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UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

GEOLOGY OF THE GORE CANYON-KREMMLING AREA, GRAND COUNTY, COLORADO

by

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ABSTRACT

The Gore Canyon-Kremmling area is in the southwestern portion of the Kremmling 15-minute quadrangle, Colorado.

Precambrian rocks are biotite gneiss, the Boulder Creek Granodiorite, granophyre dikes, and quartz veins. The Boulder Creek intrudes the biotite gneiss, and both of these units are cut by north-northwest-trending granophyre dikes and quartz veins. Biotite gneiss contains structure elements of a northwest and a northeast fold system. Lineations and foliations in the Boulder Creek are generally concordant to the northeast fold system of the gneiss.

Late Paleozoic to Mesozoic and Mesozoic sedimentary formations, in ascending order and with their approximate thicknesses, are the State Bridge Formation, 15 feet; the Chinle and Chugwater Formations undivided, 0-95 feet; the Sundance Formation, 0?-100 feet; the Morrison Formation, 250 feet; the Dakota Sandstone, 225 feet; the Benton Shale, 340 feet; the Niobrara Formation, 600 feet; and the Pierre Shale. Quaternary deposits are terrace, landslide, and modern flood-plain deposits.

Laramide rock deformation is related to the Park Range uplift and includes faulting and, in the sediments, some folding. Some of the faults, including the regional Gore fault, are Precambrian structures reactivated in Laramide time.

INTRODUCTION

Location, Size, and Accessibility

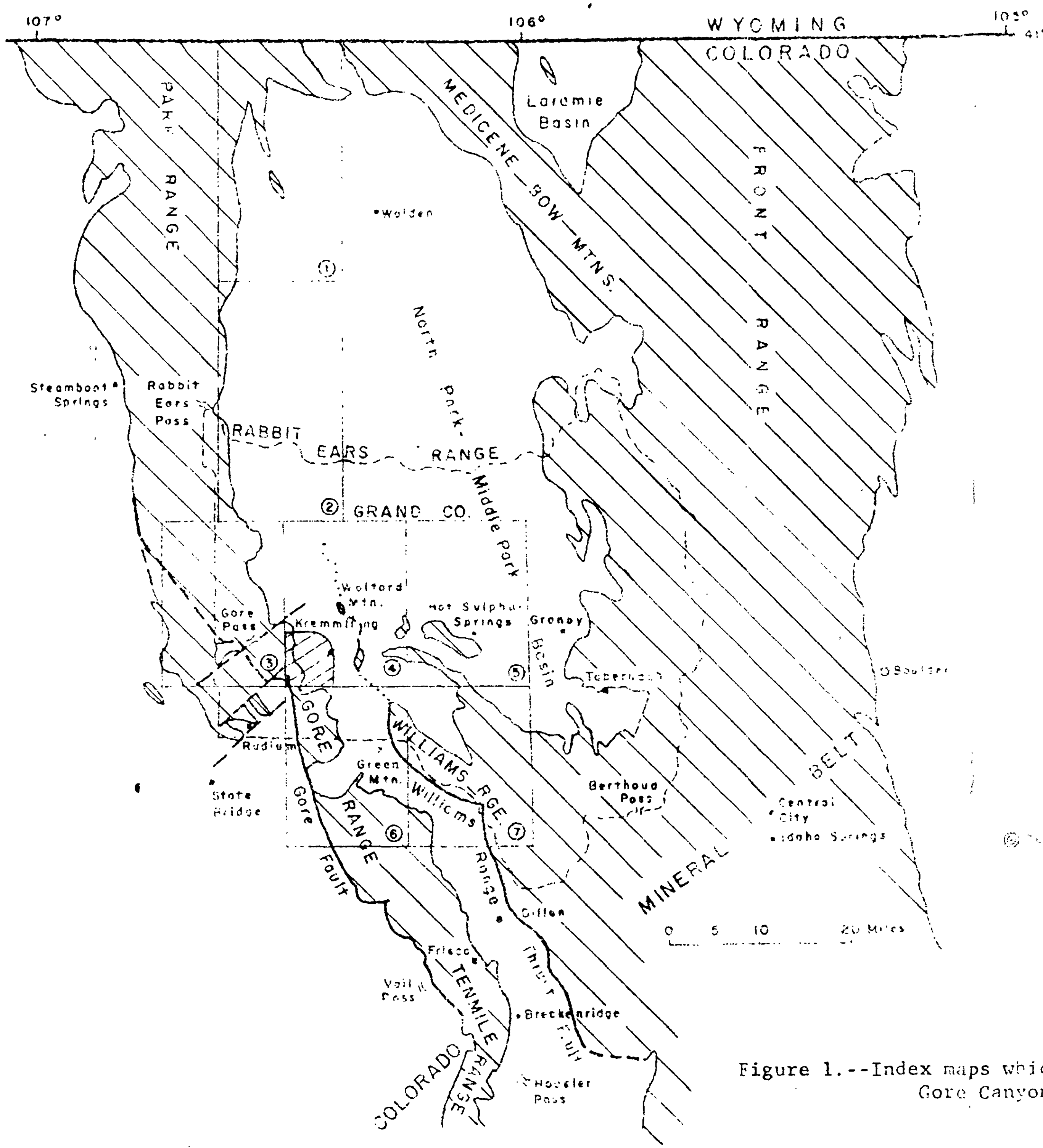
The Gore Canyon-Kremmling area (fig. 1) lies just west of Kremmling, a small ranching, sawmill, and railroad town on the Colorado River at the west edge of Middle Park in the southwestern part of Grand County, Colo. The south boundary of the area is lat 40°00' N., and the west boundary is long 106°30' W.

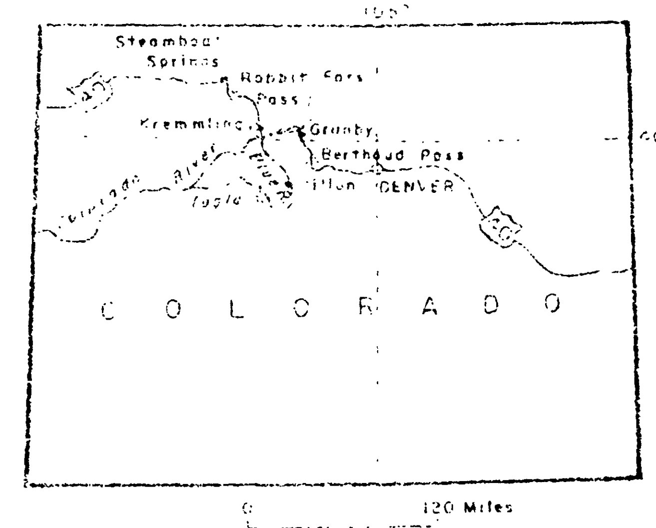
The area comprises approximately 40 square miles in parts of T. 1 S., T. 1 N., and T. 1½ N., R. 81 W., and T. 1 N., R. 80 W., sixth principal meridian, in the southwest quarter of the Kremmling 15-minute quadrangle, Colorado (U.S. Geol. Survey topographic map, 1956). In addition, peripheral areas east of the Blue River and U.S. Highway 40 and north of T. 1½ N. were mapped in reconnaissance.

Kremmling is on the Denver and Rio Grande Western Railroad's main line between Denver, Colo., and Salt Lake City, Utah, 120 miles west of Denver, and on State Highway 9, 40 miles north of Dillon. From Kremmling, access to the northern part of the area is by U.S. Highway 40 and ranch roads, and to the southern part by State Highway 9, by State Highway 11, an improved gravel road that enters Highway 9 from the west 2 miles south of Kremmling, and by ranch roads. The Denver and Rio Grande Western Railroad follows the Colorado River through Gore Canyon, and the railroad grade provides access to the north wall of Gore Canyon.

Present Investigation

The Gore Canyon-Kremmling area was mapped as part of the U.S. Geological Survey's mapping program in the Kremmling 15-minute quadrangle, Colorado. Several square miles peripheral to the Gore Canyon-Kremmling area were mapped in reconnaissance. Geologic investigations in the Kremmling quadrangle were undertaken to (1) furnish a basis for classification of lands in the eastern part of the quadrangle, which were





EXPLANATION

Precambrian rocks

Faults

Gore Canyon-Kremmling area

Areas covered by some of the U.S. Geological Survey reports and topographic maps mentioned in text.

1. Northwestern North Park (Hail, 1965).
2. Southwestern North Park and vicinity (Hail, 1968).
3. Gore Pass quadrangle.
4. Kremmling quadrangle.
5. Hot Sulphur Springs quadrangle.
6. Mount Powell quadrangle.
7. Ute Peak quadrangle.

Figure 1.--Index maps which show the location and the topographic and tectonic framework of the Gore Canyon-Kremmling area. Tectonic map modified from Oriel (1954).

withdrawn by the Federal Government pending classification for coal, and (2) to contribute to the geologic map atlas of the United States.

Fieldwork

Most of the fieldwork was done during June through October 1963 and the end of May through the first part of July 1964. Brief visits to the field area were made on a few weekends during the spring of 1965.

Mapping was done on a 1:24,000 mylar enlargement of the southwest quarter of the Kremmling 15-minute quadrangle (U.S. Geol. Survey topographic map, 1956, scale 1:62,500) and on U.S. Forest Service aerial photographs, approximate scale 1:20,000 and 1:40,000, flown in 1955. Map positions were determined by compass resection, hand leveling, and aerial photograph inspection.

Stratigraphic sections were measured by Jacob's staff, Abney level, and tape.

Laboratory Work

Laboratory investigations were confined principally to thin-section studies of the Precambrian crystalline rocks and of a few Niobrara Formation carbonates by means of the petrographic microscope. Thin sections of fossiliferous Niobrara Formation carbonates and hand specimens of clastic rocks from several formations were examined with a stereomicroscope. Other laboratory work included a diffractometer study of a sulfide nodule from the Niobrara, grain studies of some disaggregated samples from the State Bridge Formation, and panning of crushed samples from a Precambrian(?) quartz vein.

Previous Work

The first geologic study in the area was conducted by Marvine (1874). Working in the nearby Rabbit Ears Pass area, Grout, Worcester, and Henderson (1913) first introduced many of the stratigraphic names used in this report. More recent work, which extended into the area of the Parks and Park Ranges, includes Lovering and Goddard's (1950) monumental regional study of the Colorado Front Range and Tweto's (1957) summary of Middle Park geology. Recent, as yet unpublished, work has been done by U.S. Geological Survey personnel in quadrangles bordering the Kremmling quadrangle: W. J. Hail, Jr., to the north. G. A. Izett to the east, and G. N. Pipiringos, W. J. Hail, Jr., and G. A. Izett on problems of the regional stratigraphy of the marginal marine and marine Jurassic.

Theses and dissertations which border or cover parts of the map area are Richards' (1941) geologic reconnaissance of the Kremmling area, which includes the eastern part of the area; less extensive areal studies which extend into the southwest corner of the Kremmling quadrangle by Steinbach (1956) and Parsons (1954); an areal study in the Pass Creek-Wolford Mountain area of the Kremmling quadrangle to the north by Miles (1961); a project emphasizing Precambrian rocks in the Mount Powell quadrangle to the south by Taggart (1963); an areal study in the Blue River Valley to the south of the Kremmling quadrangle by Holt (1961); and a Columbia University thesis on the Williams Range thrust fault which lies to the east of the map area by Howard (1966).

Acknowledgments

The work for this thesis was done while the author was employed by the U.S. Geological Survey, and the author is grateful for permission to use Survey data for a thesis.

Fossil determinations were made by W. A. Cobban, R. A. Scott, and J. F. Mello, U.S. Geological Survey, and the results of their work are incorporated in this report. C. E. Hedge of the U.S. Geological Survey made age determinations on a group of samples collected by the author from a granophyre dike in the Gore Canyon area. W. N. Lockwood of the U.S. Geological Survey used four samples which the author collected from the Niobrara Formation in his research on differential thermal analyses techniques for carbonate, and the results of his determinations are included in this report.

Several U.S. Geological Survey geologists visited the area and advised on specific problems. In June 1964, W. J. Hail, Jr., spent two days with the author studying Mesozoic units which he had mapped to the north. During the same month, R. B. Taylor spent a day with the author studying Precambrian rocks of the area. In June 1963, G. N. Pipiringos of the U.S. Geological Survey spent three days in the Kremmling and adjacent areas as part of his regional study of marine Jurassic rocks, and he gave the author considerable aid in understanding the Jurassic and adjacent rocks.

Special acknowledgment is given to G. A. Izett of the U.S. Geological Survey who suggested the area for a thesis and advised the author during the investigation. In 1964, A. M. Thompson, at that time field assistant to Izett and a student at Brown University, assisted in the field for three days.

The author is most grateful to Dr. E. B. Mayo, Professor of Geology at the University of Arizona and faculty advisor for this thesis, who has critically read the manuscript and who has supported this thesis by generous contributions of his time and effort.

The people of the Kremmling area were most helpful; deserving special mention are the Messrs. Yust, De Berard, and Martin, all ranchers of the area, who allowed the author free access to their property.

Finally, the author wishes to acknowledge the support rendered by Mrs. C. S. V. Barclay who typed the first draft of the manuscript.

PHYSIOGRAPHY

Middle Park basin is the middle of three north-northwest-trending intermontane valleys bounded on the east by part of the Colorado Front Range and on the west by segments of the Park Range. Most of the map area is along part of the west edge of Middle Park and on the flanks and crest of the Gore Range, one of the Park Ranges, a chain of ranges which borders North, Middle, and South Parks on the west.[1] The southwest corner of the area extends down the west flank of the Gore Range.

Relief

Maximum relief in the area is more than 2,720 feet. The high point, more than 9,760 feet, is on the crest of the Gore Range in sec. 20, T. 1 N., R. 81 W. The low point, less than 7,040 feet, is on the Colorado River in sec. 6, T. 1 S., R. 81 W.

Topography

The eastern part of the area lies along the west margin of the floor of Middle Park and the first gentle slopes of the bordering Gore Range. Local relief is low, and flood plains and terraces of the Colorado River and its tributaries and low cuestas are the dominant land forms. The land surface rises progressively more steeply, but evenly, to the west and culminates in the rounded crest characteristic of the northern part of the Gore Range. The west slopes of the Gore Range at Gore Canyon and to the south are steeper than the east slopes but become more gentle to the north.

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[1] In this paper, the term "Park Range" (singular) refers to the northernmost of the Park Ranges, the mountain segment which extends from Gore Pass north through Rabbit Ears Pass and beyond. "Park Range uplift" is used in this paper to refer to the uplift of the entire chain of Park Ranges.

Drainage

Middle Park is drained by the Colorado River which flows west-southwestward across the area and cuts the Gore Range at Gore Canyon. In the map area the large tributaries of the Colorado River are Muddy Creek and Blue River, both of which join the Colorado River west of Kremmling; small tributaries are Beaver Dam Gulch and Sheep Creek, which drain the east slopes of the Gore Range, and Canyon Creek, which drains the west slope of the Gore Range. Water from the Colorado River and its tributaries is used locally for irrigation. A tributary of Sheep Creek has been dammed to form a reservoir for Kremmling's water supply.

Climate[1]

A large part of the floor of Middle Park is semiarid and has warm summer days, cool summer nights, and cold winters. The highland areas bordering Middle Park receive substantially more moisture, most of which is snow. Thunder showers are common in the middle of the summer. Measurable snowfall on the slopes of the Gore Range as late as June and as early as August occurs but is not common.

Kremmling is near the west edge of Middle Park, within an area covered by the rain shadow of the Gore Range. A U.S. Weather Bureau station at Kremmling has recorded annual precipitation totals ranging from about 8 to 16 inches; the average is probably between 9 and 11 inches. No recording stations are on the Gore Range in the map area, but data from a station on Rabbit Ears Pass to the north suggest the crest of the range may have an average annual precipitation between 30 and 40 inches.

Fragmentary data indicate that the annual mean temperature along the base of the east flank of the Gore Range in the area ranges from

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[1] Climatological data are from U.S. Weather Bureau, Annual summary climatological data for the U.S. by sections: Colorado.

36° to 40°F. The highest temperature on record at Kremmling is 92°F on July 27, 1947, and July 28, 1964; the lowest, a -49°F on February 1, 1951.

Vegetation

On the crest and the upper east slopes of the Gore Range, cool temperatures and relatively high amounts of precipitation support dense forests of pine (mostly lodgepole) and lesser amounts of fir, spruce, and aspen on predominantly Precambrian crystalline rocks of Dakota sandstone terrains. Claystone and siltstone of the Morrison Formation are generally involved in landslides, and the resulting hummocky terrain characteristically hosts large clumps of aspen with scattered conifers. The drier and warmer lower east slopes of the range and the west edge of the floor of the park are underlain by Cretaceous marine shales and are commonly covered only by sagebrush, although along water courses or in slide areas willows or small clumps of aspen are found. Gravel-capped Quaternary terraces along the Colorado and Blue Rivers and their tributaries are also covered by sagebrush. The flood plains of the Colorado and Blue Rivers are generally irrigated for hay.

Vegetation on the upper west slopes of the Gore Range is similar to that on the east. The lower west slopes support numerous juniper trees and a pervasive sagebrush cover.

Rock Exposures

In general, good exposures of the rocks are sparse. The Precambrian crystalline rocks are resistant, but high on the slopes and the crest of the Gore Range they are covered by soil and heavy stands of timber. The Mesozoic pre-Cretaceous rocks are in less heavily timbered areas but are predominantly nonresistant siltstones and claystones. The resistant Cretaceous Dakota Sandstone is in sagebrush as well as in relatively open timbered areas, but it is commonly involved in landslides with the underlying Morrison. Even where it forms cliffs, it generally covers its basal beds and the underlying Morrison Formation with extensive talus deposits of sandstone blocks and slabs. The gentle sagebrush-covered slopes formed on the shales of the Benton, the Niobrara, and the lower part of the Pierre Shale are commonly broken only by the thin slabby petroliferous limestone beds at the top of the Benton Formation, the blocky dense limestone beds at the base of the Niobrara Formation, and the first sandstones and subordinate lenticular limestones characteristic of the upper part of the Pierre Shale.

The principal exceptions to the general paucity of rock exposures are the excellent exposures of the Precambrian metamorphic rocks in the walls of Gore Canyon, especially the north wall; of the Dakota Sandstone in the cliffs at the east end of Gore Canyon, especially on the north side of the river; and of the Niobrara Formation on the east side of the Blue River in sec. 32, T. 1 N., R. 81 W.

GENERAL GEOLOGY

Most of the area lies along part of the west margin of Middle-North Park basin and the eastern flanks of the Gore Range, but the southwestern part extends over the crest and down the west flanks of the range to the edge of the Central Colorado trough. The Gore Range is a remnant of part of the west edge of a Paleozoic highland which was subjected to repeated uplift during the Laramide orogeny and the late Tertiary. It separates Middle-North Park basin, a north-northwest-trending structural basin that formed during the early phases of the Laramide orogeny, from the Central Colorado trough.

The rock units of the area may be grouped into three units (fig. 2): (1) the crystalline rocks of the core of the Gore Range; (2) the sedimentary rocks on the east edge of the Central Colorado trough on the west flank of the Gore Range; and (3) the sedimentary rocks of the west edge of Middle Park basin.

(1) The core rocks of the Gore Range in the southwest quarter of the Kremmling quadrangle are Precambrian crystalline rocks. In the area south of Gore Canyon and on the north and south walls of Gore Canyon, these crystalline rocks are gneisses, migmatitic gneisses, and associated crosscutting and intercalated pegmatites and aplites. The rocks are similar to the Precambrian Idaho Springs Formation of the Idaho Springs-Central City area in the Colorado Front Range. Compositionally, the predominant rock type is biotite gneiss, locally modified by small amounts of sillimanite, garnet, hornblende, muscovite, and microcline. Lenses and pods of amphibolite are locally present.

North of Gore Canyon the gneisses are cut by Precambrian granitoid rocks of the Boulder Creek Granodiorite. The bulk composition of this unit ranges from granodiorite to quartz monzonite, but local variations include leucocratic quartz monzonite, quartz diorite, and diorite. The Boulder Creek locally contains pods and lenses of recrystallized amphibolite(?) and, near the contact with the biotite gneiss, lenses of migmatitic biotite gneiss.

The contact between the gneisses and the Boulder Creek Granodiorite is gradational through a wide zone of interlayered gneiss and granodiorite. Locally the gneiss has been partially assimilated by the invading granodiorite. At least for that part of the contact exposed in the area, the structures in the Boulder Creek are generally concordant, only locally discordant, to those of the biotite gneiss.

Layers of gneiss and granodiorite are cut by thin north-northwest-trending granophyre dikes and quartz veins near the west edge of the area.

The gneisses and, to a lesser degree, the granodiorite are well foliated and lineated. In the gneiss, the most conspicuous planar and linear structural elements define a fold system which trends northeast to east-northeast. The structural grain of the Boulder Creek Granodiorite parallels this trend. Some evidence for an older northwesterly to north-northwesterly trending fold system is present in the gneiss unit.

The crystalline rocks are broken by faults, the majority of which are either subparallel or nearly perpendicular to the northeasterly regional foliation. Many of the fault zones show evidence of both Precambrian and Laramide movement.

(2) At the southwestern corner, the map area extends onto the edge of the Central Colorado trough. Outcrops of Precambrian crystalline rocks at the west portal of Gore Canyon are beveled by a thin (14-17 ft) wedge of red beds which belong to the State Bridge Formation of Late Permian and Early Triassic age. The State Bridge Formation is unconformably overlain by massive sandstone beds of the Late Jurassic Sundance Formation. Beds of both the State Bridge and Sundance Formations are locally mantled by Colorado River Quaternary terrace gravels. The sedimentary pile thickens abruptly to the west and basinward beyond the map area by the addition of more rock units and the thickening of individual units.

The Morrison Formation is overlain by the Lower Cretaceous Dakota Sandstone, about 225 feet thick. The Dakota is composed of a lower nonmarine series of lenticular conglomerates, sandstones, and variegated siltstones and an upper marginal marine unit of sandstone interbedded with some siltstone and claystone.

