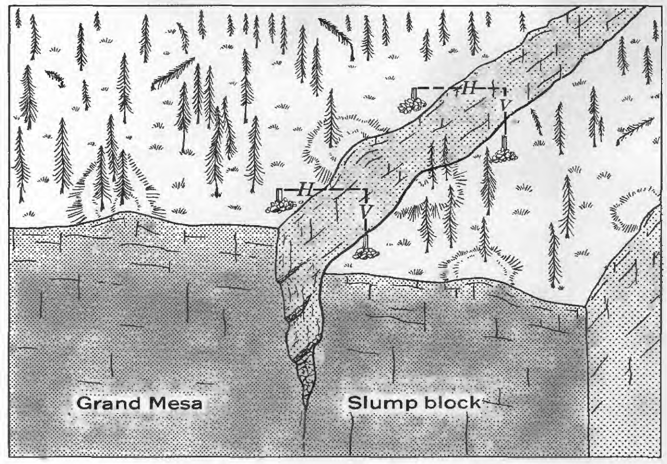

FIGURE 32.—Diagrammatic sketch of a typical staking locality on Grand Mesa. *H*, horizontal separation; *V*, vertical separation.

Of the many localities near the edge of Grand Mesa where incipient slumps are present, six were selected for study over a long-term period. Wood stakes were put in the ground on both the slump blocks and the undisturbed part of the mesa. At each locality several sets of stakes were established across the linear fracture to give some sort of linear control along the block. The slope distance and vertical angle between the individual pairs of stakes were measured with a steel tape and Brunton compass. Horizontal and vertical separation of respective pairs of stakes was calculated (fig. 32). At the time of this writing in 1966, data for only 2 years have been collected. Although displacements as much as 0.5 foot have been measured between several stakes within 1 year, most differences are less than 0.05 foot. Vertical displacements are generally 5–10 times greater than horizontal displacements, as would be expected when dealing with a steeply dipping fracture plane. Two years is much too short a period on which to base any conclusion concerning the true movement rate of the slump blocks. It is hoped that by obtaining data over several more years, significant quantitative values on the movement of the blocks can be determined.

FABRIC STUDIES OF TILL AND MASS-WASTED DEPOSITS

As a possible method of differentiating tills from mass-wasted deposits (such as from earthflow and mudflow), internal fabrics were determined and compared. It was also hoped that directions of ice and landslide movements, more accurate than those obtained from external field relations, could be determined by such a study. Visual inspection does not reveal a preferred orientation of the cobbles and pebbles in any of the deposits sampled.

METHODS OF STUDY

The long-axis orientation of 100 fragments (pebbles and cobbles) was measured for each of four mass-moved deposits and six deposits of Grand Mesa till believed to be undisturbed (fig. 33). Determinations were made below the frost-disturbed zone and on only those fragments with a long axis to short axis ratio of 2.5:1 or greater. Following the removal of a rock fragment from the matrix, a toothpick was placed in the vacant space in approximately the attitude of the long axis of the pebble or cobble. The strike and plunge of the toothpick was then measured with a Brunton compass. Most measurements were determined on a vertical face.

The long-axis orientation was plotted on the lower hemisphere of an equal-areal net (fig. 34). The mean plunge azimuth (mpa) and standard deviation (sd) for each suite of pebbles and cobbles was determined by the radius-vector summation method and "moment method" described by Krumbein (1939) and Curray (1956). The Rayleigh test of significance (Curray, 1956) was used for finding the probability that a particular sample distribution represents a true preferred, rather than a random, orientation. For example, an observed preferred sample distribution with a probability of 0.05 has 5 chances in 100 of being due to pure chance sampling. A distribution is generally accepted as being significantly different from randomness if there are less than 5 chances in 100 of its being due to chance (<0.05 probability). Eight of the samples show orientations with a high order of significance (0.01–0.00001) and two of low significance (0.30).

Directions of movement of the mudflows, slides, and glacial ice, as determined from external field relations, were placed on the petrofabric diagrams (black ar-

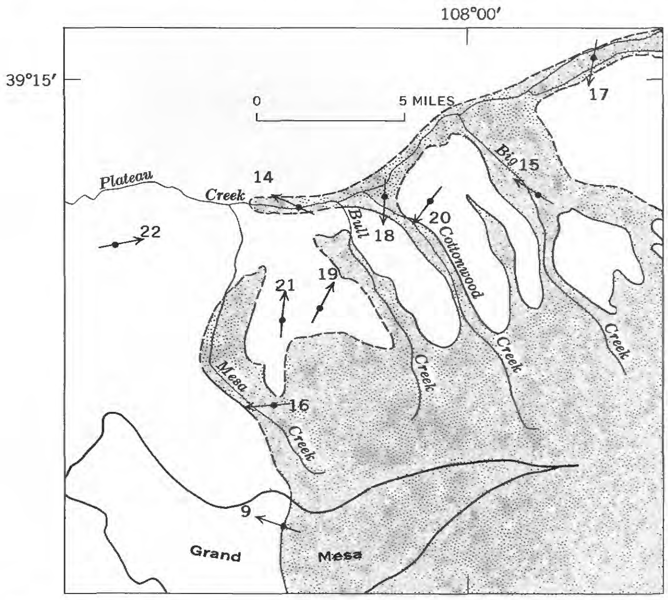

FIGURE 33.—Index map showing location of fabric studies. Patterned area is inferred maximum extent of ice in Grand Mesa time. Arrows indicate movement directions as determined from fabric studies.

rows). The movement direction was determinable in the field only within a certain range in two of the till samples (fig. 34, locations 14, 17); two dotted arrows on the diagrams represent the range.

INTERPRETATIONS

The fabric is generally better defined in the mass-wasted deposits than in the till. This fact is evidenced by a more preferred orientation of the long-axis plunge with smaller standard deviations in the mass-wasted deposits. The mean standard deviation of the till samples is ±91.9° and is ±88.1° for the nonglacial deposits. The mean azimuth movement direction, determined statistically, corresponds closely (within 20°) to the field-determined movement direction in 10 of the 14 samples. The mean azimuth corresponds to within 10° of the field-determined movement direction in four of the samples.

It is particularly significant that the fabric pattern shows a preferred upslope plunge of the pebbles and cobbles within all but one (fig. 34, location 18) of the suspected till samples. It has been suggested that the orientation of disk- and blade-shaped particles parallels the slip planes of the debris-charged basal zones of the glacier that deposited the till (Harrison, 1957, fig. 9). These slip planes tend to dip up-ice in the lower parts of valley glaciers. The mass-wasted deposits, on the other hand, display a heavy concentration of pebbles plunging downhill, parallel to the slope, in the direction of movement (fig. 34, locations 19–22).

Four of the till samples are from ground moraine deposited by valley glaciers; one is from a recessional moraine deposited by a valley glacier; and one is from a terminal moraine deposited by the ice sheet that existed on the surface of Grand Mesa. Several of the till samples (fig. 34, locations 14, 15) show a secondary long-axis maximum at right angles to the fabric-determined ice-flow direction. The tendency for long axes to be oriented transverse to the flow direction has been reported for till in New York State (Holmes, 1941). A secondary peak does not show up in the landslide and mudflow deposits.

The fabric of the till sampled in Cottonwood Creek (fig. 35, location 18) seems to depart markedly from the fabric of the other till samples in reference to predetermined flow direction if the till sampled was, in fact, deposited from ice flowing down Cottonwood Creek. If, however, the till was deposited by ice flowing down Plateau Creek and extending into the mouth of Cottonwood Creek, then the measured fabric is explainable. Postglacial mass movements may have altered the original till fabric at this locality.

In summary, fabrics of till seem to be well defined. Although fabrics of mass-moved materials are not so well defined, this study suggests that the fabrics of the two materials are sufficiently dissimilar to allow differentiation.

RECONSTRUCTED PROFILES OF THE COLORADO RIVER

To gain a better understanding of the history of the Colorado River within the project area, a series of longitudinal profiles representing the earlier levels of the river were drawn (fig. 35). Both alluvial terraces and pediment surfaces were used in reconstructing the profiles. It was necessary to project the gradients of the pediments and terrace remnants down to the present position of the Colorado River to obtain the data for most of the profiles. This was particularly important in constructing the older profiles where terrace and pediment remnants are high up and far back from the present position of the river. Because of the few pediment remnants, correlation and reconstruction of the oldest and highest levels is uncertain.