Above the Dakota is a sequence of marine rocks more than 5,000 feet thick. The basal unit of this sequence is the Benton Shale of Early and Late Cretaceous age, about 340 feet thick, which is composed of shale and, near the top, sandstone and petroliferous limestone. Above the Benton is the Niobrara Formation of Late Cretaceous age. The Niobrara is approximately 600 feet thick and consists of a thin (12-15 ft) basal limestone unit, a middle shale, and an upper unit of chalky shale interbedded with a few thin limestones. The Pierre Shale of Late Cretaceous age is the highest formation of the sequence and consists of shale sparsely interbedded with thin siltstone beds in the lower 1,500 feet and of siltstone, sandstone, minor shale, and a few impure limestone beds in the upper 2,500 feet (G. A. Izett, oral commun., 1968). The Benton and the Niobrara crop out along the lower eastern flanks of the Gore Range and the west edge of Middle Park. In the northeastern part of the area, the lower part of the Pierre and the first sandstone beds of the upper part of the Pierre crop out.

The most important structural feature of this small area is a northwest- to north-northwest-trending shear zone, a zone of multiple faulting which contains evidence of both Precambrian and post-State Bridge movements. This shear zone is an extension of the Gore fault, a high-angle reverse to normal fault, east side up, which bounds the Gore Range on the west from the latitude of Breckenridge, Colo., about 45 miles southeast of Gore Canyon, northward to the Colorado River at Gore Canyon and beyond.

(3) Rocks of several sedimentary units ranging in age from Late Paleozoic(?) to Quaternary are present along the west edge of Middle Park. The number and the thickness of rock units and the age of the basal unit exposed between the Precambrian crystalline rocks and the Early Cretaceous Dakota Sandstone increase from south to north within the map area. At the crest of the Gore Range in the southern part of the area, the Precambrian crystalline rocks are commonly overlain by beds of

the Late Jurassic Morrison Formation, a continental sequence of mudstones that contain lenticular sandstone beds and thin discontinuous fresh-water limestone beds. In much of the area north of the Colorado River, sandstones and shales of the Sundance Formation crop out above the Precambrian rocks and below the Morrison Formation. Near the north edge of the area, conglomeratic sandstones and red siltstones of the Triassic Chinle and Permian and Triassic? Chugwater Formations undivided are locally present between the Precambrian crystalline rocks and the Jurassic sedimentary rocks. In the northern part of the area, the maximum thickness of the Chinle and Chugwater(?) Formations undivided is at least 63 feet, the Sundance is at least 68 feet, and the Morrison is near 250 feet.

The Cenozoic era is represented by extensive Quaternary landslide deposits which involve, along the east flank of the Gore Range, beds of all the sedimentary formations. Quaternary terrace gravels occur along the Colorado and Blue Rivers and their tributaries.

The most prominent structural features along the east flank of the Gore Range are northeast to east-northeast faults and related subparallel monoclinal flexures in the Mesozoic marine sequence. Many of the faults occur along and are the projections of Precambrian shear zones which were reactivated during the Laramide orogeny and in late Tertiary(?) time.

Precambrian Rocks

BIOTITE GNEISS AND ASSOCIATED ROCKS

The rocks mapped as biotite gneiss and associated rocks include the oldest rocks in the area. They comprise a high-grade layered locally migmatitic folded and injected metasedimentary sequence which forms the core of the Gore Range in the Gore Canyon-San Toy Mountain area (cross section C, fig. 2). The dominant rock type in this unit is biotite quartz plagioclase gneiss, and this map unit is hereafter called the biotite gneiss unit or, more simply, the biotite gneiss. In addition to the dominant rock type of the unit, compositionally similar gneisses containing varying amounts of sillimanite, garnet, microcline, muscovite, or hornblende are present in the biotite gneiss. Also included in the biotite gneiss are crosscutting and concordant aplites and pegmatites and intercalated amphibolites. Most of the various rock types of the map unit are displayed along the walls of Gore Canyon (fig. 3).

The biotite gneiss is intruded by the Boulder Creek Granodiorite, and near the contact of the two units the biotite gneiss is intercalated with granodiorite and is locally migmatitic. Hybrid rocks, mixtures of gneiss or amphibolite and granodiorite, are common. Most of the areas of occurrence of interlayered biotite gneiss, granodiorite, and hybrid rocks are included in a zone in the biotite gneiss, mapped as biotite gneiss intercalated with Boulder Creek Granodiorite. The rocks of this zone are discussed both in this section and in the section on the Boulder Creek Granodiorite.

To the east in the Hot Sulphur Springs quadrangle, Izett and Barclay (1964) mapped a sequence of Precambrian biotite gneisses and associated rocks similar to the biotite gneiss of this map area. Southeast of the map area, in an area covered by the Ute Peak quadrangle, Lovering and Goddard (1950, pl. 1) assigned lithologically similar gneisses to the Idaho Springs Formation of the Front Range. In the Mount Powell quadrangle, Taggart (1963) mapped a layered sequence of Precambrian gneisses and schists which he informally divided into an "older series" and a "younger series" separated by an unconformity. He subdivided the rocks in each series into various units named according to dominant mineral assemblages. The biotite gneiss unit of the Gore Canyon-San Toy Mountain area appears to be regionally concordant and, at the common boundary between the Kremmling and Mount Powell quadrangles, continuous with units of Taggart's "younger series" and migmatite.

Complex folds and the absence of marker beds prevented thickness measurements of the biotite gneiss. In the Mount Powell quadrangle, Taggart (1963) estimated 19,500 feet of layered Precambrian rocks which may include rocks similar to the Boulder Creek Granodiorite of this report as well as rocks of the biotite gneiss unit.

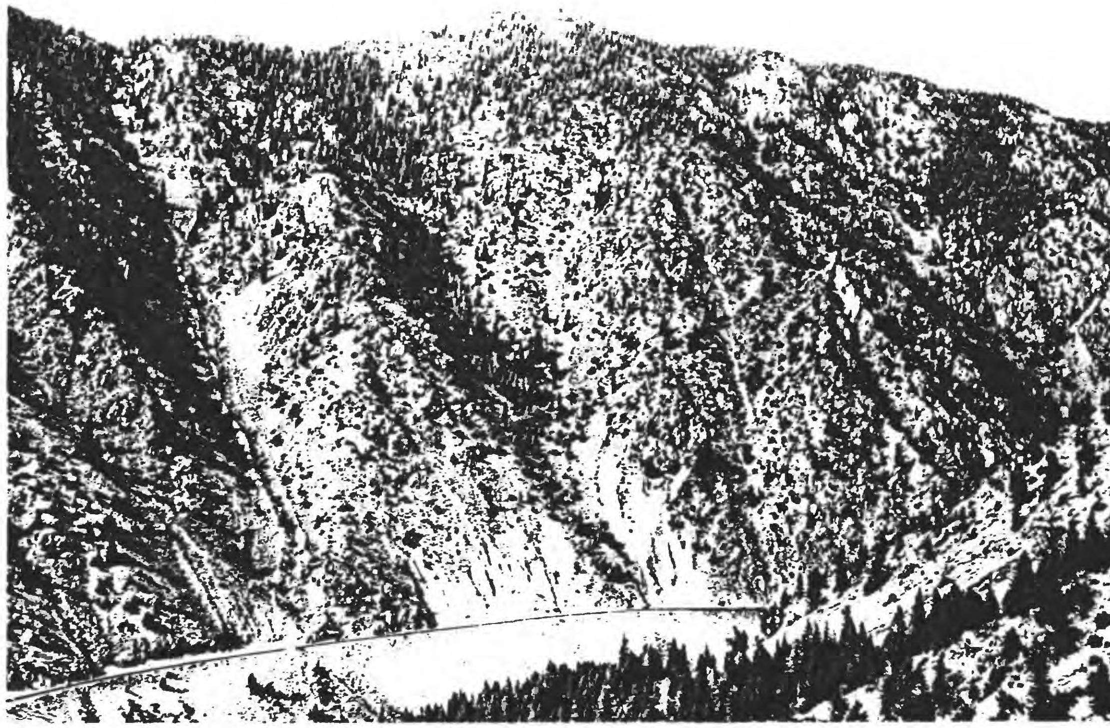

FIGURE 3.--View of a portion of the north wall of Gore Canyon, near middle of canyon, chiefly in sec. 28, T. 1 N., R. 81 W. Foreground is south wall of canyon in sec. 33.

Rock Descriptions

Biotite Gneiss. The biotite gneiss unit is named for the most abundant rock type in the sequence--compositionally banded gneiss which consists predominantly of varying proportions of quartz, plagioclase, and biotite. Typically, it is a rock of alternating fine- to medium-grained gray to light-gray biotite-rich layers and thinner coarser grained tan to milky-white quartz-feldspar-rich layers (fig. 4). The layering is commonly about a few millimeters to several tens of millimeters thick, irregularly spaced, and lenticular.

In thin section, the typical biotite gneiss consists of lepidoblastic layers of biotite that contain subordinate quartz and plagioclase and coarser gneissose layers of plagioclase, quartz, and sparse biotite. The schistosity within quartz-feldspar layers is principally determined by subparallelism of quartz lenticles and, to a much lesser extent, tabular plagioclase metacrysts. Common minor mineral constituents of the biotite gneiss include zircon, apatite, iron ore (principally magnetite and hematite), muscovite, epidote, and sericite. Rarely, sphene is associated with iron ore, epidote, and biotite, and calcite with sericite. Potash feldspar, generally grid-twinned microcline, is not uncommonly present as small antiperthitic intergrowths in large plagioclase metacrysts. Quartz is anhedral, commonly strained, and locally sutured. Plagioclase is anhedral to subhedral, and rarely shows slightly bent or broken crystals. Twinning, especially on the albite law but also on the carlsbad and pericline laws, is commonly distinct. The composition as determined by flat-stage optical methods ranges from calcic oligoclase to sodic andesine with most grains tested falling between An_{30} and An_{34}. Myrmekite is present, though commonly sparse in most sections. Sericitization of plagioclase is pervasive and locally strong. Where it is strong, mats of sericite, commonly accompanied by a few conspicuous muscovite flakes and by single crystals or crystal aggregates of the epidote group, completely replace parts or all of individual plagioclase metacrysts. Biotite metacrysts are subhedral,

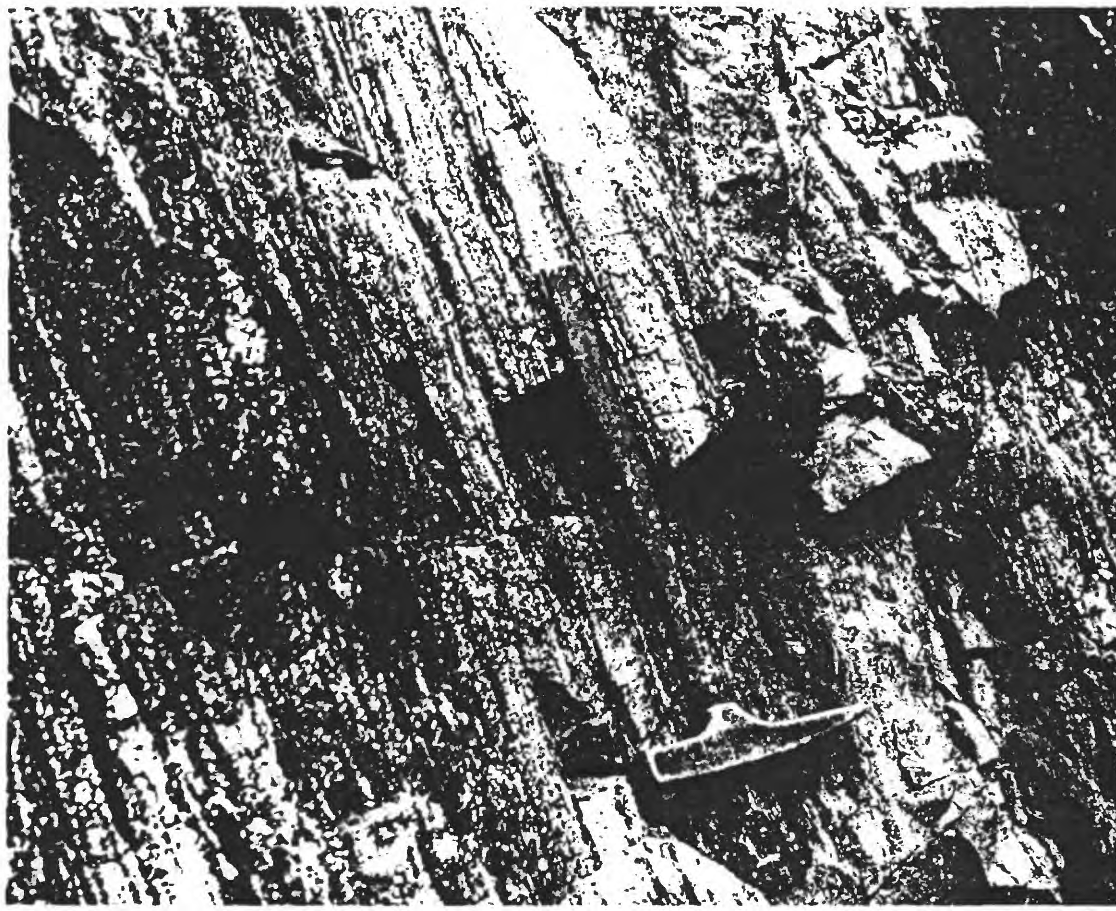

FIGURE 4.--Outcrop of typical biotite gneiss, on south wall of Gore Canyon in the NE¼ sec. 33, T. 1 N., R. 81 W. Note the quartz-feldspar and biotite-rich layers.

are not uncommonly slightly bent, and are locally replaced by white mica and iron ore or by epidote.

There are several compositional varieties of gneiss which are interlayered with the typical biotite gneiss, commonly on the same scale as compositional banding in the typical gneiss. Most of these are varieties of biotite gneiss but in some biotite is locally subordinate. Garnetiferous biotite gneiss crops out locally in all parts of the biotite gneiss terrain. Sillimanitic biotite gneiss crops out on both walls of Gore Canyon. The most abundant outcrops of both types were found around Inspiration Point and on the lower part of the north wall of Gore Canyon. Both commonly occur in medium- and coarse-grained gneisses but a sillimanitic biotite schist occurs near the top of the north wall of Gore Canyon. This schist is a dark-gray fine-grained rock that contains abundant subparallel white sillimanite needles on foliation planes. In thin section it consists predominantly of layers of quartz and thinner layers of biotite, sillimanite, and replacing sericite. Plagioclase is very sparse in both layers, though some of the sericite in the biotite layers was probably derived from plagioclase. A few large flakes of muscovite that show random orientation are in the biotite layers. Sillimanite and garnet also occur together in banded medium-grained biotite gneiss in which neither is abundant nor readily discernible megascopically. A thin section of one rock of this last type showed most of the sillimanite in biotite-quartz (minor or rare plagioclase) layers, and garnet with thin sericite-chlorite rims in adjacent plagioclase-quartz (minor biotite) layers. A few sillimanite(?) needles were also observed in plagioclase in garnetiferous layers. In the sillimanitic layers, sillimanite appeared to be replacing muscovite and muscovite replacing biotite. Some sillimanite bundles showed extensive alteration to felty masses of sericite. Some of the sillimanitic (and garnetiferous) gneisses examined in the thin section contained a few patches of myrmekite and muscovite and (or) potash feldspar. The potash feldspar occurred as thin interstitial patches and (or) antiperthitic intergrowths in plagioclase.

Fine- to medium-grained biotitic hornblende gneiss is irregularly and sparsely distributed within the biotite gneiss as thin layers in compositionally banded biotite gneiss. Thin-section studies revealed that the hornblende-rich layers consist predominantly of hornblende, quartz, plagioclase, and biotite in decreasing order of abundance. Common accessory minerals include sphene, iron ore, zircon, and apatite. Retrograde effects, including those produced by proximity to shear zones, are locally pronounced. Sericitic replacement of plagioclase, and to a lesser extent, biotite is commonly extensive. Sericite is always more abundant than biotite and, not uncommonly, more abundant than plagioclase. Other retrograde minerals are epidote from hornblende, biotite, and plagioclase and lesser amounts of calcite from hornblende and chlorite from biotite. Extensive sericitization made flat-stage optical determination of plagioclase composition difficult to obtain. The approximate determinations achieved suggest that sodic-andesine is the usual composition but plagioclase as calcic as An_{55} may be present in some layers.

Thick layers of pale-orange to pink medium-grained biotite to biotitic-microcline gneiss are exposed along the north side of the San Toy Mountain fault and its westward projection. Thin sections of a series of samples taken from normal biotite gneiss and an adjacent microcline gneiss layer show a gradation from biotite gneiss that has plagioclase of a composition of about An_{25-32} to a microcline gneiss predominantly composed of a more sodic oligoclase (An_{16-25}), a slightly lesser amount of quartz, and subordinate microcline. In this series from biotite gneiss to microcline gneiss, the alteration of plagioclase increased to sericite and subordinate epidote and the abundance of antiperthite and myrmekite increases; the biotite content decreases and the biotite remaining is increasingly altered to muscovite and subordinate epidote. The thin section of the microcline gneiss that ends the series also shows some degree of cataclasis--bent crystals, finely and complexly sutured grain boundaries, and healed fractures.

Migmatitic gneisses and porphyroblastic gneisses are locally present in most areas of outcrop of the biotite gneiss unit. They are most abundant in the zone mapped as biotite gneiss intercalated with Boulder Creek Granodiorite. The migmatitic gneisses are biotite gneisses in which an appreciable amount of granitic material is thinly and complexly interlayered with biotite gneiss (figs. 5, 6). These gneisses commonly contain muscovite and are locally garnetiferous and (or) sillimanitic. The porphyroblastic gneisses are biotite gneisses that contain large metacrysts of feldspar. The porphyroblasts of some of these rocks are plagioclase (An_{27-32}) but most are microcline. In all the porphyroblastic gneisses observed--except for some of the gneissic hybrid rocks associated with the Boulder Creek Granodiorite--the porphyroblasts are commonly in a micaceous lens-shaped envelope and these gneisses are hereafter referred to as augen gneisses.

The microcline-bearing variety is the most abundant type of augen gneiss (fig. 7). It is characteristically migmatitic, especially where it occurs near the contact with the Boulder Creek Granodiorite. Porphyroblasts are generally lenticular and range in size from 4 to 6 cm long and 2 to 3 cm wide. Even larger augen of intergrown masses of quartz and feldspar are locally common where the gneiss is very migmatitic. Thin-section studies revealed the presence of small-scale structures typical of the classic augen gneiss: biotite wrapped around the porphyroblasts; strained quartz and bent biotite and plagioclase lamellae; finely and complexly sutured granulated and healed grain boundaries--especially between quartz metacrysts; and, locally, fractures filled with feldspar, quartz, calcite, apatite, and an unidentified zeolite(?). Study under the petrographic microscope of a thin section of a single porphyroblast, 4 cm long and 1½ cm wide, from a migmatitic garnetiferous biotite gneiss showed relatively fresh microcline poikilitically enclosing small rounded embayed sericitized and commonly myrmekitic crystals of plagioclase, small flakes of biotite partially altered to muscovite, scraps of muscovite, small blebs and larger anhedral grains of quartz, a small anhedral grain of garnet, a smaller subhedral epidote metacryst, and a very small round zircon.

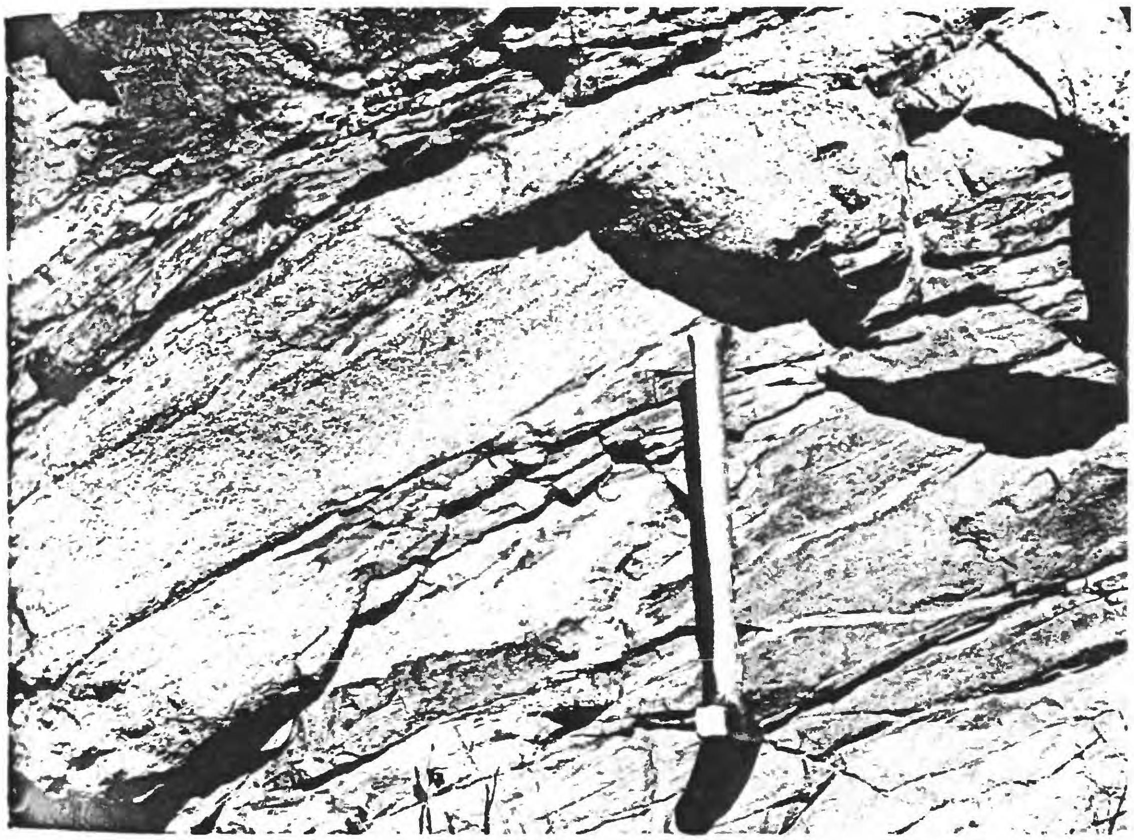

FIGURE 5.--Outcrop of fine-grained biotite gneiss which contains a conspicuous layer of granitic material, in N½ sec. 29, T. 1 N., R. 81 W. This gneiss has an appreciable amount of granitic material, but it can be termed only locally migmatitic because it lacks the thin and complex interlayering of biotite gneiss and granitic material which is characteristic of migmatitic gneiss as defined in this report.