Eight former levels of the Colorado River are evidenced: four of Bull Lake(?) and Pinedale(?) age, three of pre-Bull Lake(?) age, and one of Pliocene(?) age. The former gradients of the Colorado River, based on the reconstructed profiles, were very similar to the present gradient of the river. About 900 feet separates the oldest (Pliocene?) reconstructed level from the next oldest pre-Bull Lake(?). It is not necessarily interpreted that continual downcutting occurred during the

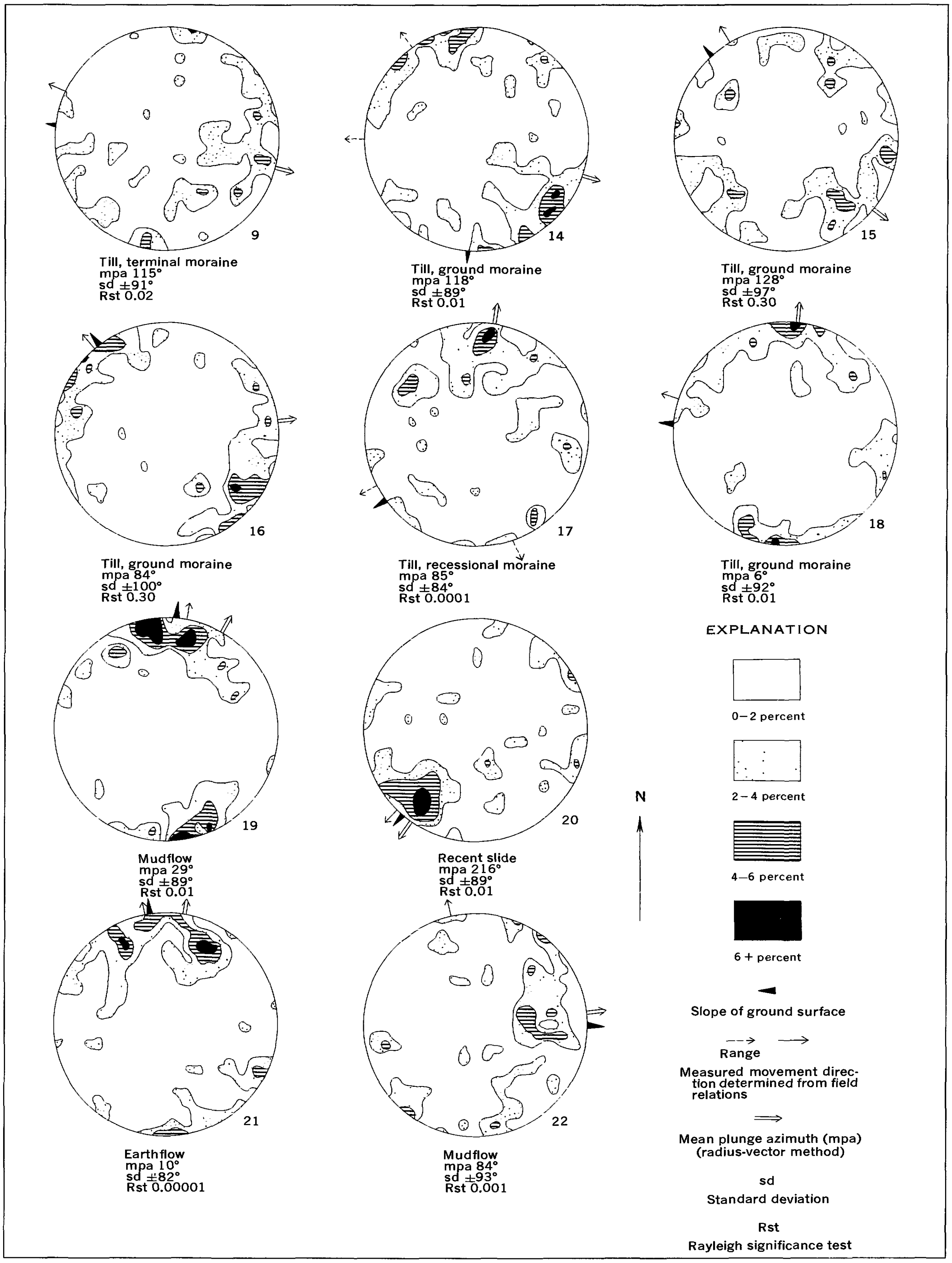

FIGURE 34.—Fabric diagrams (lower hemisphere) showing direction of plunge of pebble long axes in till and mass-wasted deposits.

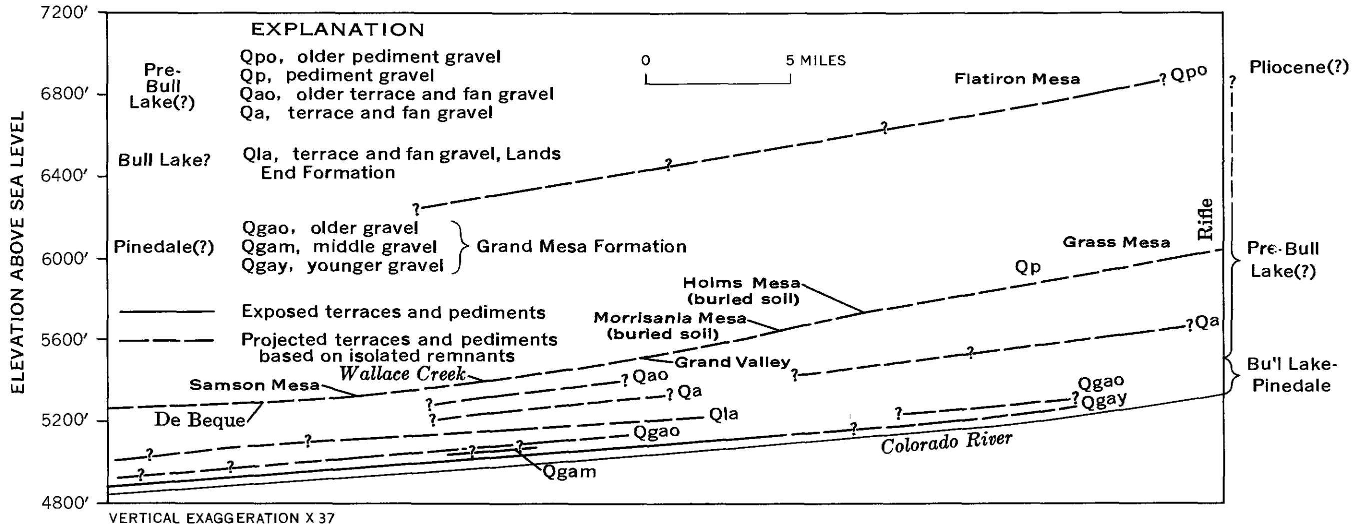

FIGURE 35.—Projected longitudinal profiles of the Colorado River.

interval represented by these old profiles. It is entirely possible that all evidences of terraces or pediments that were formed during this interval have been eroded.

Downcutting by the Colorado since Bull Lake(?) time has amounted to 150–200 feet. Because of the uncertainty of age of the older levels, a figure denoting the amount of downcutting since the beginning of the Pleistocene is unobtainable. Maximum and minimum values are calculated, respectively, at 1,500 and 400 feet.

RATES OF DOWNCUTTING

Potassium-argon dating of the basalt flows capping Grand Mesa give a Pliocene age of 9.7±0.485 million years (J. R. Donnell, oral commun., 1965). The surface of these flows is now about 5,000 feet above the Colorado River. On the assumption that the basalt covered the area now occupied by the river, an average rate of downcutting by the river can be calculated. An average rate of 6 inches per thousand years is obtained. This rate compares closely with the current rate for the Colorado River basin, estimated at 6.5 inches per thousand years (Judson and Ritter, 1964).