FIGURE 6.--Outcrop of migmatitic gneiss in N½ sec. 29, T. 1 N., R. 81 W.

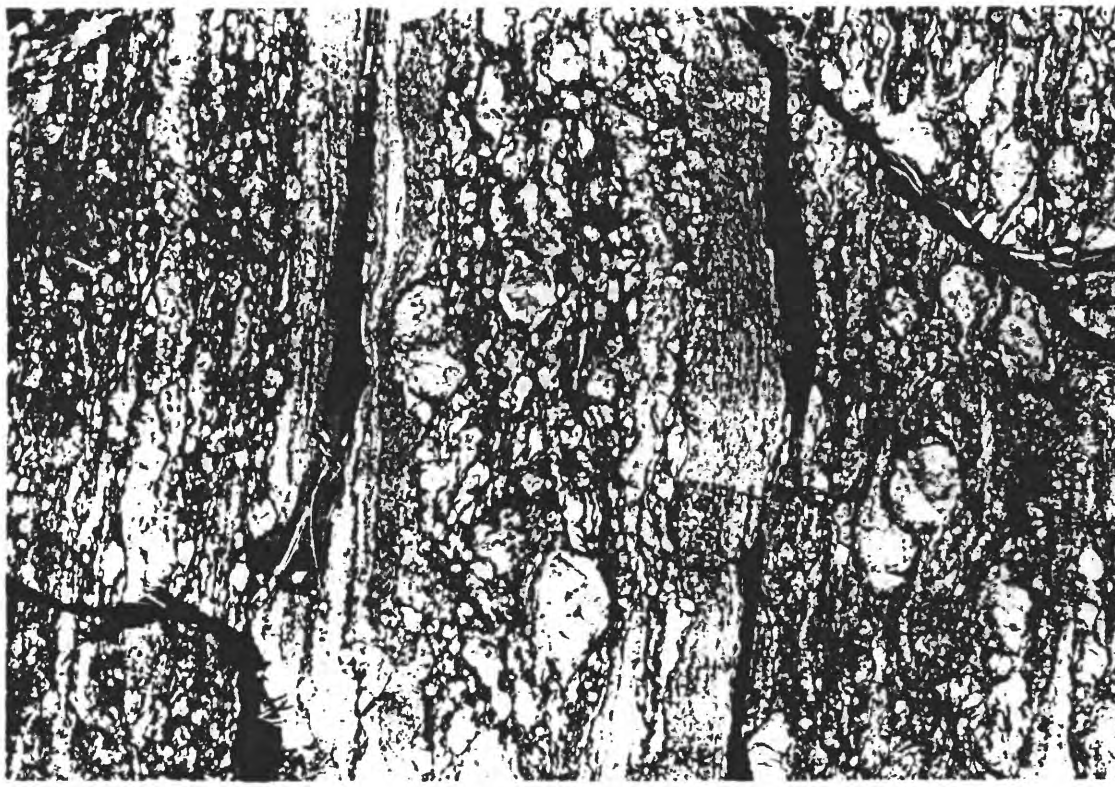

FIGURE 7.--Close view of an outcrop of augen gneiss that contains microcline porphyroblasts, at top of south wall of Gore Canyon in the SW¼NE¼ sec. 27, T. 1 N., R. 81 W.

Amphibolites. Mapped with the biotite gneiss unit are amphibolites, which are biotitic, hornblende- and plagioclase-rich, and quartz-poor rocks that occur in lenticular layers and pods ranging in thickness from little more than 1 foot to at least a few tens of feet. These bodies of rock are variable in texture, rock fabric, thickness, persistence, and structural relations to enclosing gneiss layers. The range in mineral composition of the amphibolites is as follows: 39-67 percent amphibole (predominantly hornblende) and 43-10 percent plagioclase (ranges from Ca-andesine into Ca-labradorite); 0-14 percent biotite and 11 percent to trace amounts of chlorite; 2-7 percent quartz; trace to 16 percent sericite; trace to 7 percent iron ore; trace to 2 percent apatite; and trace amounts to less than 1 percent each of epidote, sphene, calcite, zircon, and prehnite. Most of the sericite and calcite are alteration products of plagioclase, the chlorite is after biotite, the epidote is after plagioclase, hornblende, and biotite, and the prehnite is after biotite.

The most widespread type of amphibolite is a dark-gray and black mottled, weakly to well-foliated and lineated fine- to medium-grained rock which characteristically occurs in thin (1-3 ft) conformable layers. A few very thin (generally less than 1 cm) quartz-plagioclase bands may be present within a layer, and the layers themselves are not uncommonly associated with quartz-feldspar-rich gneiss. Thin sections of the amphibolite generally show subparallel arrangement of biotite plates and hornblende prisms. Mineralogically, this type of amphibolite is differentiated from all the other amphibolites by its relatively high (5-6 percent) quartz content; from a cumuloblastic variety by its very high hornblende to plagioclase ratio; and from a very dark coarse weakly to nonfoliated variety by the presence of abundant biotite. Most flat-stage determinations of feldspar compositions in thin sections of this variety of amphibolite suggest that calcic andesine is the dominant plagioclase.

Another widespread type of amphibolite is a greenish-black medium- to coarse-grained nonfoliated to very weakly foliated nonlineated rock which characteristically occurs in discontinuous lenticular conformable layers less than 1 foot to several feet thick. The layers are commonly, though not abundantly, irregularly and very thinly veined with plagioclase and subordinate quartz. A high hornblende to plagioclase ratio accounts for the melanocratic nature of the rock, and coarse hornblende and the absence of biotite accounts for its weakly foliate to nonfoliate character.

Texturally, the most distinctive and volumetrically the most abundant variety of amphibolite in the biotite gneiss unit is a light-greenish-gray to grayish-green, greenish-black mottled rock with dime- to quarter-size pits on weathered surfaces (fig. 8). The pits are produced by the weathering out of biotite clots, and the texture of the rock is cumuloblastic. The biotite clots are slightly flattened in planes parallel to the foliation of the surrounding rocks. These flattened clots and the subparallel planar orientation of hornblende prisms and streaks of biotite define a weak foliation. The hornblende prisms also locally impart a lineation to the rock. This amphibolite occurs in a few generally conformable, locally crosscutting, lenticular layers and pods which range in thickness from several feet to several tens of feet. The best exposures are in the lower part of the north wall of Gore Canyon in a zone in which biotite gneiss is abundantly intercalated with discontinuous layers of various types of amphibolite for some distance along the strike. It is also fairly well exposed in the San Toy Mountain area where a layer, approximately 40-50 feet thick, sandwiched between biotite gneiss crops out in the scarp of the San Toy Mountain fault just west of the access road to the beacon on San Toy Mountain.

In thin section, the cumuloblastic amphibolite is a hypidioblastic granular rock of which 80-90 percent is nearly equally proportioned plagioclase and amphibole--principally hornblende. The plagioclase is commonly but not always twinned (carlsbad, albite, and

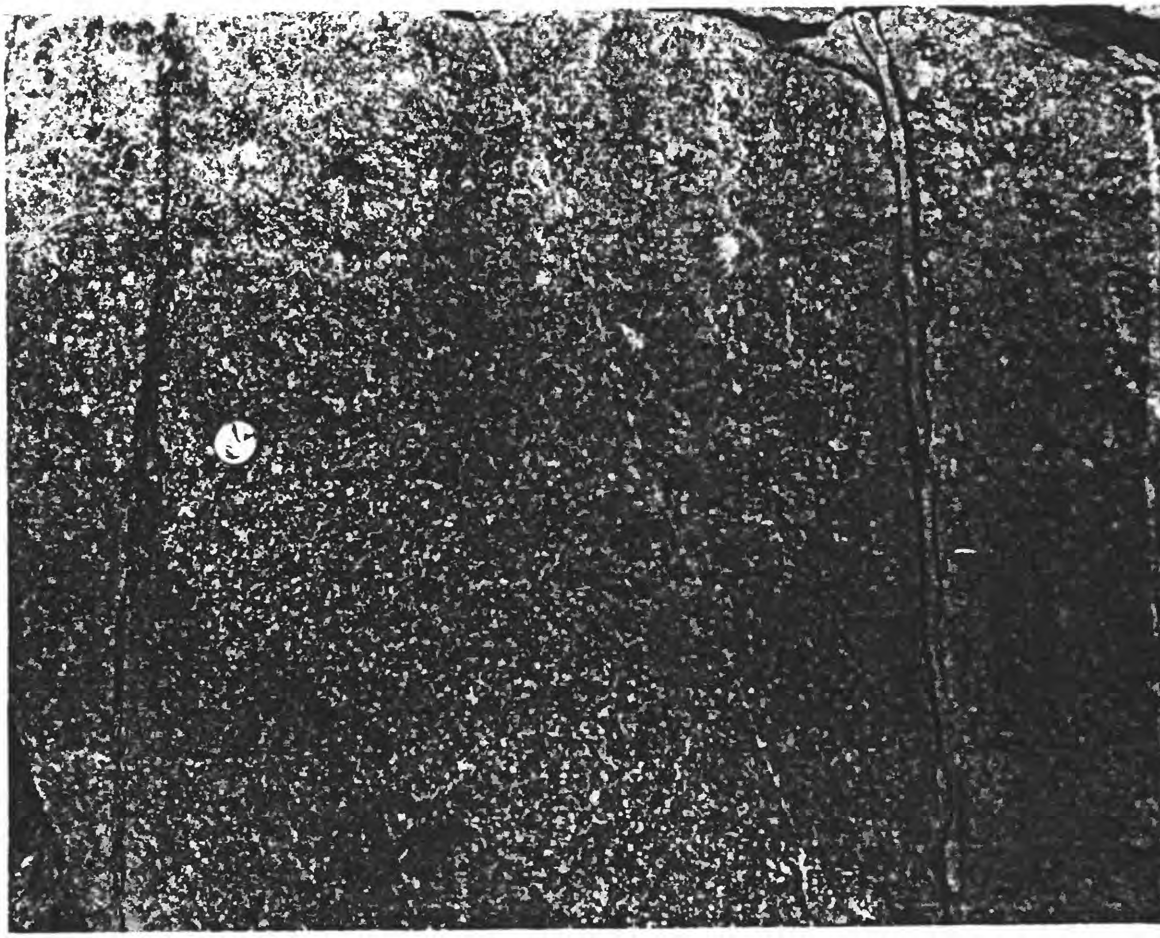

FIGURE 8.--Close view of an outcrop of cumuloblastic amphibolite, in NW¼SE¼ sec. 32, T. 1 N., R. 81 W. Conspicuous pits in surface of rock are from weathering of biotite clots; penny shows scale.

pericline) and very faintly bi-zoned and has a composition ranging from An_{45} to An_{65} by flat-stage determinations. The amphibole is pleochroic, green, yellow-green, and brownish-green hornblende, though some samples also contain lesser amounts of nonpleochroic, colorless optically positive amphibole, which is probably cummingtonite, intimately intermixed with the hornblende. Biotite and lesser amounts of quartz are always present as the next most abundant minerals (4-10 percent total). Sericite, muscovite, epidote, chlorite, prehnite, iron ore, apatite, zircon, and sphene are all commonly present. All the mineral constituents generally appear fresh. Even sericitization of plagioclase is generally restricted to cores and is not strong, though some samples from the strongly folded area just east of the north Gore fault and near the first layers of granodiorite do show strong sericitization.

Other varieties of amphibolite and hornblende gneiss are closely associated with the cumuloblastic variety of amphibolite in exposures within a generally amphibolitic interval or zone of the biotite gneiss unit in Gore Canyon. A coarsely crystalline zone of amphibolite occurs locally in a layer of cumuloblastic amphibolite which crops out near the west end of Gore Canyon (figs. 9, 10, 11). The coarsest rocks of this zone have an almost pegmatitic texture and are composed of large stubby prisms of randomly oriented hornblende in a matrix of milky-white plagioclase. Thin concordant layers of a greenish-black variety of amphibolite that is composed almost entirely of hornblende are not uncommon in cumuloblastic amphibolite. Thick layers of biotitic amphibolite and (or) hornblende gneiss, locally complexly interlayered with biotite gneiss are abundant within and, more especially, along the margins of the amphibolitic zone of the biotite gneiss in Gore Canyon (fig. 12).

Cumuloblastic amphibolite is locally injected with quartz-feldspar. Injections are commonly less than 1 inch thick and in small concentrations; but at the east end of the amphibolitic zone in Gore Canyon, irregularly spaced generally concordant layers of quartz-feldspar, 2-6 inches thick, are very abundant in medium-grained locally hornblende-rich and generally cumuloblastic amphibolite (fig. 13). Quartz-feldspar

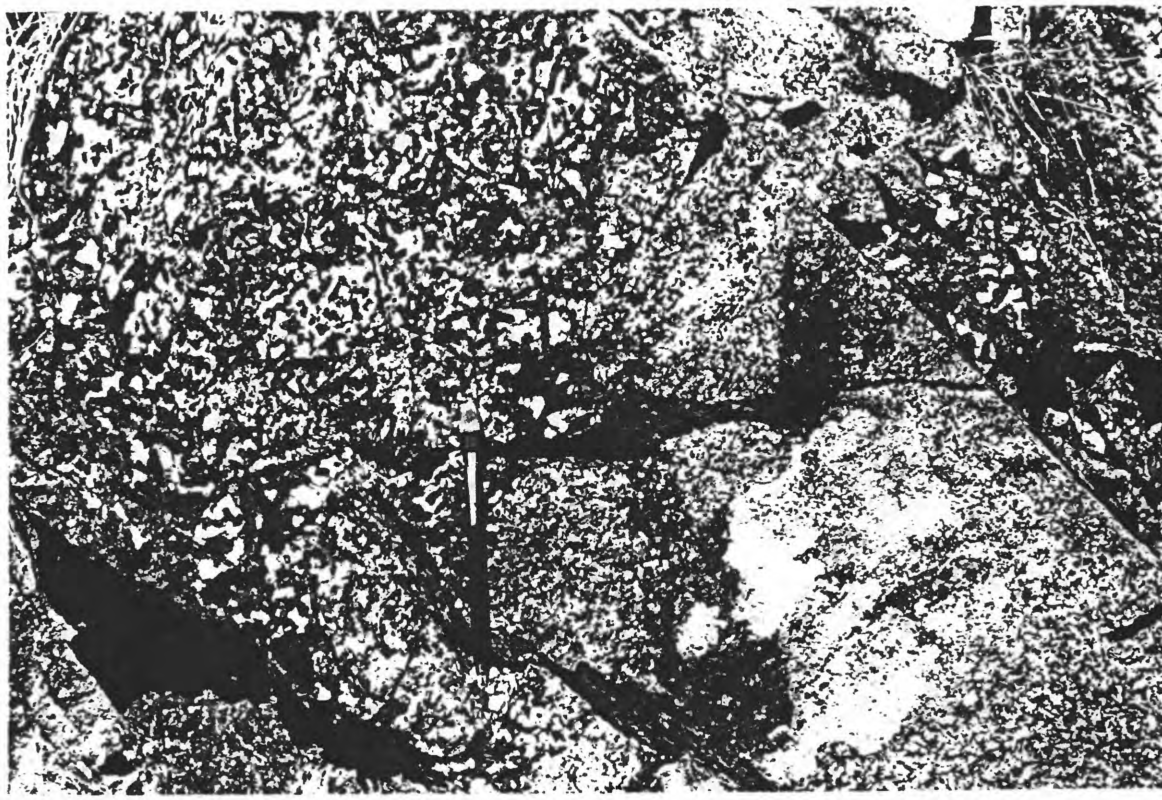

FIGURE 9.--Portion of a coarsely crystalline zone in the interior of a cumuloblastic amphibolite layer that crops out near the railroad tracks in the SW¼SE¼ sec. 32, T. 1 N., R. 81 W. Note the irregular contact between the coarsest rocks of the zone and the enclosing more finely textured amphibolite.

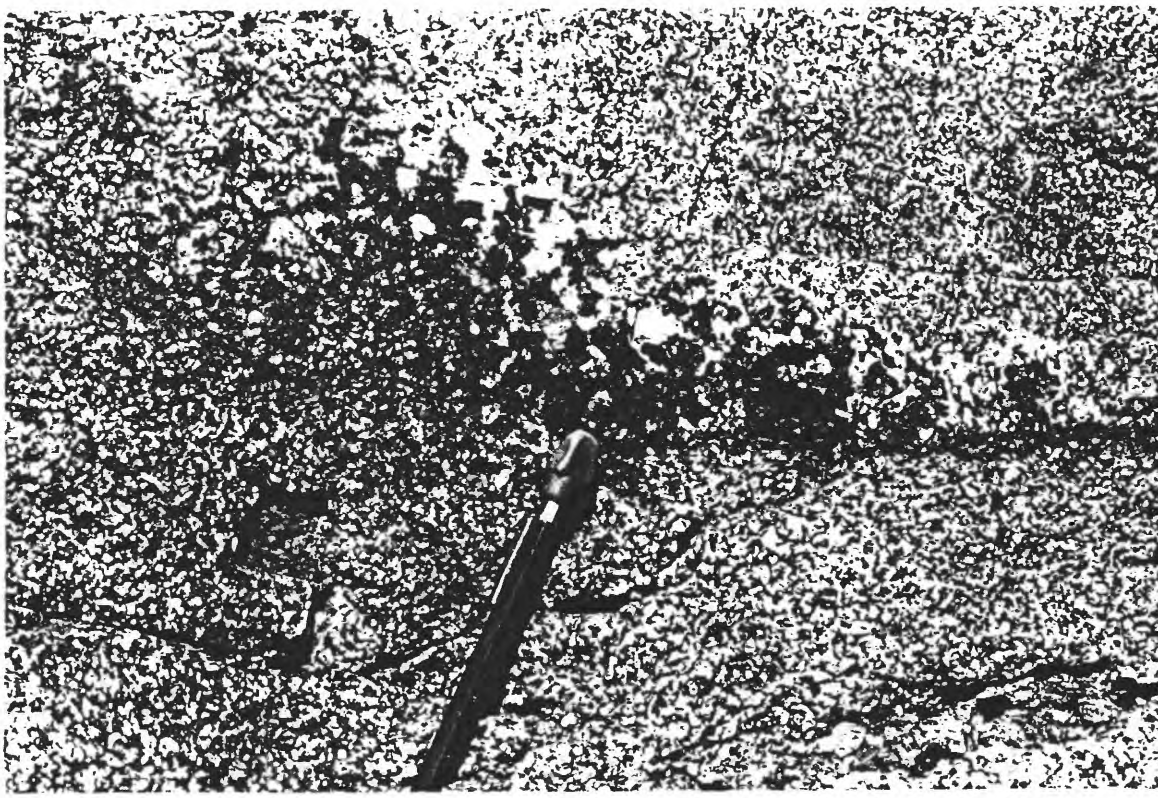

FIGURE 10.--Close view of rock near the margin of a coarsely crystalline zone in the interior of a layer of cumuloblastic amphibolite, showing the details of the contact between the very coarse grained amphibolite of a small lenticle and the enclosing more finely textured amphibolite; in the SW¼SE¼ sec. 32, T. 1 N., R. 81 W.

FIGURE 11.--Close view of very coarse grained amphibolite of a coarsely crystalline zone in the interior of a layer of cumuloblastic amphibolite that crops out near the railroad tracks in the SW¼SE¼ sec. 32, T. 1 N., R. 81 W.

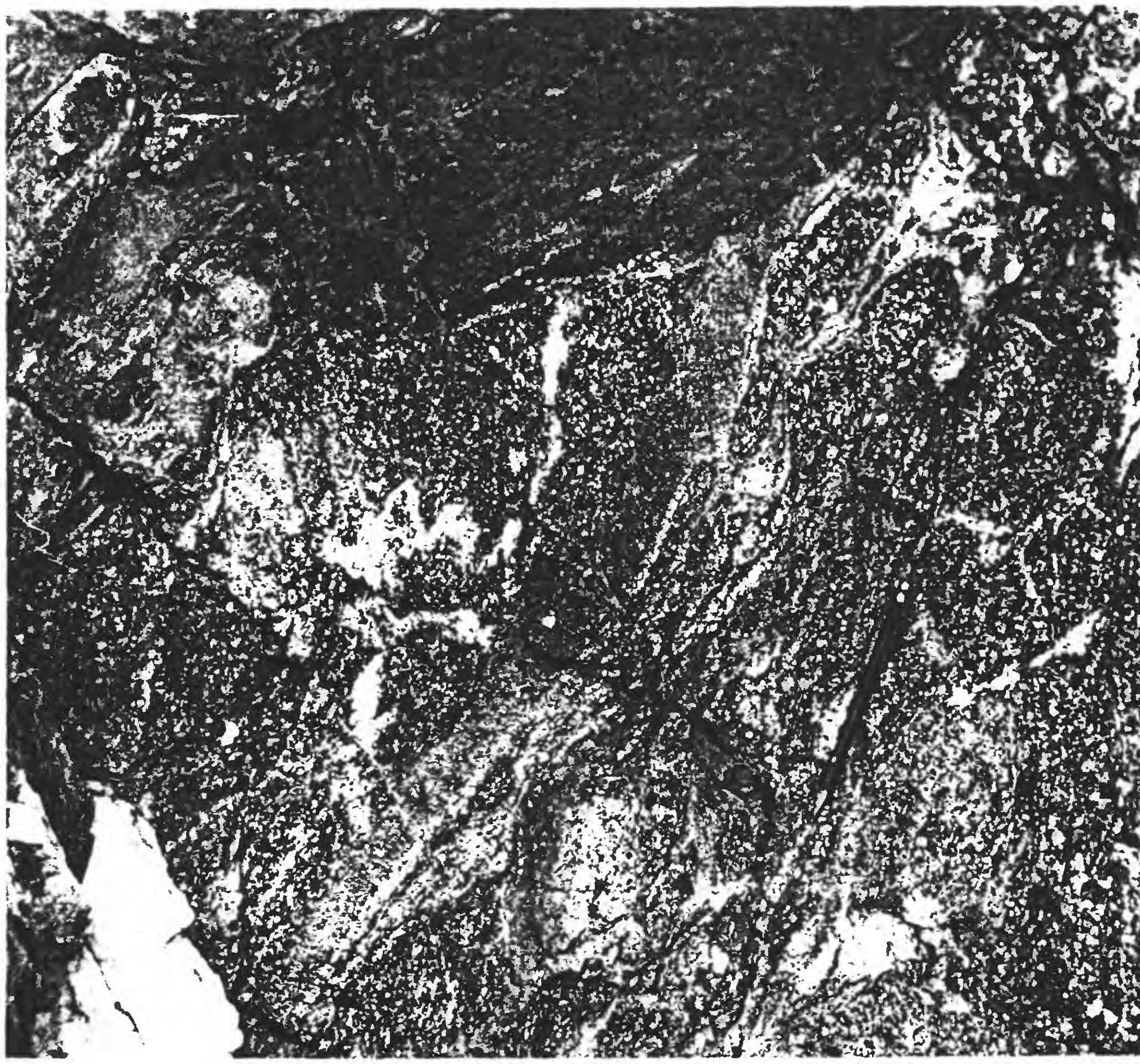

FIGURE 12.--Cumuloblastic amphibolite (lower right) in contact with fine-grained biotitic hornblende gneiss, near the northwest margin of an amphibolitic zone in the biotite gneiss; in the NE¼ sec. 32, T. 1 N., R. 81 W.