STREAM AGGRADATION AND DEGRADATION

It is interesting to investigate the theoretical values of sediment yield and runoff in the area, as these data should give some indication of stream aggradation and (or) degradation. Using precipitation and temperature values obtained for Collbran and Rifle, it is possible to calculate sediment yield and runoff values from data summarized by Schumm (1965, figs. 1, 2).

At the low elevations, sediment yield now should be at a maximum on the basis of current average precipitation values of approximately 12 inches and a mean annual temperature of about 48°F (Schumm, 1965, fig. 2). At the high elevations, although rainfall and temperature records are not available, precipitation may average as much as 30 inches, and a mean annual temperature of 40°F can be postulated. Using these figures, sediment yield should be relatively low at the higher elevations, although runoff would be high. Consequently, stream aggradation might be expected at the low elevations and degradation at the high elevations. Aggradation is observed at the low elevations along small local ephemeral streams. But along all the major perennial streams, degradation seems to be prevalent, probably because the high runoff coming from the high elevations aids in flushing the high sediment yield derived at the low elevations beyond the area; consequently, downcutting along the streams occurs even at the low elevations.

Using the curves determined by Schumm (1965) relating mean annual precipitation, temperature, and sediment yield, it is interesting to postulate what effect a climatic change might have on the sediment yield and runoff. At the low elevations almost any type of climatic change, either warmer, colder, wetter, drier, or a combination of these, would result in decreased sediment yield. At the high elevations, if the postulated values of precipitation and temperature are valid, only if the climate were to get warmer and (or) drier would there be any change in sediment yield. Such a change would probably increase the sediment yield. This increase in sediment yield at the high elevations would be offset by a much greater decrease in sediment yield at the lower elevations, assuming that the same climatic change affected the low area, such that downcutting would probably prevail at a more rapid rate than at present.

Cooler and wetter conditions would probably produce a net decrease in sediment yield owing to expected increase in amounts of vegetation holding the soil, particularly at the lower and intermediate elevations. Runoff would increase with greater precipitation and lessened evaporation, resulting in downcutting, which would also proceed at a more rapid rate than at present.

The increased sediment yield, contributed to the streams by mass wasting during wetter and cooler times, could alter this regimen appreciably. Stream aggradation might occur at the lower elevations when the amount of surficial debris contributed by mass wasting becomes unusually large.

SUMMARY OF AGE AND CORRELATION OF GLACIAL DEPOSITS

An attempt is made to correlate the glacial and cold-climate deposits in the Grand Mesa area with described sequences elsewhere in the Rocky Mountains (table 5). Similar correlations have been made by Richmond (1965a, table 1). The correlation is tenuous because of the lack of ample material for absolute dating. Topographic relations and weathering characteristics of the tills and rubble deposits are the primary element on which the correlations are based.

Pre-Bull Lake(?) glaciation is recognized in only the one locality capping east Chalk Mountain. Although thick mature soils are not observed, the high isolated occurrences of the till with respect to younger tills suggest a pre-Bull Lake age.

The amount of erosion, the characteristics of the loess mantle, and the soil development on the Lands End till indicate that it is similar to the Bull Lake till described in other areas of the Southern Rocky Mountains (Richmond, 1962, 1965a).

The Grand Mesa till is correlated with the Pinedale till because of the fresh topography and very slight soil development similar to other Pinedale tills in the Rocky Mountains (Richmond, 1962, 1964a, 1965a). The outer part of the low extensive till plains representing the greatest advance are probably correlative with the earliest Pinedale advance. The radiocarbon age of 19,730±500 years B.P. from the older terrace of the Grand Mesa Formation would probably fall within the interstade separating the early and middle stades of the Pinedale Glaciation (Richmond, 1965a). Recessional moraines found in several of the drainages may correlate with the middle stage of the Pinedale. The upper till member would seem to correlate with the latest Pinedale. This correlation is based on the virtually unmodified topography of this youngest till, the lack of soil development on it, and its restricted occurrences high on the landslide bench bordering much of Grand Mesa. The lack of an altithermal soil separating the upper till from the lower till also supports this correlation.

Rock glaciers, frost rubble, and earthflow and mudflow deposits are correlated with the Recent glaciation because of their very fresh, unweathered character.