FIGURE 13.--An outcrop of hornblende-rich cumuloblastic amphibolite that contains numerous generally concordant quartz-feldspar injections; near the railroad tracks in the NE$\frac{1}{4}$SE$\frac{1}{4}$ sec. 22, T. 1 N., R. 81 W.

bodies in lesser abundance and with more random orientations are in the same amphibolitic zone further to the east. In these more easterly outcrops, shown in figure 14, a complex sequence of injections is documented by the presence of fragments of the enclosing amphibolite in one quartz-feldspar body and by outcrop relations showing that another quartz-feldspar body was cut by a dike of fine-grained (remobilized?) amphibolite.

Amphibolitic Dike Rocks. Thin (½-3 ft) discordant tabular bodies of fine-grained rock with a composition similar to the amphibolites were seen at three localities within the biotite gneiss unit. All occurrences observed are in general areas of outcrop of thick amphibolite layers. Two of these localities are near the west end of the north wall of Gore Canyon. The third locality is in the NW¼ sec. 16, T. 1 N., R. 81 W., where a 3-foot dike cuts biotite gneiss at a large angle to the foliation. At this last locality, abundant amphibolite occurs not far to the west in a portion of the zone mapped as biotite gneiss intercalated with Boulder Creek Granodiorite.

The dikelike body near the west end of Gore Canyon appears to cut layers of cumuloblastic amphibolite and biotite gneiss. Thin sections of the dike show a strongly gneissose fabric produced by the subparallel arrangement of hornblende prisms and epidote-white mica and hornblende-rich zones. The rock is composed of 45-50 percent hornblende, 35-40 percent epidote, 5-10 percent muscovite, 2-4 percent iron ore (mostly magnetite-ilmenite?), 2 percent or less plagioclase, about 1 percent or less each of quartz and biotite, and less than 1 percent to trace amounts each of prehnite(?), leucoxene, sphene, apatite(?), chlorite, and sericite. The epidote may be principally after plagioclase with lesser amounts after hornblende; the muscovite and sericite are after plagioclase and biotite; the prehnite, which occurs as very thin spindle-shaped fibers between biotite lamellae, is after biotite; the chlorite is after biotite and hornblende(?); and the leucoxene is after sphene or titaniferous magnetite. Study of a thin section of a sample collected at the border of this dike revealed more complete epidotization and sericitization of the rock there than in the body of the dike.

FIGURE 14.--Outcrop of hornblende-rich cumuloblastic amphibolite that contains a few conspicuous discordant quartz-feldspar injections. One of the two thickest injections that is shown contains amphibolite xenoliths; the other appears to be cut by fine-grained amphibolite. The outcrop is near the railroad tracks in the NW¼SW¼SW¼ sec. 23, T. 1 N., R. 81 W.

Thin sections of the dike in the NW¼ sec. 16, T. 1 N., R. 81 W., show a fine-grained rock which has a gneissose texture produced mostly by the subparallel alignment of hornblende prisms. It is cumuloblastic and contains clumps of hornblende phenocrysts. In plan the clumps are generally about 3 by 1 mm but some are 5 by 3 mm. The long direction of the clumps is parallel to the general alignment of hornblende prisms. The dike rock is composed of 2 percent or less of quartz, more than 50 percent hornblende, nearly 35 percent plagioclase (andesine), more than 10 percent biotite, and approximately 1 percent epidote. Other minerals present include sericite, iron ore, sphene, apatite, and zircon.

A thick (7 ft) fine- to medium-grained amphibolitic dike crops out low on the north wall between Canyon Creek and the Gore fault. It cuts the biotite gneiss and is cut by a granophyre dike. No thin sections of it were studied but it appears to be composed essentially of hornblende and plagioclase.

Granodiorite, Granodioritic Gneiss, and Mixed Granodiorite-Amphibolite and Granodiorite-Hornblende Gneiss. Granodiorite and various hybrid rocks which are similar and (or) genetically related to rocks of the Boulder Creek Granodiorite are locally present as thin concordant layers or zones within the biotite gneiss unit. Almost all occurrences of these rocks are north of the river and most are within the zone mapped as biotite gneiss intercalated with Boulder Creek Granodiorite.

The granodiorite layers within the biotite gneiss unit vary in composition from biotite granodiorite to biotite-hornblende quartz diorite (fig. 15) and locally contain thin discontinuous layers of partially assimilated migmatitic biotite gneiss. This granodiorite quartz diorite is commonly very gneissic, but outcrops are somewhat rounded and foliation is not conspicuous except where it contains biotite gneiss xenoliths. The granodioritic gneisses are very similar to the granodiorite and may be the result of extensive "soaking" of biotite gneiss by emanations associated with the emplacement of the Boulder Creek Granodiorite. Granodioritic gneisses were distinguished in the

FIGURE 15.--Outcrop of granodiorite-quartz diorite in the zone of biotite gneiss intercalated with Boulder Creek Granodiorite, in the NW¼ sec. 32, T. 1 N., R. 81 W. Foliation dips about 85° NW. toward upper left side of photograph.

field from gneissic granodiorite by their higher biotite content and their fine compositional and textural banding composed of medium- to coarse-grained quartz-feldspar bands and finer grained biotite granodiorite bands.

The most distinctive of the hybrid rocks in the biotite gneiss unit are the mixed granodiorite-amphibolite and granodiorite-hornblende gneiss rocks. They are locally abundant within and north of the amphibolitic zone on the north wall of Gore Canyon. They are commonly composed of fine-grained amphibolite or biotitic hornblende gneiss discontinuously veined and, locally, pervasively soaked with granodioritic material (fig. 16). West of the Gore fault at the west end of Gore Canyon are outcrops of a poorly foliated rock composed of fine-grained amphibolite and hornblende gneiss intimately and irregularly mixed with fine- to medium-grained granodioritic material. Within the mixed rock are knots and thin discontinuous layers of very coarse dark-green amphibolite which consists almost wholly of hornblende.

Petrographic studies were made of samples of the granodiorite and various hybrid rocks which occur within the biotite gneiss unit. The results of these studies, including modal analyses, are discussed in the section on the Boulder Creek Granodiorite.

Pegmatites and Aplites. Conformable and crosscutting pegmatites and aplites occur throughout the biotite gneiss unit. The pegmatites are commonly 2-5 feet thick, but thinner and thicker ones are also present. The thickest pegmatite seen in the area crops out on the south side of the San Toy Mountain fault, west of the beacon access road. This pegmatite body is approximately 30 feet thick and makes a small angle with the general attitude of the enclosing biotite gneiss. It has a quartz-rich core, a few undisturbed conformable biotite gneiss inclusions near its margins, and is locally "ribbed" with northeast-plunging crinkles at its contact with gneiss.

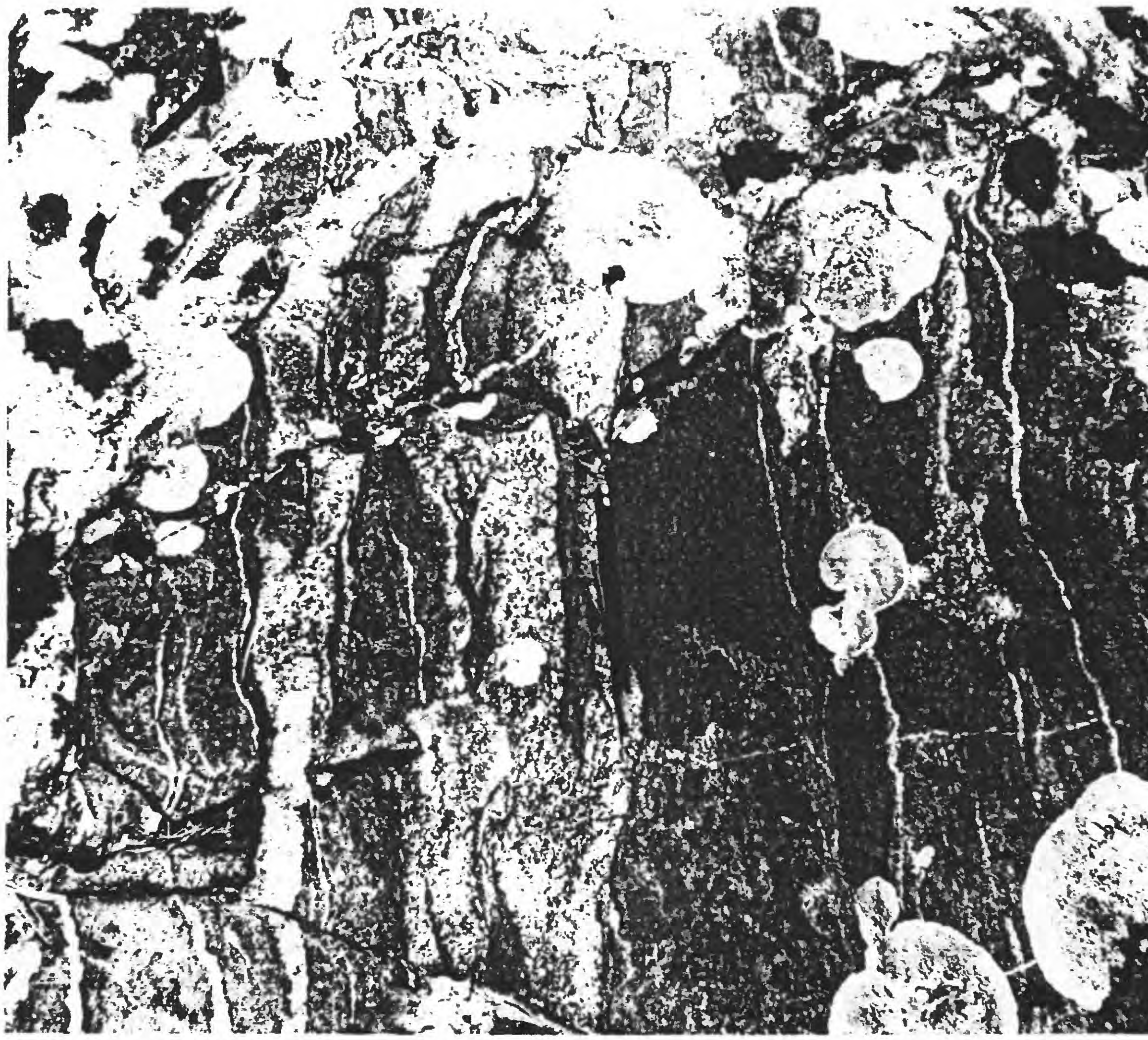

FIGURE 16.--Outcrop of biotitic hornblende gneiss concordantly veined with granodiorite; location is not far north of a zone of amphibolitic rocks in the biotite gneiss; SE¼ sec. 29, T. 1 N., R. 81 W.

The aplites are much less numerous and commonly thinner (generally 1-2 ft thick) than the pegmatites. A thin pinkish-gray, pale-orange-weathering mildly discordant aplite that crops out at Inspiration Point is shown in figure 17. A thin section of a sample from this aplite shows a composition of approximately 49 percent quartz, 20 percent plagioclase, sericite, and microcline, and 30 percent muscovite. The plagioclase is sodic oligoclase, and the sericite appears to have been derived chiefly from plagioclase. Accessory minerals include zircon, apatite, and iron ore. Graphic, myrmekitic, perthitic, and antiperthitic intergrowths are present. One thin section contained a clump of garnet, 2 cm long and 0.5 cm wide, interspersed with poikilitic quartz and shreds of chloritized biotite. This garnetiferous sample was taken near the edge of the aplite, and the enclosing biotite gneisses are garnetiferous. This garnetiferous sample has a higher proportion of microcline than the more central parts of the dike sampled.

The age of the aplites and pegmatites in the biotite gneiss unit is unknown; they are probably of various Precambrian ages.

Structure

The rocks of the biotite gneiss unit are strongly foliated and locally well lineated. Mapping of foliations and lineations revealed that the rocks contain elements of at least two fold systems and that the principal axis of the dominant fold system has a general southwest-northeast trend.

Foliation. Foliation in the rocks is determined principally by planar orientation of platy (biotite, muscovite), tabular (feldspar), and prismatic (sillimanite, hornblende) minerals and by mineral lenses (quartz and quartz-feldspar) and streaks (biotite, muscovite). Compositional layering in the biotite gneiss is parallel with foliation.

In most of the area the foliation strikes northeastward to eastward and dips moderately to very steeply to the northwest on the northwest side of the unit, very steeply northwest to southeast and vertically in

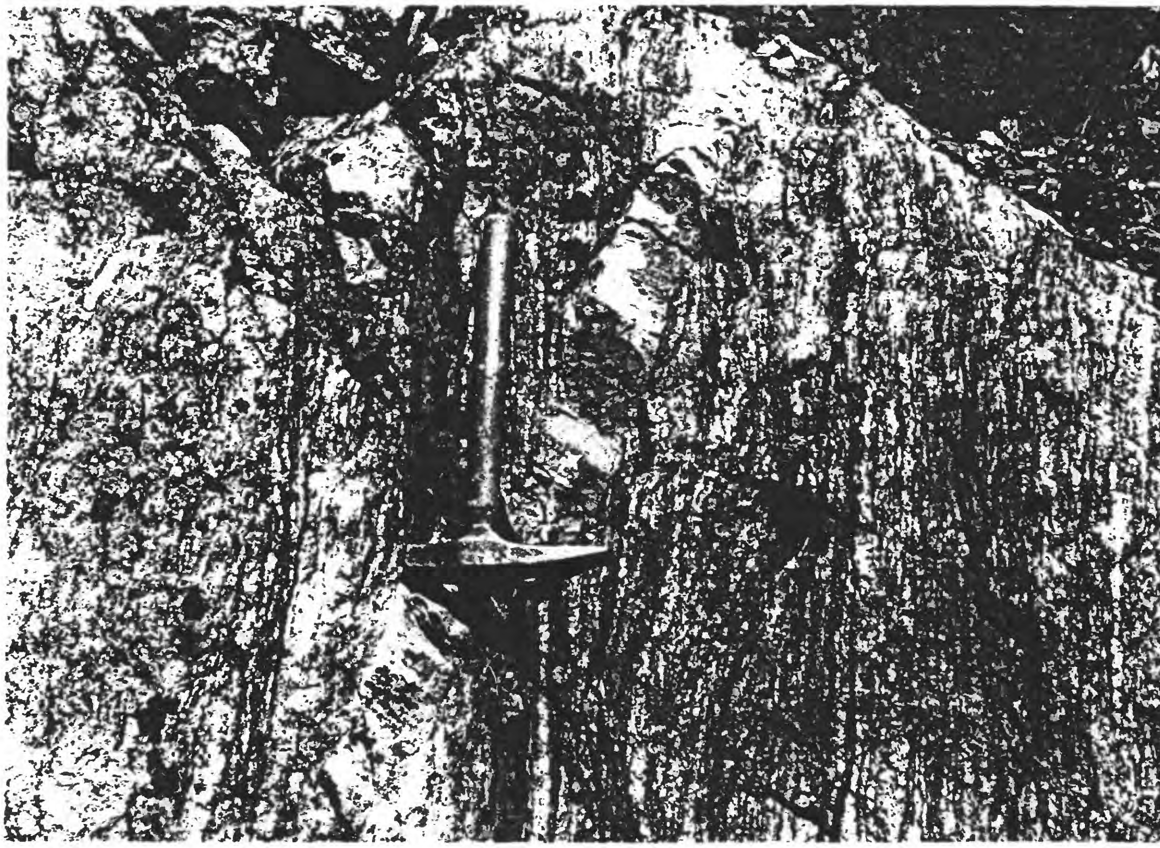

FIGURE 17.--Aplite dike in garnetiferous biotite gneiss at Inspiration Point, SW. cor. sec. 33, T. 1 N., R. 81 W.

the middle and on the south wall of Gore Canyon (fig. 18), and very steeply southeast in the San Toy Mountain-Inspiration Point area. In the far southwestern part of the area, the foliation swings to north-northeast as it approaches the Gore fault zone.

Lineation. Lineation is expressed principally by preferred orientation of prismatic minerals (sillimanite and hornblende), mineral streaks (biotite, muscovite), and mineral lenticles (quartz), by quartz-feldspar or quartz boudins, by slickensides, by the axes of crenulations--sharp "wrinkles" with an amplitude and wave length approximately equal and less than 2 inches each, by the axes of "welts"--slight wrinkles with an amplitude of less than a couple of inches and a wave length about twice that magnitude, and by the axes of small- and, rarely, medium-scale folds. A small-scale fold is herein defined as one with an observable wave length and (or) amplitude of less than 5 feet, and a medium-scale fold is one with an observable amplitude and (or) wave-length of 5-15 feet. An example of a small-scale fold is shown in figure 19. Folds larger than what is herein defined as a medium-scale fold were not seen in the field but their presence is suggested by foliation patterns.

Lineation orientations in the biotite gneiss unit were measured in the field and plotted on the geologic map (fig. 2). The measurements were also plotted on two lower hemisphere Schmidt equal-area projections and the plots were contoured. One of these plots is of measurements taken in the northeastern part of the biotite gneiss outcrop area (fig. 21); the other is of measurements from the southwestern part (fig. 22). Figure 20 is a sketch map showing the data-collection area for each plot. Two separate plots were made to separate the effects of the general swing in structure to a more southerly course in the southwestern part of the area as revealed by foliation and lineation plots on the geologic map.

The geologic map (fig. 2) shows that lineations in the biotite gneiss unit are principally of two general trends. One of these lineation trends parallels the regional northeasterly foliation in the

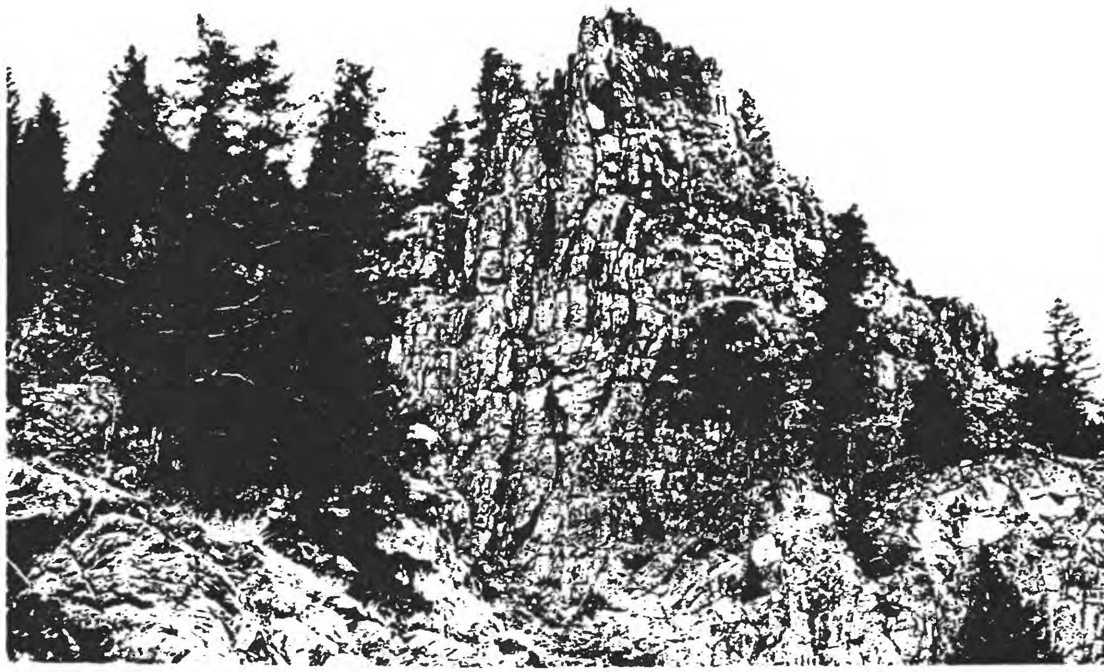

FIGURE 18.--Spire formed in near vertically foliated biotite gneiss on the north wall of Gore Canyon, in the SE¼SE¼ sec. 22, T. 1 N., R. 81 W.; view is to the northeast.

FIGURE 19.--Small-scale northeast-plunging fold in biotite gneiss at Inspiration Point in the SW. cor. sec. 33, T. 1 N., R. 81 W. The handle of the hammer is approximately parallel to the axis of the fold and to crenulation axes on the fold.

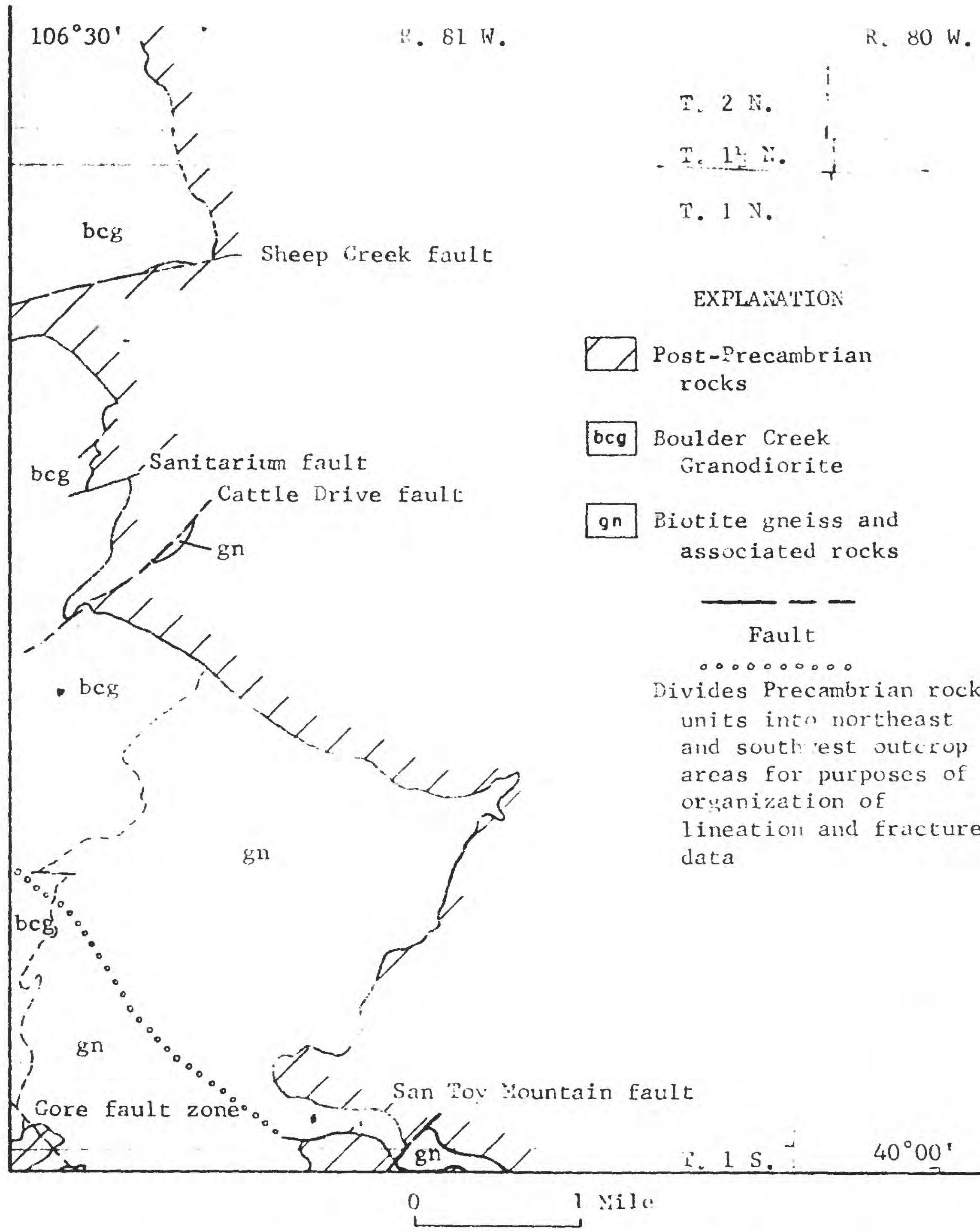

Figure 20.--Sketch map showing the distribution of major Precambrian rock units and the areas covered by lineation, shear, and joint plots of figures 21, 22, and 42-46.

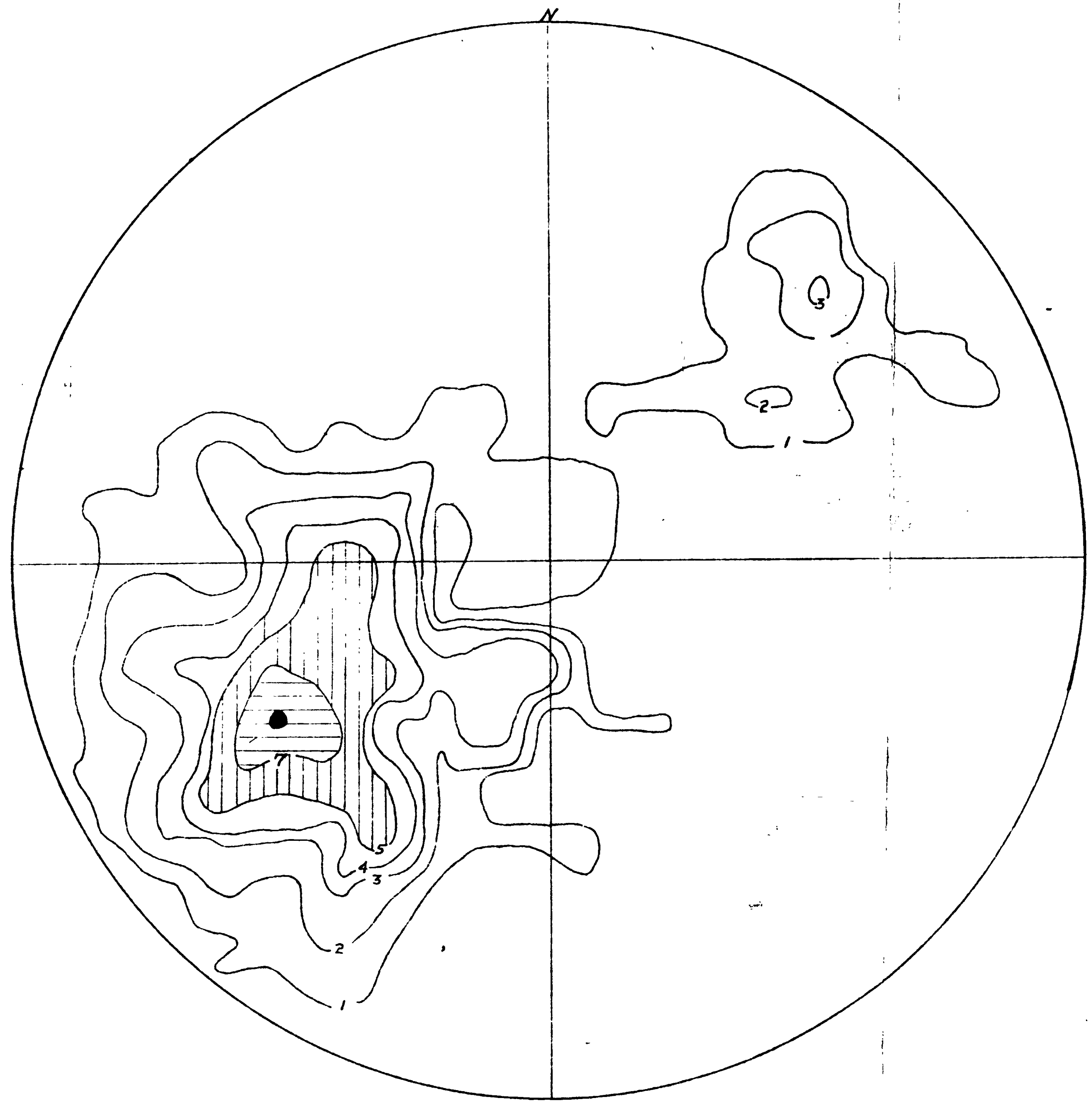

Figure 21.--Lineations in the biotite gneiss unit, northeastern part of its outcrop area. Contour diagram of lower hemisphere of Schmidt equal-area projection of 224 poles. Contours, in percent: 1, 2, 3, 4, 5, 7

Area containing 5-7 percent of pole projections

Area containing 7-9 percent of pole projections

Area containing over 9 percent of pole projections

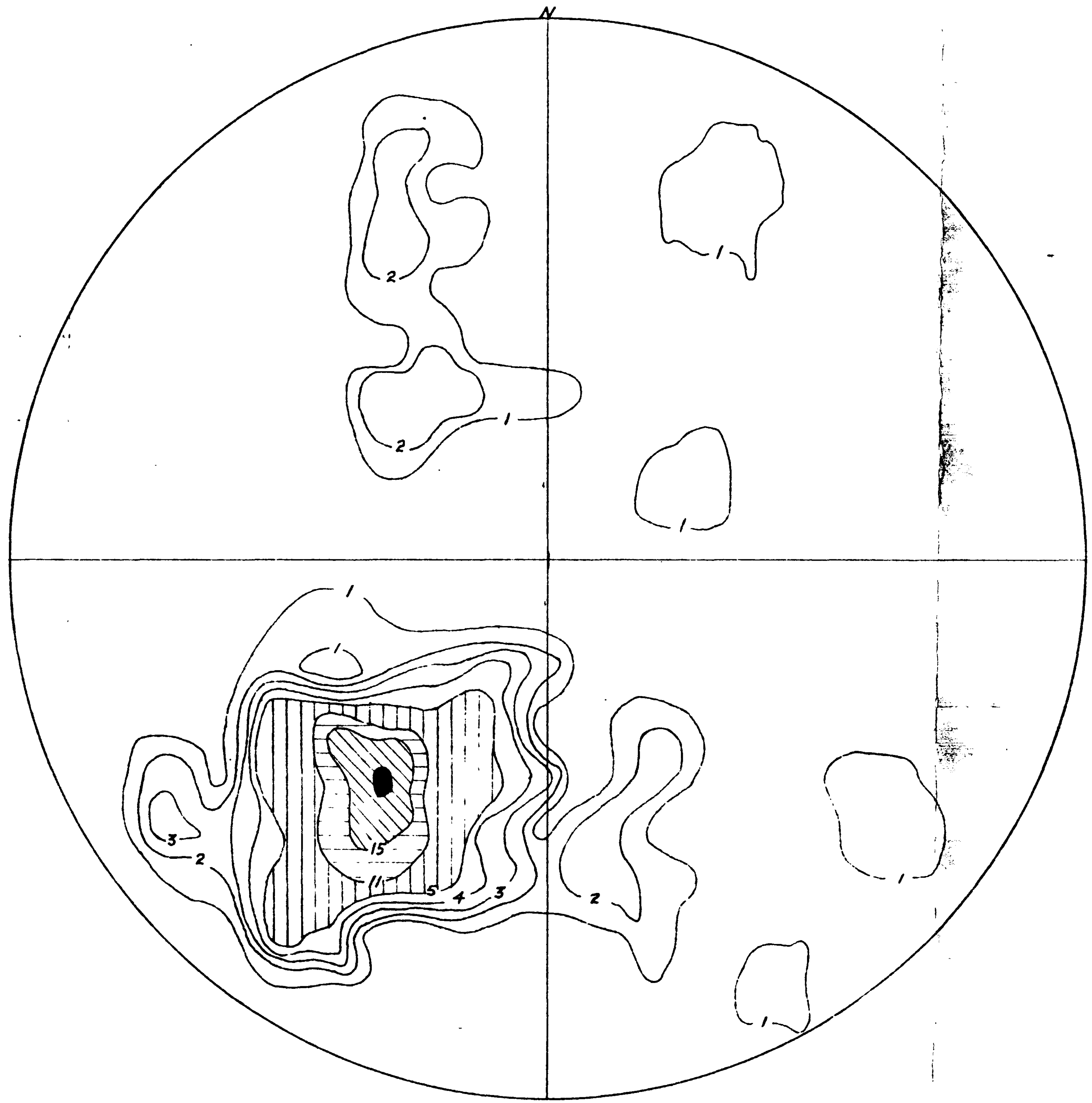

Figure 22.--Lineations in the biotite gneiss unit, southwestern part of its outcrop area. Contour diagram of lower hemisphere of Schmidt equal-area projection of 110 poles. Contours, in percent: 1, 2, 3, 4, 5, 11, 15

Area containing 5-11 percent of pole projections

Area containing 11-15 percent of pole projections

Area containing 15-20 percent of pole projections

Area containing over 20 percent of pole projections

biotite gneiss and is very conspicuous. The other is a much less conspicuous northwesterly one at an acute angle to the first. Detailed outcrop studies were made to determine the geometric relationships among the various linear structure elements and foliation in the biotite gneiss. Some of these studies are summarized in table 2, a table of paired or grouped lineation measurements. These studies, supported by analysis of Schmidt equal-area net plots of lineation measurements (figs. 21, 22) suggest that the rocks of the biotite gneiss unit contain elements of at least two fold systems.

In this paper the linear elements of the two fold systems are referred to a letter-designated coordinate system similar to the scheme used by Sims and Gable (1964, p. 41). Lineations parallel to the principal axis of each fold system are designated B; those lineations perpendicular to the B direction are designated A. B is a b axis, the axis of internal rotation of petrofabric terminology; A is an a axis, the axis of tectonic transport relative to a B axis; it is also commonly a b axis.

The principal axis of the oldest fold system of the biotite gneiss unit for which there is evidence is paralleled by lineations that now trend northwest to north-northwest and is designated B_1. The fold system of B_1 is referred to in abbreviated form as the northwest fold system at some places in the text. Lineations parallel to B_1 are represented by the very weak maxima between 20° N. 20° W. and 36° N. 26° W., 59° N. 29° W. and 58° N. 47° W., and 55° S. 29° E. and 42° S. 10° E., as shown on figure 22. Lineations whose plots form these maxima are mostly the axes of small-scale folds and crenulations and some indistinct biotite and muscovite streaking. Some quartz-feldspar boudins and quartz rods with maximum cross-sectional area on the order of a few inches were also plotted on figure 22 and fall within B_1 maxima although they probably represent A lineations of a superposed northeast fold system (see (1) of table 2).

The principal fold axis of the youngest fold system in the biotite gneiss unit is paralleled by lineations which trend northeast to east-northeast and is herein labeled B_2. The fold system of B_2 is referred to in abbreviated form as the northeast system at some places in the text. The B_2 axis is represented by a strong lineation maximum near 41° S. 60° W. and a weaker one near 30° N. 45° E. in the northeastern part of the biotite gneiss (fig. 21) and a strong maximum near 47° S. 35° W. in the southwestern part of the area (fig. 22). B_2 lineations are axes of small folds and crenulations, biotite and muscovite streaking, and--not present in the northwest fold system--alignment of hornblende and sillimanite prisms. Northeast- and southwest-plunging striae or grooves on northeast-striking foliation planes are locally present and are abundant on the south wall of the canyon: they are A_2 lineations for steep-limbed near-isoclinal B_2 folds. At a few locations these striae or grooves are paralleled by crinkles and by quartz and quartz-feldspar boudins and (or) mullions, all of which are also A_2 lineations of the near-isoclinal folds. North-northwest- and south-southeast-plunging quartz rods and quartz-feldspar boudins with cross-sectional areas on the order of a few inches occur in moderately dipping rocks just east of Canyon Creek. These linear features occur near a swing from NE. to NNE. in the regional foliation and are believed to be A_2 lineations.

Some departure from the conditions of plastic deformation occurred during the later stages of northeast-east-northeast folding of the biotite gneiss unit and the emplacement of the Boulder Creek Granodiorite. Evidence for this includes the following features, all of which occur in foliation layers or in zones concordant with the structural grain imposed by folding about the northeast-trending major fold axis, B_2: augen gneiss in the biotite gneiss unit, faint but widespread protoclastic structures in the Boulder Creek Granodiorite, and cataclastic structures in rocks of the zone of biotite gneiss intercalated with Boulder Creek Granodiorite and in shear zones in the Boulder Creek Granodiorite. All these features suggest that as northeast folding of the biotite gneiss and syntectonic intrusion of the Boulder Creek Granodiorite progressed, deformation took place at higher and higher levels in the crust.

The evidence for the two proposed fold systems and their relative ages consists of single outcrop examples of one fold system warping or folding a fold or lineation of another system (table 2). Identification of these two fold systems on the contoured Schmidt plots is difficult and can only be approximate, even though their existence is convincingly documented by field evidence, for the A folds of one system are close enough to the B folds of the other to distort the B-axis maximum for each system. In figure 22 the maxima in the northwest and southeast quadrants contain A_2 and B_1 lineations. The general case requires A lineations of a given fold system to be near right angles to B lineations of the same system. Such geometric considerations of paired lineation data as presented in table 2 and of the relationships among maxima on the lineation plot of figure 22 suggest that the B axis of the older fold system is most nearly represented by maxima near 58° N. 37° W. and 55° S. 29° E. The maxima in the NW. and SE. quadrants which represent lineations with a more shallow plunge in combination with a trend closer to the north-south line are probably A_2 lineations. The abundance of these A_2 lineations in the southwestern part of the area is related to the deflection of the general trend of structure elements of the B_2 system to a more southerly trend.

There is some field evidence (table 2) for a third, and possibly, a fourth fold system, both intermediate in age between the northwest and northeast systems. One of these systems has lineation trends of N. 80° W. to east-west, and the other has lineation trends of N. 30° E. to north-south. Most of the lineations in these two systems are the axes of small folds and crenulations or, less commonly, biotite and muscovite streaks. In the very few outcrops displaying both of these possible additional systems, the more northerly trending system appears to deform the other. However, rather than representing two additional fold systems, these lineations probably only represent scatter in the orientation of structural elements of the principal northwest and northeast systems.

The interpretation of the presence of more than one fold system in a given body of rocks is uncertain. In the Colorado Front Range, Harrison and Wells (1956) in the Freeland-Lamartine district and Moench, Harrison, and Sims (1962) and Moench (1964) in the Idaho Springs-Central City area have identified and related two different fold systems in Precambrian paragneisses to two different Precambrian deformations. In the Hot Sulphur Springs quadrangle (fig. 1) Izett (1968) interprets two principal fold directions in similar rocks as representing two periods of Precambrian folding. In the general case, other interpretations are possible. More than one major fold system could develop in one general period of folding as a result of the continuously changing geometry of the rock body being folded. Faulting and foundering of confining walls, intrusion, and (or) migration of the deforming body into new sites could also produce more than one fold system during one fold episode. Additionally, fold systems with different orientations could develop during the same fold episode in different parts of a nonhomogeneous structure. In the Gore Canyon area, small-scale folds of the northeast fold system appear to deform linear elements of the northwest system; it is not known if these two systems represent two separate Precambrian deformations or if remnants of fold systems developed during successive phases of a single episode of folding.

Folds. The absence of stratigraphic markers in the gneisses and the generally steep to near-vertical foliation prevented the identification and tracing out of large-scale folds. The only large-scale fold that was found is known only from interpretations of data on planar and linear structure elements.

The only large-scale fold that could be located in the biotite gneiss unit is a large B antiform of the northeast-east-northeast-trending fold system. The position and general trend of the axis of this antiform is approximately defined by the northwest to southeast change in regional dip of the foliation supported by a less pronounced shift in the same sense of B_1 and A_2 lineations. A few small drag folds slightly overturned to the southeast were seen in biotite gneiss outcrops on the lower half of the south wall of Gore Canyon (cross section C-C', fig. 2). The drag folds indicate that the axial trace of the antiform lies near and to the south of the Colorado River. The map (fig. 2) and the lineation plots (figs. 21, 22) show a preponderance of southwest-plunging over northeast-plunging B_2 lineations, especially in the southwestern part of the area, which suggests that this antiform has a southwest plunge which steepens toward the southwest corner of the map area and the Gore fault.

Origin and Age. Compositional layering on a small and a large scale and the mineralogy of the various layers suggest that the biotite gneiss unit was probably derived from a sequence of interbedded quartzose and argillaceous clastic sedimentary rocks which were regionally metamorphosed, folded, and migmatized at high temperatures and pressures. A metasedimentary origin for Precambrian metamorphic rocks which are very similar to the biotite gneiss in the map area was proposed by various authors working in the Colorado Front Range. Sims and Gable (1964, p. 25) believed that "biotite gneisses [of the Central City district] were derived from graywacke sandstone and shaly sediments" and "microcline gneiss * * * from feldspathic sandstones (arkose?)."

The amphibolites within the biotite gneiss are probably of various origins, a conclusion also reached by Sims and Gable (1964, p. 30) for those intercalated with the biotite gneisses in the Central City district. Some of the thin fine-grained layers were undoubtedly derived from iron carbonate-rich rocks interbedded with the sandstones and shales. The thick irregular bodies and concordant layers of massive cumuloblastic amphibolite may have been basaltic flows and (or) basaltic or gabbroic sills.

The origin of the rare hornblende-rich dikes is not known. The close association of those near the west portal of Gore Canyon to thick lenticular layers of cumuloblastic amphibolite suggests that some may have been feeders for mafic flows or sills.

The mineral assemblage quartz-almandine-sillimanite-microcline occurs in some layers of the biotite gneiss unit and indicates that metamorphism reached the upper part of the almandine-amphibolite facies as described by Fyfe, Turner, and Verhoogen (1958, p. 230-232). These high-grade conditions prevailed during at least part of the last plastic deformation of the biotite gneiss unit, for sillimanite needles parallel to B_2 fold axes are characteristic of that deformation. Later, and perhaps initiated by the nonplastic deformation in the late stages at the end of the last period of folding and (or) the syntectonic intrusion of the Boulder Creek Granodiorite, the rocks were retrograded. Retrograde effects include development of sericite after sillimanite and plagioclase, some decalcification of plagioclase as indicated by the formation of epidote in plagioclase, the formation of epidote after hornblende and biotite, and the partial replacement of biotite by muscovite and, less commonly, by chlorite. Microcline in the microcline-sillimanite assemblages of the highest grade rocks is commonly only represented by patches of muscovite adjacent to myrmekitic borders of plagioclase.