SUMMARY OF LATE TERTIARY AND QUATERNARY HISTORY

There is little evidence for reconstructing a detailed history for late Tertiary and early Quaternary time. During the early Pliocene when the general elevation of the region was probably much lower, basalt was ex-

TABLE 5.—*Correlation of some Quaternary glacial deposits in the Rocky Mountains with those in the Grand Mesa area*

Epoch	Grand Mesa, Colo. (this report)		Wind River Mountains, Wyo. (Richmond, 1964b)		La Sal Mountains, Utah (Richmond, 1962)		Aquarius Plateau, Utah (Flint and Denny, 1958)	San Juan Mountains, Colo. (Richmond, 1965b)		Wasatch Range, Colo. (Nelson, 1954)
Recent	Earthflow, mudflow, solifluction deposits		Neoglaciation	Gannett Peak Stade	Gold Basin Formation	Upper member	Slide rock, frost rubble	Rock glaciers		
	Frost rubble, talus, and rock glaciers(?)			Temple Lake Stade		Lower member	Rock glaciers	Moraines and rock glaciers		Chapman Gulch Glaciation (Pleistocene)
Pleistocene	Till of the Grand Mesa Formation	Upper till member	Pinedale Glaciation	Late stade	Beaver Basin Formation	Upper member	Blind Lake Drift	Pinedale Glaciation	Upper moraine	Hell Gate upvalley recessional
		Recessional moraines		Middle stade		Lower member	Donkey Creek Drift		Middle moraine	Hell Gate Glacial Substage
		Extensive till plains		Early stade					Lower moraine	Ivanhoe Glacial Substage
	Till of the Lands End Formation		Bull Lake Glaciation	Late stade	Placer Creek Formation	Upper member	Carcass Creek Drift	Bull Lake Glaciation	Upper moraine	Bigelow Glacial Substage
				Early stade		Lower member			Lower moraine	Thomasville Glacial Substage
	Pre-Lands End till		Sacagawea Ridge Glaciation		Harpole Mesa Formation	Upper member		Type end moraine of Durango Till		Lime Creek Glacial Stage
			Cedar Ridge Glaciation			Middle member				
			Washaki Point Glaciation			Lower member				

truded (9.7±0.485 m.y. B.P.) on a wide, flat, alluvial plain. The alluvial plain may have contained scattered fresh-water lakes. Successive flows built a pile of basalt averaging 400 feet thick and probably extending over much of the southern Piceance Creek basin and perhaps over the northern extension of the Uncompahgre Plateau. A drainage system, most likely ancestral to the Colorado River, was established on these flows and drained areas beyond the Piceance Creek basin to the northeast. The igneous and metamorphic pebbles and cobbles on the west end of Grand Mesa were gravels deposited by this early drainage system.

Epeirogenic uplift in early to middle Pliocene time caused intrenchment and eventual superposition of the major streams upon the older buried structures. The Colorado River and its tributary, Plateau Creek, were the first drainages to breach the flows and begin cutting into the underlying sedimentary rocks. Broad gentle uplift may have continued throughout much of the Quaternary Period.

Between 3,000 and 4,000 feet of downcutting occurred (Pliocene) before any recognizable deposits were left. Only one pediment level that may date from the Pliocene has survived.

During the Quaternary Period the record of events is much more completely preserved. Along the major streams, cycles of downcutting followed by deposition occurred throughout the Quaternary. During pre-Bull Lake(?) time, when the areal extent of the undisturbed basalt was much more widespread than at present, ice covered much of the highlands at least once and probably several times. Three distinct levels of alluvial terraces of pre-Bull Lake(?) age may evidence three periods of glaciation; however, the till deposits, if originally present, have been all but destroyed.

Throughout the Quaternary, mass wasting was a dominant process in the degradation of the landscape. Large "Toreva blocks" composed of basalt slid away from the basalt cliffs. Such breakup of the basalt flows facilitated rapid removal by glacial and colluvial processes of the high, originally much more extensive surfaces of Grand and Battlement Mesas.

By the beginning of Lands End time (late Quaternary) the present configuration of the topography had been roughly blocked out. Drainages and divides were in their approximate present positions. An icecap formed over much of the upland of Grand Mesa, covering the present extent of the basalt surface completely and extending ice tongues into the surrounding valleys. Several recessional moraines on the mesa surface record minor fluctuations of the cold climate during this time.

In the interglacial interval following Lands End time, the ice melted during a climatic warming(?). Eolian activity associated with the more arid climate was common. Abundant quartz-rich sand and silt were blown up on the surface of Grand Mesa and accumulated preferentially in the low depressions on the till surface. Streams began to cut into the outwash aprons at the lower elevations, while on the mesa surface, weathering of the till cover produced a thin soil often enriched with windblown sand and silt.

Glaciation again interrupted the cycle of stream erosion during Grand Mesa time. Ice initially built up on the landslide bench and eventually encompassed much of the top of Grand Mesa. The icecap continued to grow, and ice flowed down the major drainages much as it had during the previous glaciations. Tongues of ice, 10–20 miles in length, extended into Plateau Creek in several tributary drainages and even flowed down Plateau Creek to an elevation of about 5,400 feet. The ice attained a minimum thickness of perhaps 400–500 feet on the mesa surface and 200 feet in the lower parts of the valleys. It covered all but a few of the slump blocks on the landslide bench and filled the many troughs between the blocks. These high, linear topographic ridges seem to have exerted little control over the flow of the ice; striations on the slump blocks suggest that ice flowed across the blocks at nearly right angles to the trends of the blocks. End and lateral moraines either were not formed or have not been preserved. Recessional moraines are present upvalley in some of the drainages, recording a partial halt in the ablation regimen of the ice. Two levels of outwash terraces would seem to further record this slight fluctuation in the climate during Grand Mesa time. The last phase of ice (upper till member) movement in the area is recorded by crevasse-fill deposits and very hummocky topography on the landslide bench and in the high protected drainage heads peripheral to Grand Mesa. This is thought to be a final phase of the earlier, much more extensive Grand Mesa icecap and may be correlative with the late Pinedale Glaciation. Outwash derived from these local glaciers was small in volume and did little more than fill narrow channels cut into the earlier tills. In the vicinity of Plateau Creek, numerous fans of basalt-rich debris were dumped on the Plateau Creek flood plain during this short interval of stream aggradation. These fans are still fresh and show little dissection.

While glaciers were eroding and modifying Grand Mesa during Lands End and Grand Mesa time, Battlement Mesa was undergoing degradation by a multitude of mass-wasting processes. Earthflow slumping, frost breakup of basalt, and landslides in general moved debris from the high parts of the mesa onto the surrounding slopes and into the bordering stream valleys. Mudflows were common in the lower parts of the valleys and repeatedly poured out on the older pediments and alluvial terraces bordering the Colorado River on the south. Increased amounts of moisture during the glacial periods were primarily responsible for extensive mass movements.

Evidences of Recent glaciation are lacking. Widespread talus deposits, rock glaciers(?), earthflows and solifluction debris would seem to correlate with deposits of the Recent glaciation recorded elsewhere in the Rocky Mountains.

Downcutting has been the dominant stream process since the disappearance of the last ice mass at the close of Grand Mesa time. Windblown fine sand and silt have buried many of the bedrock-defended terraces north of Plateau Creek on the south-facing slopes at the base of Battlement Mesa and have filled local depressions.

Present conditions show permanent streams cutting into their flood plains, arroyo development on the hot dry barren slopes below Battlement Mesa, stability of most talus slopes, and small active slumps and earthflows within the claystones of the Wasatch Formation and younger rocks. Movement of the large basalt blocks peripheral to Grand Mesa seems to be going on at present, although the rate may be less than it was in glacial times. Rainfall and temperature records show a climatic warming and drying during the years followin 1930. How much of the present stream downcutting is due to the influence of man through overgrazing and removal of timber, and how much is due to the increased climatic aridity, is difficult to say.

ECONOMIC GEOLOGY

Surficial sand and gravel deposits have been used most extensively in the area as road metal. Potential sources of gravel for concrete aggregate and riprap exist at various locations throughout the area.