The age(s) of the rocks from which the biotite gneiss unit was derived is unknown. Hutchinson and Hedge (1967) believed that the regional metamorphism which produced the biotite gneisses of the Colorado Front Range is part of an orogeny, their Boulder Creek orogeny, which extended from 1.74 billion years to 1.69 billion years. The biotite gneiss of the Gore Canyon area was probably produced during the same orogeny and within approximately the same time interval as the Front Range gneisses.

BOULDER CREEK GRANODIORITE

Granodiorite of Precambrian age is the predominant core rock of the Gore Range in the northern part of the area. Along its southern border, this granodiorite intrudes and is generally concordant to and interlayered with the biotite gneiss unit. In the western part of the map area, the granodiorite is cut by Precambrian micrograngphyre dikes and thick quartz veins. The compositional range of rocks included within the granodiorite unit is quartz monzonite to quartz diorite. This granodiorite is termed the Boulder Creek Granodiorite on the basis of its similarity in composition, texture, style of emplacement, and age to the Precambrian Boulder Creek Granodiorite of the Front Range west and southwest of Boulder, Colo. (fig. 1), and to rocks mapped as Boulder Creek in the Hot Sulphur Springs quadrangle (Izett, 1968) and in the Bottle Pass quadrangle near Fraser, Colo. (R. B. Taylor, oral commun., 1964).

The Boulder Creek Granodiorite is exposed along the west flanks, the crest, and the upper east slopes of the Gore Range north of Gore Canyon. Reconnaissance outside the area indicates that the Boulder Creek extends beyond Gore Pass to the north and into much of the Blacktail Creek drainage to the west.

The Boulder Creek Granodiorite was not mapped south of the Colorado River, although rocks which were mapped as part of the biotite gneiss unit but which may be related to the Boulder Creek Granodiorite occur in a few widely scattered outcrops in the northwestern part of sec. 4, T. 1 S., R. 81 W., and the SW¼ sec. 34, T. 1 N., R. 81 W. The largest of these outcrops is in sec. 4. It shows the southeast edge of an apparently concordant layer of rock several tens of feet thick with a composition and fabric similar to hybrid rock mixtures of granodiorite and biotite gneiss that occur near the contact between the Boulder Creek and the biotite gneiss unit.

The best outcrops of the Boulder Creek Granodiorite were found along the crest and thinly wooded to open western slopes of the Gore Range in the upper part of the Canyon Creek drainage.

Outcrops of the Boulder Creek Granodiorite are generally rounded; the more biotitic varieties are commonly deeply weathered and have a crumbly surface. Most of the other areas in which the Boulder Creek is at the surface are heavily timbered and a gritty soil mantles the rocks.

The Boulder Creek Granodiorite intrudes and is generally concordant to the biotite gneiss north of the Colorado River along a northeast-trending zone, 0.1-0.5 mile wide, within which the two units are complexly interlayered. This zone of interlayering is mapped as a mixed zone of biotite gneiss intercalated with Boulder Creek Granodiorite. North of this mixed zone, the Boulder Creek contains inclusions of migmatitic biotite gneiss and coarsely recrystallized partially assimilated amphibolitic rocks. The biotite gneiss xenoliths and at least some of the amphibolitic xenoliths were probably derived from the biotite gneiss unit. The largest of the xenoliths are shown on the map (fig. 2).

Rock Descriptions

The Boulder Creek Granodiorite is a predominantly medium- to coarse-grained light- and dark-mottled gray, tan, or pale-orange to pink generally gneissic granitoid rock which chiefly contains visible quartz, feldspar, and biotite and small amounts of hornblende. Characteristically, the Boulder Creek is a granodiorite (-quartz monzonite) but locally where large amounts of xenolithic material, especially amphibolite, have been partially assimilated, rock composition differs markedly from granodiorite (-quartz monzonite). Amphibolitic contamination and the presence of late quartz-alkali feldspar-rich rocks account for a compositional range of melanocratic quartz diorite (diorite) to leucocratic quartz monzonite (monzonite) for rocks of the Boulder Creek Granodiorite. In addition, the Boulder Creek contains some late pegmatite and aplite. The relation among the various rock types and the identification of the principal intrusive phases were difficult to determine owing to poor exposures and widespread contamination by invaded rocks.

Mineralogic compositions characteristic of the various rock types were determined by modal analyses (point-count method) of thin sections of outcrop samples. A representative collection of these analyses are presented in table 3.

Hornblende Biotite Granodiorite-Biotite Quartz Monzonite. The most abundant rock types of the Boulder Creek Granodiorite of the area are in a gradational series from light- and dark-gray-mottled medium- to coarse-grained hornblende biotite granodiorite to a pale-orange-tan, greenish-black-mottled coarse- to medium-grained locally porphyritic biotite quartz monzonite. Preferred orientation of biotite, hornblende, quartz lenticles, and tabular feldspar phenocrysts impart a gneissic structure to the rocks, although locally this structure is faint. Rocks in this series are most abundant and best exposed in portions of secs. 8, 17, and 20, T. 1 N., R. 81 W. (fig. 23).

Thin sections of rocks in the compositional series hornblende biotite granodiorite-biotite quartz monzonite were studied. Typically, rocks in this series have an inequigranular seriate texture. Porphyritic varieties with microcline phenocrysts as large as 3 cm on an edge are also present. Fine- to medium-grained rocks which comprise a very minor amount of this compositional series commonly have a texture approaching hypidiomorphic granular. In thin section, most rocks of this series reveal a gneissose fabric defined by parallel to subparallel arrangement of platy and tabular minerals and lenses of monomineralic aggregates. Because of the coarseness of most textures of rocks of this series, this fabric is not as conspicuous as its megascopically discernible counterpart, the gneissic structure seen in outcrop. Modal analyses (table 3A) by the point-count method suggest that the following are the normal ranges in the abundance of compositionally significant minerals: 15-35 percent quartz, 45-30 percent plagioclase, 5-25 percent microcline, trace to 2 percent myrmekite, 10-15 percent biotite, and 5-0 percent hornblende. Other minerals generally present are, in normal order of decreasing abundance, sericite and very subordinate clay, epidote, muscovite and subordinate hydromuscovite?, sphene, iron ore, apatite, prehnite and hydrogarnet?, chlorite, zircon, calcite, and leucoxene. Quartz is in variously sized anhedral grains which not uncommonly are strained and have a slight undulatory extinction. Plagioclase is subhedral to anhedral and, except for locally occurring phenocrystic

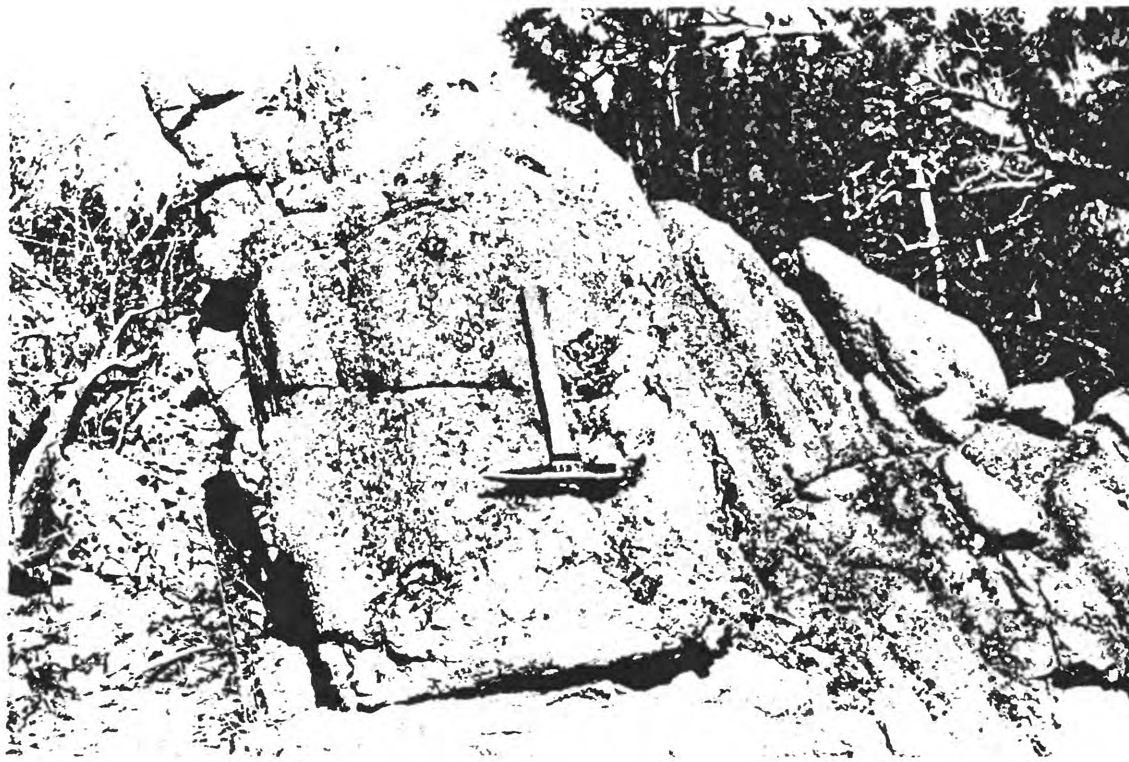

FIGURE 23.--A typical outcrop of rock within the granodiorite-quartz monzonite series of the Boulder Creek Granodiorite, in the SE¼ cor. NW¼ sec. 20, T. 1 N., R. 81 W. Geologic pick lies in plane of foliation which dips very steeply to right or southeast.

microcline, forms the largest phenocrysts in the rock; it is normally twinned on one or more of the albite, carlsbad, and pericline laws. Albite twin lamellae are slightly bent in some samples. Plagioclase commonly has a poorly defined normal igneous or a "mottled" zoning and an approximate composition of 29-37 percent anorthite as determined by flat-stage optical methods. Microcline occurs mostly as antiperthitic platelets toward the granodiorite end of the series and tends to be anhedral and porphyrocrystic and perthitic toward the quartz monzonite end. Brown to tan to greenish biotite and (or) green to brownish-green hornblende form subhedral phenocrysts which commonly occur in clumps with iron ore, sphene, epidote, apatite, and zircon. Iron ore occurs principally as hematite in scattered grains, between plates of "bleached" or chloritized biotite, or in irregularly shaped clumps with hornblende, sphene, and (or) epidote. Lesser amounts of black iron oxide are present in similar association. Rarely, red and orange iron-oxide pseudomorphic after euhedral pyrite is also present. Epidote is mostly light-yellowish-green optically negative pistacite and occurs in anhedral and subhedral prisms with biotite and hornblende and in plagioclase. Rare euhedral to subhedral phenocrysts of reddish-brown primary allanite are also present. Sphene is common to the Boulder Creek Granodiorite; it has a coating of leucoxene in some samples and may be after titaniferous magnetite. Apatite is in single euhedral crystals and in aggregates of anhedral ones associated with sphene, iron ore, and epidote. Bleached biotite (hydromuscovite?) and muscovite and, much less commonly, chlorite occur with iron-ore grains after biotite. Prehnite and, tentatively, a hydrogarnet have been identified by C. T. Wrucke (1965) in the Boulder Creek Granodiorite and related "metagabbro" near Boulder, Colo. The minerals occur as "lens-shaped aggregates" between biotite plates. Similar material occurs in this granodiorite-quartz monzonite series and in the amphibolitic hybrids and xenoliths as well. Some sericitic alteration of plagioclase not uncommonly accompanied by well-formed coarser muscovite and, rarely, by calcite is pervasive throughout the Boulder Creek. Zircon is not abundant and when it is present is in grains so small as to be detected initially only by radiation-damage halos in biotite.

Leucocratic quartz monzonite. Locally associated with the rocks of the hornblende biotite granodiorite-quartz monzonite series are subordinate amounts of leucocratic, pale-orange to pink quartz monzonite. Included within this leucocratic phase of the Boulder Creek are fine- and medium-grained aplitic rocks and lesser amounts of medium- to coarse-grained and locally porphyritic rocks. The aplitic rocks seem to be most abundant in areas of large amounts of partially assimilated amphibolitic rocks. Aplitic quartz monzonite appears in general to be in concordant tabular bodies in sharp contact with the enclosing coarser grained rocks, but small irregularly shaped bodies and ragged contacts were also seen. Pegmatite and aplite dikes, which are thin (less than 1 ft) and commonly rare in most of the Boulder Creek Granodiorite, are relatively common, but remain thin, in the general areas of outcrop of aplitic quartz monzonite. The medium- to coarse-grained locally porphyritic variety of leucocratic quartz monzonite seems to occur in concordant lenticular bodies or zones in gradational contact with hornblende biotite granodiorite-biotite quartz monzonite and in sharp contact with aplitic quartz monzonite, although exposures sufficient to clearly determine these relations were not found.

Several samples of the leucocratic quartz monzonite, both the aplitic and the coarse-grained varieties, were studied under the petrographic microscope. Unfortunately, the best exposures of the leucocratic rocks, especially the aplitic ones, are along fracture-controlled drainages in the northern part of the area. Key samples from these exposures contain late and post-crystallization structurally induced features of texture, fabric, and composition. These secondary features have replaced or destroyed many of the primary petrographic characteristics of the rock. As a result, the early petrologic history of rocks of the leucocratic phase is only generally known.

The medium- to coarse-grained leucocratic rocks have an equigranular seriate texture. The finer grained aplitic leucocratic rocks tend toward a more equigranular texture. Many of the samples of leucocratic rocks examined under the petrographic microscope show some protoclastic and (or) cataclastic textures: bent plagioclase twin lamellae and biotite plates, "crinkles" across and slight offsets of biotite lamellae, and granulation and recrystallization along the borders of large plagioclase and quartz phenocrysts.

Compositionally, the leucocratic rocks, especially the finer grained ones, are characterized by (1) a quartz-plagioclase[1] and microcline content of more than 90 percent; (2) a microcline content generally slightly less than, rarely slightly greater than the plagioclase content; (3) a quartz content greater than but usually within 10 percent of the plagioclase content; (4) abundant perthitic, antiperthitic, and myrmekitic intergrowths; and (5) a biotite content of less than 3 percent of the rock. Also, the plagioclase tends to be more sodic; an anorthite content range of 25-33 percent was suggested by a few flat-stage determinations. Modal analyses of samples of leucocratic quartz monzonite are included in table 3A.

Hybrid rocks. Widespread assimilation of wall rock by the Boulder Creek locally created large amounts of various hybrid or mixed rocks. The Boulder Creek rocks near the contact with the biotite gneiss unit are commonly similar in composition to the predominant rock type of that unit, biotite-quartz plagioclase gneiss. Petrographically, this part of the Boulder Creek is characterized by a very gneissose medium- to coarse-grained rock which has an inequigranular seriate rarely porphyritic (plagioclase phenocrysts as much as 1.5 cm) texture. In the main, the rock contains 65-75 percent quartz and feldspar. Microcline and myrmekite are generally absent and never total more than 1 percent of the rock. Where microcline is present, it commonly occurs as antiperthitic intergrowths in plagioclase. Plagioclase composition is mostly within the An_{30} to An_{34} percent range. Biotite content is commonly more than

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[1] Including the derivatives, sericite and clay.

15 percent and in some cases forms as much as 35 percent of the total rock. In the southwestern part of the area, biotitic hornblende gneiss and amphibolite are abundant in the mixed zone and the bordering biotite gneiss unit. The Boulder Creek in this southwestern area varies from microcline-poor granodiorite (fig. 23) to quartz diorite in composition and locally contains hornblende- and (or) biotite-rich quartz-poor (plagioclase: quartz as high as 3:1) zones (figs. 15, 24) or xenolithic layers.

Where the Boulder Creek "soaked" and partially ingested masses of amphibolitic rock, reaction between these compositionally divergent rock types was strong and locally produced a variety of mixed rocks--hereafter referred to as contaminated or amphibolitically contaminated Boulder Creek. Compositions in these mixed rocks include (biotite) hornblende granodiorite, hornblende diorite, hornblende monzonite, and hornblende aplite. Textures range from very coarse grained granitic to medium-grained gneissic to fine-grained essentially hornfelsic. Extensive areas of this type of contamination occur in parts of secs. 5, 32, and 33, Tps. 1, 1½, and 2 N., R. 81 W., respectively. Figures 25 and 26 show an early stage in the assimilation of amphibolite by granodiorite.

Petrographically, the amphibolitically contaminated Boulder Creek is diverse. Modal analyses of several samples of Boulder Creek amphibolitically contaminated to varying degrees are included in table 3. These rocks range from uniformly coarse-grained inequigranular seriate rocks in which the only identifiable remains of the contaminant are abundant corroded hornblende grains to fine-grained granoblastic and granulose rocks in which the contaminant comprises the bulk of the rock and, although it is commonly shot through with felsic material, remains essentially an amphibolite. Where assimilation of amphibolitic material has occurred in an area in which the Boulder Creek is predominantly microcline-poor granodiorite, the hybrid rock is a hornblende biotite microcline-poor granodiorite to a biotite hornblende quartz diorite to diorite consisting of less than 5-20 percent quartz; 45-55

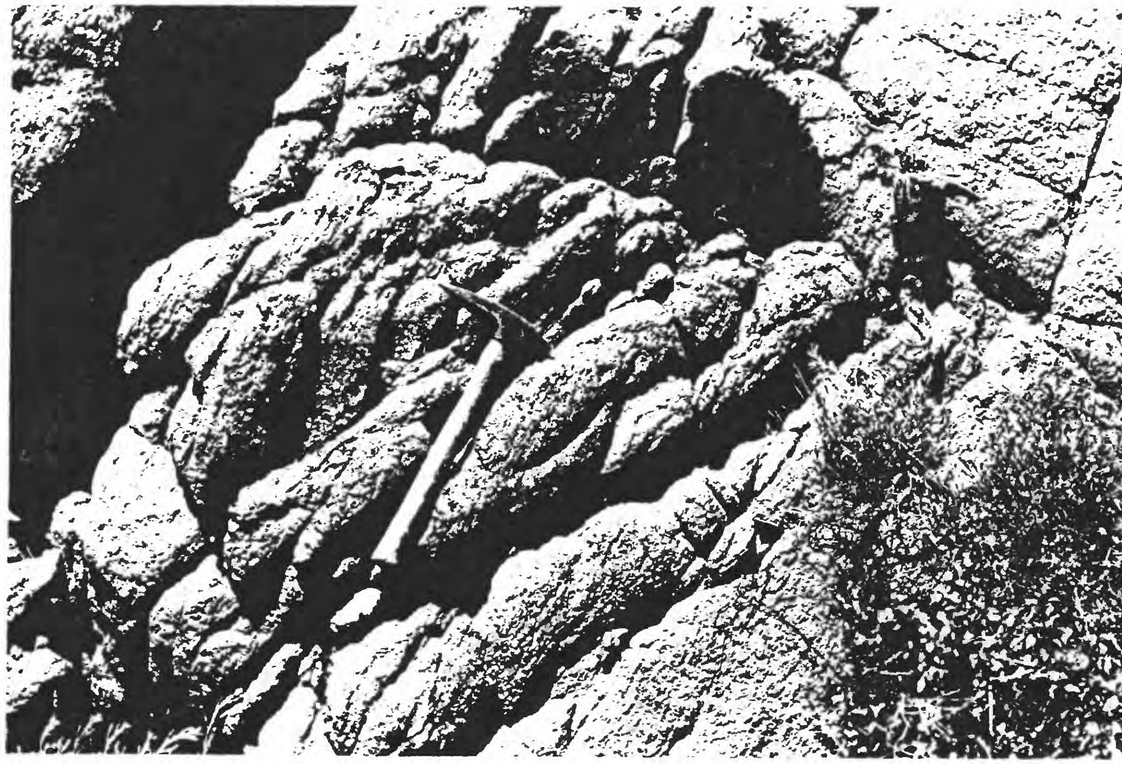

FIGURE 24.--Granodiorite-quartz diorite in the zone of biotite gneiss intercalated with Boulder Creek Granodiorite in the NW¼ sec. 32, T. 1 N., R. 81 W. Geologic pick lies in the foliation plane.

FIGURE 25.--An outcrop of contaminated Boulder Creek Granodiorite with xenoliths of amphibolite, in the SW¼ sec. 32, T. 1 N., R. 81 W.

FIGURE 26.--"Float" of contaminated Boulder Creek Granodiorite, in sec. 32, T. 1 N., R. 81 W. Note embayed borders of amphibolite xenoliths; penny shows scale. Outcrops of rock similar to float material occur nearby.

percent plagioclase (An_{32-36}); 0 to less than 1 percent microcline (as antiperthitic intergrowths in plagioclase); less than 5-25 percent hornblende; 15 to less than 5 percent biotite; minor sericite; and accessory to trace amounts of epidote (mostly pistacite), chlorite, calcite, prehnite, muscovite (including rare bleached biotite), sphene, iron ore, apatite, and zircon. Where the intrusive material appears to have been near quartz monzonite, typical hybrid rocks are quartz-poor hornblende granodiorite which show abundant evidence of strong corrosive reaction--sericite, epidote, chlorite, iron oxide, etc., replacement of plagioclase--especially of calcic cores--and of mafics. One thin section made across the interface between a thin (less than 1 cm) felsic cary in a fine-grained amphibolite within an area of widespread amphibolitic contamination of quartz monzonite shows a depletion of potash in the felsic cary and a concomitant enrichment in potash in the amphibolite (samples V-165-63a and -63b, table 3C).

Xenoliths. The Boulder Creek Granodiorite contains abundant inclusions of wallrock that it had failed to assimilate by the time of solidification. These xenolithic bodies range in size from a few cubic inches to several tens of cubic feet. The largest ones are lenticular layers of migmatitic biotite gneiss or pods of coarsely recrystallized amphibolite, and the approximate outlines of some of these are shown on the geologic map (fig. 2). Migmatitic biotite gneiss inclusions are most abundant near the contact with the biotite gneiss (fig. 27). Foliation planes within the gneiss inclusions parallel those in the enclosing rock, and contacts with the enclosing rock are gradational.

Petrographically, the migmatitic gneiss inclusions, except for very large ones, are similar to the enclosing Boulder Creek rocks except that they have a coarse compositional banding, are commonly more biotitic, and in thin section display a very gneissose fabric. Microcline occurs as antiperthitic intergrowths in plagioclase and generally makes up less than 1-2 percent of the rock.

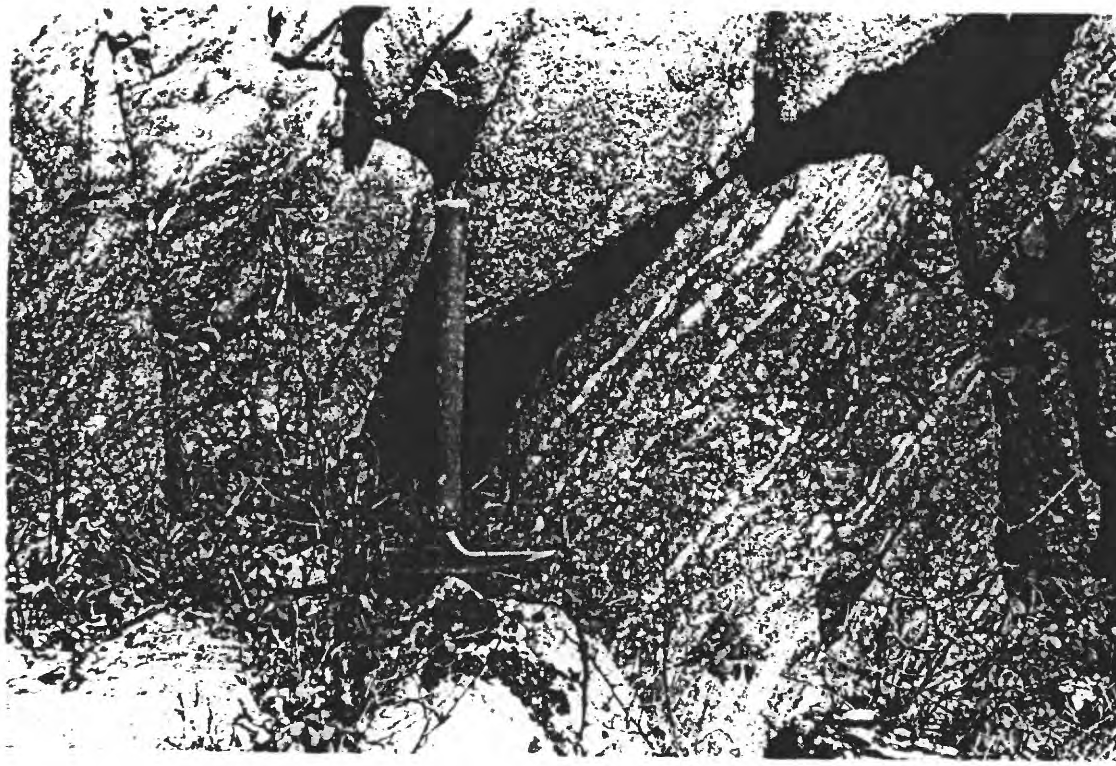

FIGURE 27.--An outcrop of a migmatitic biotite gneiss layer (lower right half of photo) in the Boulder Creek Granodiorite north of the Boulder Creek-biotite gneiss contact in sec. 16, T. 1 N., R. 81 W.

The large amphibolite pods are most abundant in northeast-trending zones located just north of the Boulder Creek biotite gneiss contact in the N½ sec. 20, S½, sec. 17, and along the section line between secs. 8 and 17, T. 1 N., R. 81 W., and in sec. 32 of Tps. 1½ and 2 N., R. 81 W. Structures within these coarsely to very coarsely recrystallized amphibolite inclusions are obscure but the long axis of each pod is parallel to the structural grain of the surrounding Boulder Creek. These amphibolites generally have sharp borders, although locally gradation across the contact occurs where there has been some assimilation by and consequent contamination of the enclosing rock. Fine-grained dikes of enclosing Boulder Creek Granodiorite cut an amphibolite pod in sec. 20, T. 1 N., R. 81 W., just west of the map area.

Samples from an amphibolite pod at the crest of the range in the S½ sec. 17 were examined under the petrographic microscope (see sample V-32a-63, table 3A). Typically, the pod is a coarsely to very coarsely recrystallized mass of hornblende (almost 85 percent) which contains minor (less than 15 percent) amounts of sericite from plagioclase, accessory quartz, and accessory epidote from plagioclase and hornblende. Iron ore and trace amounts of calcite, sphene, and prehnite(?) are commonly present. Coarse hornblende poikilitically encloses both plagioclase and smaller hornblende crystals.

The smallest xenoliths are spindle-shaped biotite or hornblende concentrations similar to those shown in figure 28. They are most abundant in areas where the larger gneiss and amphibolite inclusions are most abundant; their long axes are also generally parallel to the enclosing rock and most probably have a genesis similar to that of the larger inclusions.

Structure

The Boulder Creek Granodiorite is commonly foliated and locally lineated. Foliation is marked by parallel and subparallel planar orientation of biotite plates, tabular feldspar grains, quartz lenticles (fig. 29), hornblende prisms, and xenoliths (figs. 27, 28). Foliation is

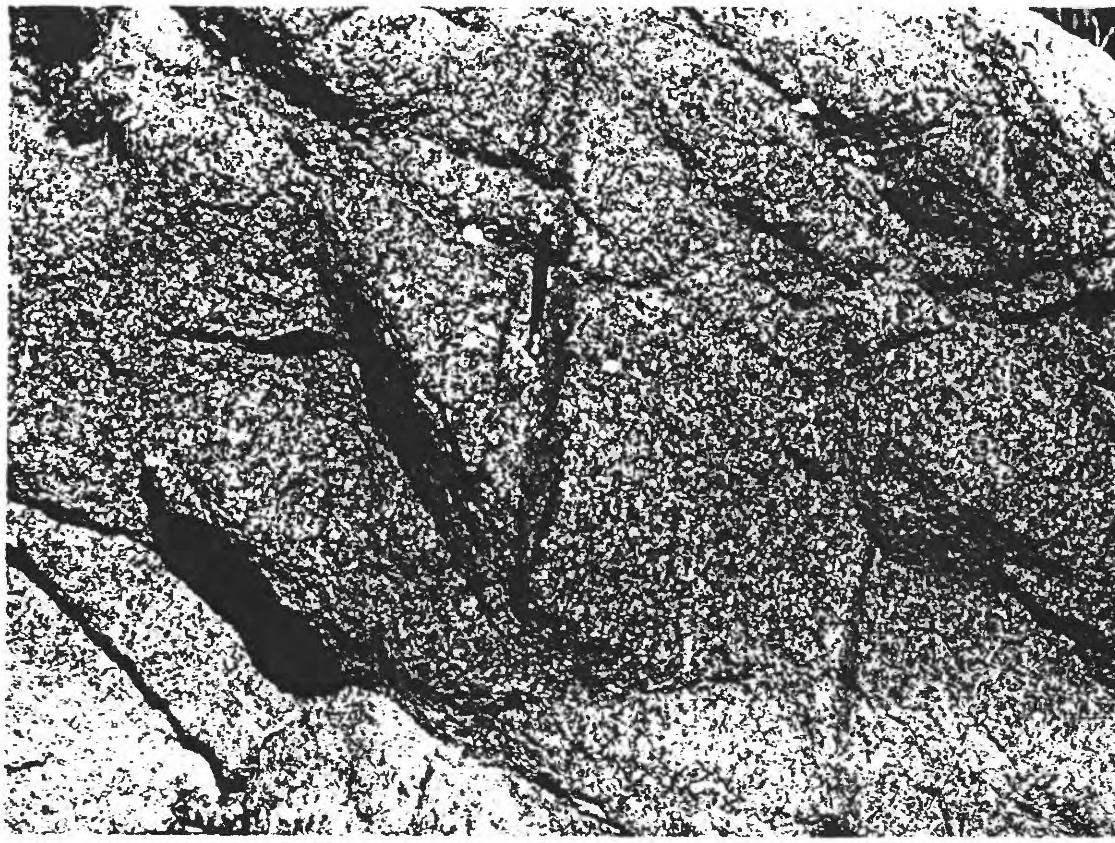

FIGURE 28.--Small spindle-shaped mafic xenoliths in Boulder Creek Granodiorite, near the Boulder Creek-biotite gneiss contact in sec. 16, T. 1 N., R. 81 W.

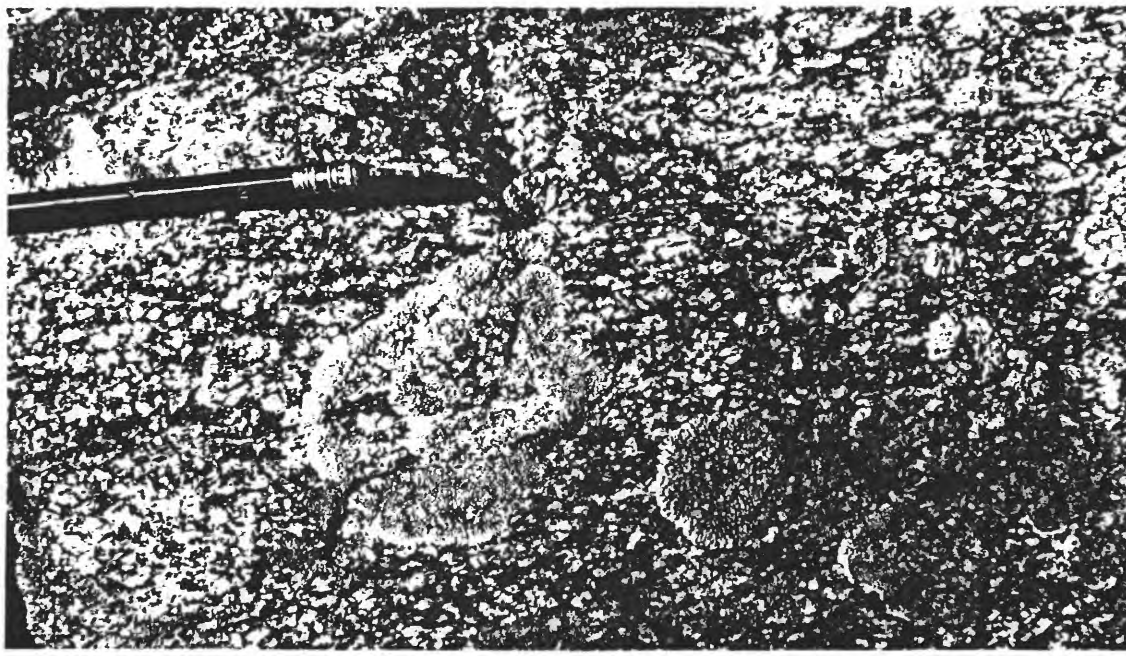

FIGURE 29.--Typical fabric of granodiorite (-quartz diorite) within the zone of biotite gneiss intercalated with Boulder Creek Granodiorite in the western part of sec. 32, T. 1 N., R. 81 W. Pencil lies in the foliation plane. Many of the light-colored mineral streaks in the plane of foliation are quartz lenticles.

most conspicuous in the rocks within and along the contact zone with the biotite gneiss unit. Foliation is faintest in the leucocratic rocks, especially the finer grained ones, which crop out within the interior of the Boulder Creek.

Linear elements within the Boulder Creek are primarily hornblende prisms, small spindle-shaped xenoliths similar to the one shown in figure 28, mafic streaks, and, rarely, fold axes of small-scale folds outlined by thin local mafic-rich layers. Because of the smooth rounded surfaces of most outcrops, usually only the trend of linear elements could be determined. These linear elements and the long axes of large xenolithic bodies and most leucocratic quartz monzonite zones or layers are parallel to the strike of the foliation. Large xenolithic bodies of coarsely recrystallized amphibolite are most abundant in three northeast-trending zones: one in the NW¼ sec. 20 and south center sec. 17, T. 1 N., one in the NW¼ sec. 17 and the SW¼ sec. 8, T. 1 N., and one in the western part of sec. 32, T. 1½ N. and the southern part of sec. 32, T. 2 N., R. 81 W. These zones constitute discontinuous partially assimilated metamorphic septa and approximately parallel the foliation in the Boulder Creek. They may be remnants of amphibolitic layers of the biotite gneiss. Cataclastic zones that are associated with some of the faults mapped in the Boulder Creek are also generally parallel and subparallel to the foliation.

For that part of its southeast border exposed in the map area, structures in the Boulder Creek are generally concordant, locally discordant, to structures in the biotite gneiss unit. Near the contact between the two units, foliations in granodiorite parallel those in biotite gneiss. Planar and linear elements throughout that part of the Boulder Creek exposed in the map area trend generally N. 55°-75° E. and approximately parallel the dominant northeast-east-northeast fold system of the biotite gneiss unit.

Mode of Emplacement and Age

Evidence in the map area indicates that the Boulder Creek synkinematically (Raguin, 1965, p. 201-202) intruded biotite gneiss at catazonal depths as the gneiss was being deformed about northeast-trending fold axes. The Boulder Creek Granodiorite is generally concordant and intimately interlayered with the biotite gneiss along their common boundary. The Boulder Creek has extensively assimilated its wallrocks.

Evidence of protoclasis is widespread though not abundant in the granodiorite. During consolidation cataclasis occurred at a few localities in zones parallel or at small angles to planar flow structure. Some movement probably extended into the post-consolidation period, and some of the mylonitization which is present in most of the zones which contain cataclasized rocks may have occurred at this time. Potash-feldspar-rich rocks, including aplite, are usually associated with cataclastic zones, which suggests that these zones of movement served as conduits for late alkali-rich emanations.

The Boulder Creek Granodiorite intrudes biotite gneiss and, accordingly, is younger than the biotite gneiss. It is older than northward-trending granophyre dikes (figs. 2, 30) which have been dated as 1.13± .15 billion years by C. E. Hedge (written commun., 1967). The age of the Boulder Creek plutons of the Colorado Front Range is 1.69-1.71 billion years, according to Hutchinson and Hedge (1967, table 1). They have suggested that the Boulder Creek batholithic rocks represent the culmination of an orogeny which began about 1.74 billion years ago with the development of the regional metamorphic series characteristic of the Front Range.

GRANOPHYRE DIKES

A few discontinuous granophyre dikes, 3 to about 15 feet thick, crop out in a north-northwest trend across the middle of secs. 29 and 32, T. 1 N., R. 81 W. The dikes intrude the biotite gneiss and the Boulder Creek Granodiorite. The thickest and best exposed of the granophyre dikes extends northward for at least 1½ miles along the east side of the Canyon Creek drainage from the north side of the railroad near the west end of Gore Canyon. This one dike cuts rocks of the biotite gneiss unit--including thick layers of cumuloblastic amphibolite of that unit--and of the Boulder Creek Granodiorite. South of the river and just south of the map area, very fine grained granophyre crops out on the slope just below State Highway 11 in the E½ sec. 6, T. 1 S., R. 81 W. This outcrop lies along the projected strike and may be a segment of the long dike in the Canyon Creek drainage to the north.

Rock Description

The granophyre is light-brownish-gray to moderate-brown-weathering very fine grained hard hypabyssal rock which has a hackly fracture. The very fine grain size of the constituent minerals suggests that "micro-granophyre" might be a more accurate, though more cumbersome, rock name. Small pits, maximum size ½ inch long and ¼ inch wide, define a faint planar structure parallel to the wallrock of the dike.

Precise identification of minerals and their relations were not made because of fine grain size, complex texture, and pervasive deuteric alteration. The most characteristic petrographic feature of the rock is its micrograophyric texture. The approximate mineral composition is 40-60 percent quartz, feldspar, and intergrowths; 14-19 percent biotite; 15-25 percent muscovite; 12-13 percent iron ore; 1-4 percent epidote (mostly pistacite, rare allanite); 1-2 percent each of apatite and chlorite; and less than 1 percent each of sphene, calcite, and leucoxene. Amounts of quartz, plagioclase, and potash feldspar are proportioned as 1, 5, and 2-3, and amounts of quartz, feldspar, and intergrowths are proportioned as 1, 1, and 2. Most of the potash feldspar appears to be crudely grid-twinned microcline; the plagioclase appears to be albite which has poorly developed albite twinning. Implication textures of various kinds are present but the most common are myrmekitic intergrowth of quartz around the rims of plagioclase phenocrysts which contain core areas occupied by muscovite. Iron ore occurs abundantly as acicular grains of iron oxide scattered throughout the rock. A fine pervasive leucoxene dust or film in the rock suggests that much of the iron ore of these rocks was titaniferous magnetite. Iron ore also occurs as clumps of iron-oxide grains and (or) euhedral pyrite partially replaced by oxides. These iron-ore clumps also contain epidote, calcite, and apatite and are commonly surrounded by an inner rim of chlorite and an outer one of muscovite. These clumps of late magmatic minerals weather out to form the pits which are common to weathered surfaces of the granophyre and which may have an origin similar to miarolitic cavities of granite. Some thin sections studied contained thin (less than 1 mm thick) veinlets of calcite and minor quartz enclosed in walls lined with muscovite.

The granophyre dikes are monotonously alike in outcrop appearance and, at least for those sampled, in texture and composition. C. E. Hedge (written commun., 1967), who determined Rb/Sr ratios for seven samples, reported that the strikingly similar results of each analysis suggested a close genetic relation among the rock bodies represented. The sample localities are shown in figure 30; the results of Hedge's analyses are given in the section on age.

Wallrock alteration in rocks cut by granophyre appears to have been minor. Hand-sample examination of wallrocks along the course of the dike that crops out along the east side of the Canyon Creek drainage revealed only a small amount of iron-oxide discoloration and, perhaps, some chloritization of biotite within a few inches of the contact.

Structure

The granophyre dike which crops out discontinuously across secs. 32 and 29 strikes generally N. 5°-15° W., dips 80°-90° E. or locally much less steeply west. It commonly has a faint primary planar structure which is defined by subparallel arrangements of slightly flattened "micromiarolitic" cavities and which is parallel to the sides of the dike.

The granophyre dikes cut the northeast-striking regional foliation of the biotite gneiss and the Boulder Creek Granodiorite at a large angle. These dikes and their projections are nearly parallel to one another, to a thick discontinuous quartz vein, 5-10 feet thick, which cuts Precambrian rocks near the crest of the range, and to the Gore fault zone and related shears. The granophyre dikes may have filled fractures dilated in response to movements along the Gore fault zone.

Age

Seven samples of granophyre from exposures in secs. 29 and 32, T. 1 N., and sec. 6, T. 1 S., R. 81 W. (fig. 30) were radiogenically age dated by C. E. Hedge (written commun., 1967) who stated:

> "Complete analyses of three samples from the main dike indicate an age of 1.13$\pm$ 0.15 b.y. when mathematically solved simultaneously. The large uncertainty is due to the relatively low Rb/Sr ratios between the respective samples. A single sample from one of the smaller dikes (272) contains slightly more radiogenic Sr than those from the larger dike. This is probably best explained by assimilation of a small amount of Precambrian country rock."

Sample No.	Rb	Sr	Rb/Sr	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86}
V-402-63	131	434	0.301	0.876	0.7219
V-281-63	80.9	333	0.243	0.704	0.7191
V-421-63	151	399	0.378	1.096	0.7253
V-11-64	127	426	0.299	-----	------
V-392-63	138	458	0.302	-----	------
V-272-63	117	414	0.283	0.820	0.7223
V-104-65	137	443	0.310	-----	------

Hedge (oral commun., 1967) further suggested that the radiogenic age may be slightly older than the true age of the dike because of wallrock assimilation and that the dike may represent a part of the Pikes Peak plutonic event as defined by Hutchinson and Hedge (1967).

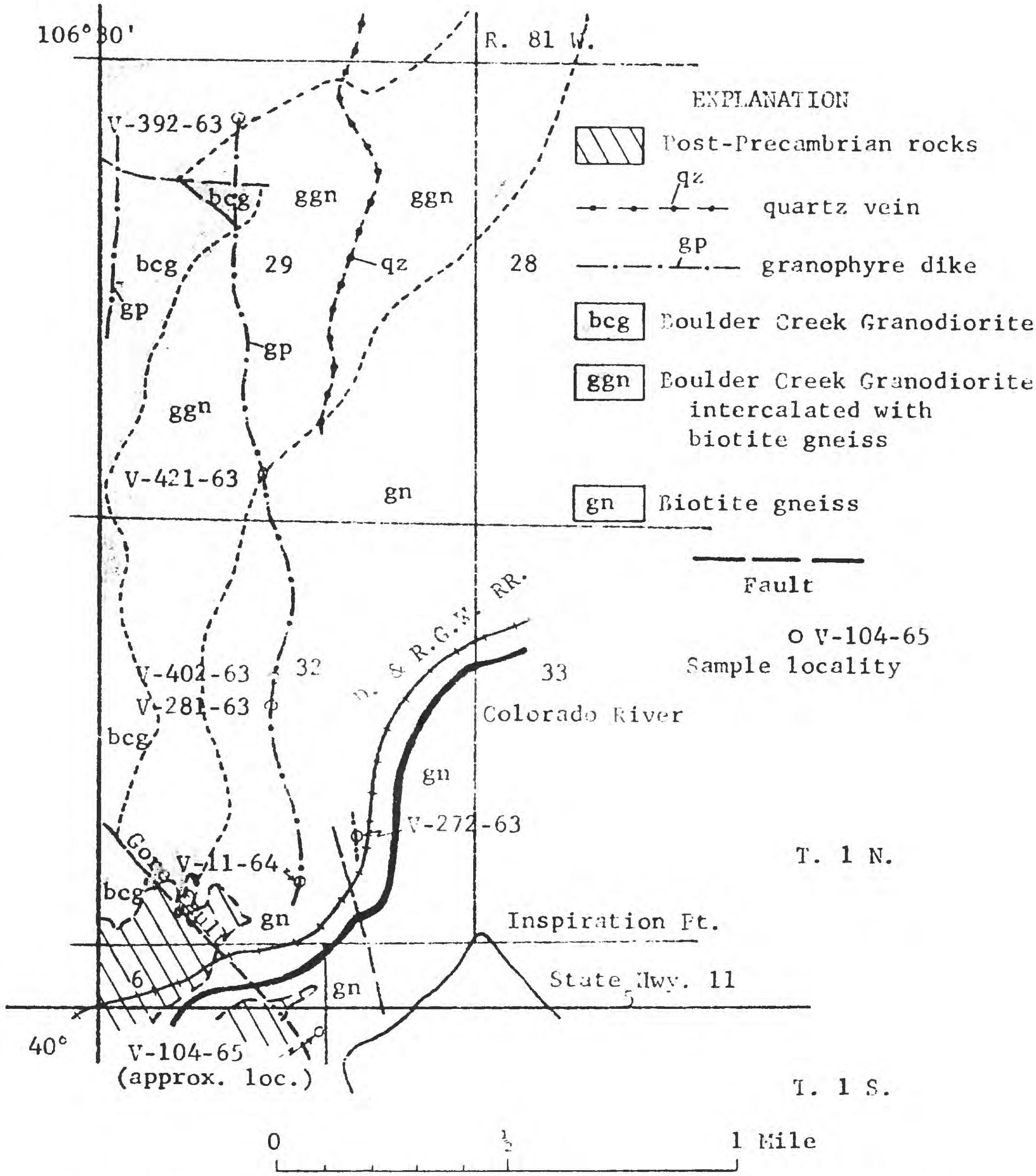

Figure 30.--Sketch map showing Granophyre dikes and collection localities for samples submitted for radiogenic (Rb/Sr) dating.