ROAD METAL

Gravel obtained from alluvial terraces of the Grand Mesa Formation along the Colorado River and Plateau Creek have been used extensively as road metal on both secondary gravel roads and as foundations for asphalt highways. During the road relocation over the top of Grand Mesa, talus and block-rubble deposits of basalt on the landslide bench bordering Grand Mesa were crushed and used as road metal. In two localities ice cementing the basalt blocks was encountered at a depth of about 15 feet. Blasting was necessary to excavate blocks below this depth. A gravel pit opened on the surface of Grand Mesa is in the terminal moraine of the Grand Mesa till (fig. 8). This gravel would seem to be of poor quality because of the poor sorting and high content of fines. Crushed marlstone from the Green River Formation has been widely used on secondary roads. The high clay content of the marlstone south of Plateau Creek facilitates the breakdown of the rock as a road metal. This clay subsequently acts as a binder, making a moderately hard surfaced road which is relatively dust free. Following a rain, such a road is very slippery. Table 6 is a summary of the characteristics of the gravel deposits in the area that might be suitable for road metal and construction.

CONCRETE AGGREGATE

Sand and gravel usable as concrete aggregate is present along the Colorado River and Plateau Creek. Gravels in the present flood plain of these rivers and the alluvial gravels of the Grand Mesa and Lands End Formations would seem to be potential sources of concrete aggregate. The composition, sorting, and grain size of these gravels is highly variable owing to locally derived slope wash and material derived from local tributary streams. The locally derived gravels on the pediments and older alluvial surfaces bordering Battlement Mesa contain a high percentage of friable, nondurable sedimentary rocks and would be poor aggregate material.

Aggregate for concrete is designated as either fine or mixed, depending on the percentage of material held on a No. 4 sieve. Fine aggregate consists of gravel of which the coarse material (that held on the No. 4 sieve) is less than 5 percent by weight. Mixed aggregate contains more than 5 percent coarse material. Table 6 summarizes the characteristics of the potential gravel sources in the area.

RIPRAP

Unlimited sources of riprap exist on the landslide bench surrounding Grand and Battlement Mesas. However, these extensive block-rubble and talus deposits are very far from many locations along the major rivers where the material might be useful. Large angular and subangular basalt blocks are common in the mudflow and pediment gravels on the north and west sides of Battlement Mesa.

TABLE 6.—*Summary of gravel characteristics*

Geologic unit	Location	Estimated quantity (cu yd)	Average thickness (feet)	Accessibility	Percent (wt) retained on No. 4 sieve (16 mm)	Remarks
Colorado River						
Low-terrace and flood-plain deposits. (Qal)	Along Colorado River	Unlimited	(?)	Good	70–80	Second best source; some organic matter present.
Grand Mesa Formation; terrace and fan gravel. (Qgay)	Borders present Colorado River flood plain.	Unlimited	(?)	Good	Poor gravel source; primarily fine sand and silt.	
Grand Mesa Formation; terrace gravel. (Qga)	Isolated outcrops along Colorado River.	Unlimited	60+	Good	65–80	Currently a gravel source at numerous localities. Best source.
Lands End Formation; terrace and fan gravel. (Qla)	Terrace remnants in NE¼ of De Beque quad.	40,000,000+	40(?)	Fair	70–75	Third best source; limited extent; extremely variable composition and texture.
Plateau Creek						
Low-terrace and flood-plain deposits. (Qal)	Flood plain of Plateau Creek.	Unlimited	(?)	Good	----------	Commonly capped with 2–6 ft of sand and silt.
Grand Mesa Formation; terrace and fan gravel. (Qgay)	Poorly sorted fan debris.	----------	----------	----------	75–85	Poor gravel source.
Grand Mesa Formation; terrace gravel. (Qga)	Prominent terrace along Plateau Creek.	Unlimited	80	Good	75–85	Currently a gravel source. Best source; predominantly basalt.
Terrace and fan gravel (Qa)	High-level terraces bordering Plateau Creek on the south.	Unlimited	40	Fair	80–85	Abundant sedimentary fragments, especially of oil shale.

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U. S. GOVERNMENT PRINTING OFFICE : 1969 O - 325-259