QUARTZ VEINS

Discontinuous outcrops of iron-oxide-stained massive vein quartz extend along a northerly trend through the Precambrian rocks, both biotite gneiss and the Boulder Creek Granodiorite, of the uppermost slopes of the Gore Range in the E½ secs. 17, 20, and 29, T. 1 N., R. 81 W. (fig. 2). This line of outcrops is punctuated by shallow prospect pits, which were probably dug for gold.

The best exposure of vein quartz is in a shallow shaft near the middle of the south edge of the SE¼ sec. 29. The outcrop in the sides of this shaft shows a vein of quartz 3-5 feet wide and a subordinate thinner branch which cut amphibolitically contaminated Boulder Creek Granodiorite. The wallrock is sheared and iron-oxide-stained and there is some chloritization of biotite and hornblende.

The veins exposed in the shaft have attitudes of N. 5° W.-60° W. to N. 15° E.-75° E. Vein-quartz outcrops north of the shaft in the Boulder Creek Granodiorite and to the south of the shaft in the biotite gneiss lie along the projection of these quartz veins. Just west of the map area near the bottom of the Canyon Creek drainage in the NW¼ sec. 32 and the SW¼ sec. 29, T. 1 N., R. 81 W., there is a 2-foot quartz vein which has an attitude of approximately N. 20° W.-70° W. within a 50-foot-wide shear zone of sheared iron-oxide-stained epidote-veined and chloritic granodiorite.

Thick quartz veins along the crest of the Gore Range and in the Canyon Creek drainage are subparallel in trend to each other, to the granophyre dikes, to major fracture directions which include the Gore fault, and to the general trend of the Gore Range in this part of the area. The veins are commonly nearly vertical or dip toward the Gore fault zone. The quartz veins and granophyre dikes appear to be structurally related and may have been emplaced at about the same time. They probably represent fracture filling along a wide zone of fracture and dilation related to uplift and associated drag along the Gore fault.

Permian and Triassic Rocks

A thin sequence of red beds occurs between Precambrian rocks and Jurassic strata in the northwestern part and the southwest corner of the map area. The rocks are poorly exposed and the nomenclature used below follows principally other workers who have mapped the rocks in adjoining areas.

STATE BRIDGE FORMATION

Definition

C. F. Bassett (1939, p. 1853, 1864) first used the name State Bridge for the upper member of the Maroon Formation in the Dotsero, Colo., area which lies west of the Gore Range near the junction of the Colorado and Eagle Rivers. His usage was based entirely upon earlier work by Donner (1936) in the vicinity of McCoy, a town about 7 miles northwest of State Bridge, Colo. (fig. 1). Donner had applied the name in the McCoy area to a sequence of interbedded red to gray siltstone and shale lying above pink and red beds of coarse clastics equivalent to part of the Pennsylvanian and Permian? Maroon Formation and disconformably below Shinarump-type conglomerates of the Upper Triassic Chinle Formation (Donner, 1949, fig. 2, p. 1222-1224, 1228-1230). Brill raised the State Bridge to formation rank, further defined it as lying above the Weber Sandstone or its equivalent horizon at the top of the Maroon Formation and outlined a fairly wide area of distribution for it in the northern part of the Late Paleozoic Colorado trough (Brill, 1942, p. 1392-1393; 1944, p. 629-652, figs. 4-6; 1952, p. 823-825).

In this report the State Bridge Formation is used for a thin sequence of red beds that occurs between crystalline rocks of the Precambrian and sandstones of the Upper Jurassic Sundance Formation near the west portal of Gore Canyon (fig. 31). This usage follows that of Steinbach (1956), whose area of study also included the west portal of Gore Canyon.

FIGURE 31.--Southwesterly dipping red beds of the State Bridge Formation and sandstones of the Sundance Formation which are locally overlain by Quaternary terrace gravels, at west end of Gore Canyon in sec. 6, T. 1 S., R. 81 W. A pediment deposit is well exposed above the terrace gravels. Middle of Gore fault zone crosses picture at bend in tracks. Precambrian rocks in right foreground and in left middle ground below tracks.

Distribution

State Bridge Formation exposures in the area of this report are restricted to the lower western slopes of the Gore Range on the north side of the Colorado River. This patch of ground is at the northeast edge of the area in which Brill (1942) located his basin of State Bridge deposition.

The siltstones and shales of the State Bridge are commonly nonresistent but a thin section is well displayed near the west portal of Gore Canyon in a railroad cut of the Denver and Rio Grande Western Railroad (fig. 32).

Thickness

On the western flanks of the Gore Range in the southwest corner of the map area, the author measured a red-bed sequence less than 15 feet thick which he has assigned to the State Bridge; Steinbach (1956) measured less than 17 feet of State Bridge at approximately the same location.

Published studies by Bassett (1939), Brill (1942, 1944, 1952), Murray (1949, 1958), and Sheridan (1950), and unpublished theses by Gates (1950), Parsons (1954), and Steinbach (1956) furnish good evidence that the State Bridge Formation thickens west and south of the map area. Approximately midway between the west portal of Gore Canyon and Radium and just north of Blacktail Gorge of the Colorado River, Steinbach measured almost 150 feet of strata which he called State Bridge. To the southwest just beyond Radium, Sheridan (1950, p. 130) reported a 389-foot section of State Bridge. At the type area on Yarmony Mountain southwest of Radium and approximately 11 miles southwest of the map area, Donner (1949, p. 1229) assigned 525 feet of strata to the State Bridge. This southward and westward thickening continues beyond the area of the type section. About 9 miles west-southwest of the type area, Sheridan (1950, p. 130, 138) described an 800-foot section of State Bridge at his Red Canyon section just south of the Colorado River, and 15-20 miles south-southwest of the Yarmony Mountain area Brill (1944, p. 648) measured about 760 feet of what he considered undoubted State Bridge at a section just north of Eagle, Colo.

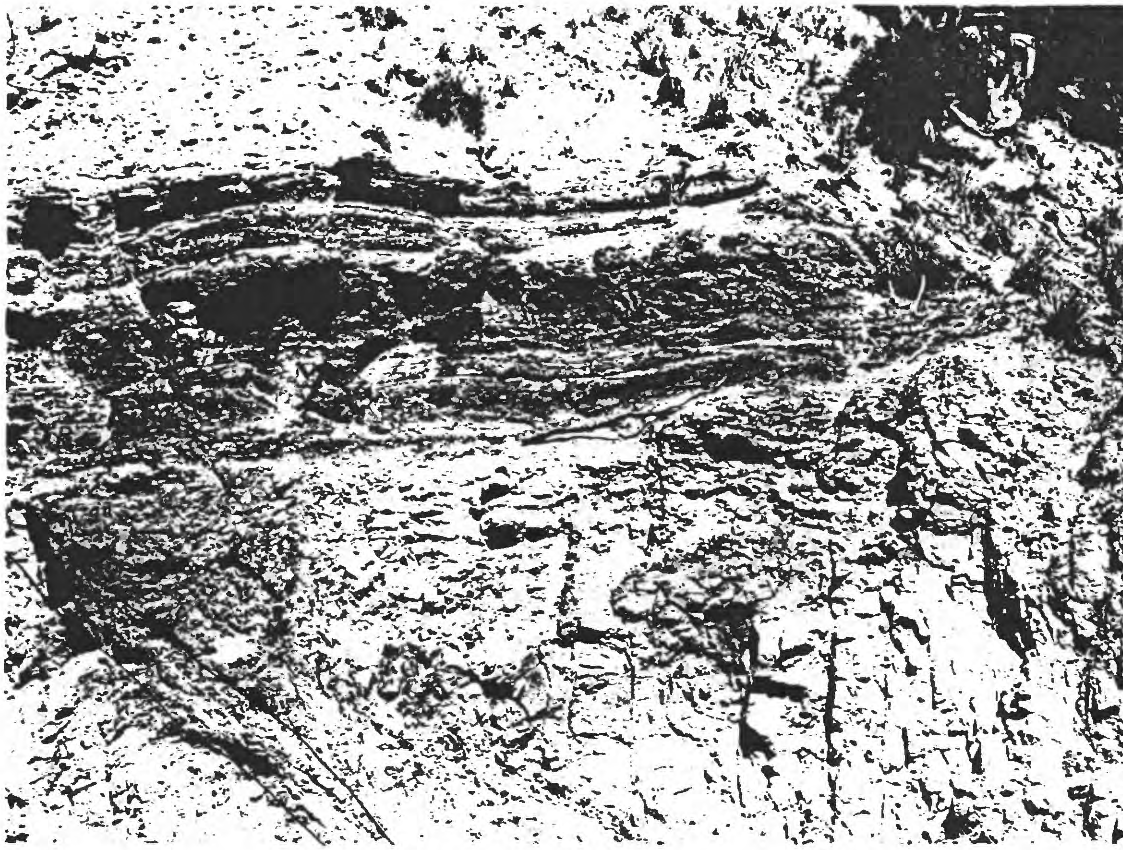

FIGURE 32.--Red beds of the State Bridge Formation on Precambrian rocks, near tracks in sec. 6, T. 1 S., R. 81 W., near west margin of the Gore fault zone. Shear zone in Precambrian rocks in lower left corner does not break the State Bridge-Precambrian contact.

Lithology

In the map area the State Bridge overlies deeply weathered Precambrian gneiss and is either overlain by sandstone of the Sundance Formation or beveled by Quaternary terrace gravels (figs. 30, 31). To the west it is overlain by the Chinle Formation.

The State Bridge strata of the map area consist predominantly of reddish-brown to dusky-red clayey siltstone, irregularly interlaminated and locally thinly interbedded with yellowish-gray to grayish-orange siltstone and very fine grained sandstone. All beds are commonly limy and micaceous. The lower third of the State Bridge becomes increasingly conglomeratic toward the base. The clasts are mostly granule- to pebble-size angular fragments of quartz, feldspar, and locally derived Precambrian rock fragments. At the base of the formation, red siltstone fills thin fractures in the rotten Precambrian gneiss.

At the type area, Donner (1949, p. 1229) described the State Bridge Formation as consisting of brick-red shale and limy micaceous siltstone, subordinate amounts of purplish- and yellowish-gray shale and siltstone, and 141 feet from the base of the formation a 7-foot impure pelecypod-bearing limestone. The fossiliferous limestone interval about 140 feet above the base of the formation has been recognized and used as a marker by several authors working in the McCoy area and was named the Yarmony Member by Sheridan (1950, p. 129). This limestone interval was not found in the map area of this report.

According to Brill (1952, p. 842) the State Bridge Formation is composed of material derived from the highlands bordering a Late Paleozoic trough which extended from northern New Mexico to northwestern Colorado and was deposited under marine or brackish-water conditions in a small basin near the north end of that trough. Studies by Brill (1942, 1944, 1952) and Sheridan (1950) suggest that the thickest State Bridge sections, and the deeper parts of the State Bridge Formation basin, are west of the Gore Range between the Eagle and Colorado Rivers.

Correlation

Accurate age assignment and stratigraphic correlations are difficult to make because of lack of diagnostic fossils. Published age assignments for the State Bridge have ranged from and included parts of the Pennsylvanian to Triassic periods (Donner, 1949, p. 1228-1229; Brill, 1942, p. 1393; 1944, p. 636; 1952, p. 823-825; Hebrew and Picard, 1955). At least part of the formation is equivalent to part of the Phosphoria Formation of Permian age. Brill (1952) correlated the limestone interval--the Yarmony Member of Sheridan (1950)--about 140 feet above the base of the formation with the South Canyon Creek dolomite of the Glenwood Springs area which was described by Northrop and Bass (1950) as being a unit of Phosphoria age in the Maroon Formation. E. M. Schell (oral commun., 1967) believes that the dolomite marker bed near the top of the Permian Park City Formation of northwestern Colorado and northeastern Utah (Schell and Yochelson, 1966) is probably equivalent to the South Canyon Creek dolomite of the Glenwood Springs area. Recent as yet unpublished work by J. H. Stewart, F. G. Poole, and R. F. Wilson of the U.S. Geological Survey shows that the State Bridge Formation is divisible into two informal members separated by the South Canyon Creek dolomite member. They conclude that most of the upper informal member is equivalent to part of the Moenkopi Formation which is considered to be of Early Triassic age in western Colorado and that the South Canyon Creek dolomite and the lower informal member are equivalent to beds of the Park City Formation of Permian age.

No fossils were found in the red-bed sequence exposed near the west portal of Gore Canyon. Assignment to the State Bridge Formation is made on the basis of stratigraphic position and lithology and mapping by Steinbach (1956) and Parsons (1954) near the west portal of Gore Canyon.

The author believes that the State Bridge strata near the west portal of Gore Canyon probably belong only to the upper part of the State Bridge and may, therefore, be equivalent to the Moenkopi Formation in part. This conclusion is primarily based upon work by Gates (1950) in the Radium area. A series of State Bridge sections measured by Gates (1950, fig. 11) shows abrupt thinning in a northeasterly direction from the Radium area toward the Gore Range and the area of this report. The northeasternmost of his sections shows only that part of the State Bridge Formation which is above the Yarmony Member of Sheridan (1950).

CHINLE AND CHUGWATER(?) FORMATIONS UNDIVIDED

Definition

Chinle Formation was originally used in northeastern Arizona by H. E. Gregory (1915, p. 102; 1917, p. 79) for a series of red, purple, lavender, green, brown, and varicolored shales, shaly sandstones, and lenticular limestone conglomerates lying between the Wingate Sandstone and the Shinarump Conglomerate. The name is now applied by the U.S. Geological Survey in northeastern Arizona and surrounding areas to the varicolored beds overlain by the Glen Canyon Group of Late Triassic and Jurassic(?) age and underlain by the Moenkopi Formation of Early and Middle(?) Triassic age. It now includes the Shinarump Conglomerate.

The Chugwater Formation was originally defined by Darton (1904, p. 397-398) as the red-bed sequence between the Pennsylvanian Tensleep Sandstone and the Jurassic Sundance Formation of the eastern Wyoming-northern Colorado area.

G. N. Pipiringos, W. J. Hail, Jr., and G. A. Izett of the U.S. Geological Survey measured several sections on both sides of the Gore Range and the Park Range between the Colorado River on the south and Rabbit Ears Pass on the north as part of a yet unpublished study of pre-Morrison Jurassic stratigraphy. Some of their measured sections included pre-Jurassic post-Precambrian rocks. Ten to fifteen miles south of Rabbit Ears Pass in the Lake Agnes quadrangle, the southwestern corner quadrangle of an area mapped by Hail (1968, fig. 1), they recognized only the Chugwater Formation between the Precambrian crystalline rocks and the sedimentary rocks of the Sundance Formation. Further to the south in the northern part of the Gore Pass quadrangle, which borders the Kremmling quadrangle on the west, the same workers recognized two formations below the Sundance: the Chugwater Formation and the overlying Chinle Formation. The contact between the formations is usually characterized by the presence of conglomeratic grits perhaps equivalent to the Gartra Grit Member of the Chinle.

In the northeastern part of the map area, a poorly exposed sequence of red beds is thought to represent the Chugwater Formation, and part of an overlying covered interval with a lenticular conglomeratic Gartra-like sandstone at the base is thought to contain beds of the Chinle Formation.

Distribution

Red beds of the Chinle and Chugwater(?) Formations undivided in the map area appear to be restricted to the north edge of the area on the east side of the Gore Range. Here a band of small scattered outcrops of a red-bed sequence trends northwest through the NW¼ sec. 4, T. 1 N., R. 81 W., and the W½ sec. 33, T. 1½ N. Rocks of this sequence could not be found south of the fault that trends east-northeast through sec. 4, and in the NE¼ sec. 21 beds of the Jurassic Sundance Formation probably lie directly on Precambrian rocks.

No definite pre-Jurassic red-bed sequences were found in the map area south of the Colorado River, although both Taggart (1963) and Holt (1961) have mapped red-bed sequences further south in the Mount Powell quadrangle. Brick-red soil and colluvium are locally exposed above Precambrian gneiss in the saddle between San Toy Mountain and the high ground on the southeast side of Gore Canyon. These red colors above the gneiss suggest that south of the river in the map area there may be thin local remnants of one or more of the pre-Jurassic red-bed sequences preserved in irregularities on top of the Precambrian rocks.

Thickness

The maximum thickness of the Chinle and Chugwater(?) Formations undivided in the map area is probably at least 63 feet and may be as much as 97 feet.

Pre-Jurassic post-Precambrian red-bed sequences are thin or absent in most areas of Middle Park; most occurrences are restricted to northwestern Middle Park (Tweto, 1957, p. 20). Hail (1968) reported that in northwestern Middle Park along the east flank of the Park Range the Chugwater is 90-150 feet thick. Further south but still north of the map area, G. N. Pipiringos, W. J. Hail, Jr., G. A. Izett, assisted by various other personnel of the U.S. Geological Survey including this author, measured a series of sections in the Jurassic and Triassic rocks. In two of these sections, the Lazy Bear and the Tyler Mountain sections, which are approximately 5.5 and 8.5 miles northwest of the Chinle and Chugwater(?) outcrops of the map area, both Chugwater and Chinle beds are present below Sundance strata. The Tyler Mountain section has 225 feet of pre-Sundance post-Precambrian rocks of which a minimum of 105 feet is assigned to the Chinle Formation and the rest to the lower, Chugwater Formation. At the Lazy Bear locality, 101 feet of Chugwater is overlain by a 79-foot partial section of Chinle strata. In the same general area and in an area slightly south of these U.S. Geological Survey studies, Jenkens (1957, p. 51) and Miles (1961, p. 70-71), respectively, reported 250 feet of Chugwater red beds between Precambrian and Jurassic rocks; their Chugwater probably includes beds of the Chinle Formation.

Pre-Jurassic post-Precambrian sedimentary rocks are absent in the Hot Sulphur Springs quadrangle in the central part of Middle Park (Izett and Barclay, 1964; Izett, 1968). East of Granby, pre-Morrison red beds which may be equivalent to the Chugwater(?) Formation are locally exposed along the Fraser River and along U.S. Highway 40 at Tabernash campground.

Permian and (or) Triassic sedimentary rocks are present within the Middle Park basin south of the map area. At Lower Cataract Lake in sec. 35, T. 2 S., R. 81 W., in the southeast quarter of the Mount Powell quadrangle, Holt (1961, p. 13-14) mapped about 40 feet of red beds which he assigned to the Chinle. To the south toward Dillon and beyond, the pre-Jurassic sedimentary section in Middle Park thickens and includes not only Chugwater and Chinle equivalents but older rocks as well (Holt, 1961, p. 12-14; Wahlstrom and Hornback, 1962, fig. 2).

In the southwest corner of the map area, the State Bridge Formation lies between Precambrian and Jurassic rocks. In adjacent areas to the west and southwest, both the Chinle Formation and the underlying State Bridge Formation are mapped by other workers (Gates, 1950; Parsons, 1954; Steinbach, 1956) whose reports indicate that the thickness of the Chinle in the Gore Canyon-Radium area probably ranges from 0 to 40 feet.

To the northwest of the first locality is another series of outcrops in the lower half of the interval assigned to the Chinle and Chugwater(?) Formations undivided. The lowest strata exposed by this second series lie directly on the Boulder Creek Granodiorite but may be stratigraphically higher than any of the rocks exposed in the first series of outcrops. At the base of the interval about 3 feet of dusky-red irregularly gritty and conglomeratic calcareous siltstone rests on crumbly Precambrian granodiorite. Clastic fragments, as much as 1 inch long, are quartz, punky feldspar, and locally derived Precambrian rock fragments. In the upper part of the lower half of the interval are small slumped(?) outcrops of red calcareous irregularly gritty siltstone, dark-reddish-brown calcareous clayey siltstone, and a 3 to 5-foot lenticular crossbedded yellowish-orange locally conglomeratic quartz grit with some punky feldspar fragments.

Lithology

Details of the lithology of the Chinle and Chugwater(?) Formations undivided in the map area are largely unknown, for outcrops are restricted to a few shallow gullys and bare spots in the sage-covered slopes between the road and the creek in the NW¼ sec. 4, T. 1 N., R. 81 W. Of these outcrops, all occur in the lower part of the Chinle(?) and Chugwater(?) interval.

One series of scattered outcrops in the interval between Precambrian granodiorite and a covered zone believed to be occupied by Jurassic sedimentary rocks is located near the SE. cor. NW¼ sec. 4, T. 1 N., R. 81 W. Outcrops at this locality consist of grayish- to yellowish-orange irregularly calcareous quartz sandstone near the base of the interval, and reddish-brown calcareous silty claystone near the middle. The sandstone near the base is a poorly sorted medium-grained slightly feldspathic quartz sandstone. The claystone above is thinly interbedded with calcareous quartz sandstone of at least two varieties: a reddish-brown or yellowish-gray silty very fine grained variety and a pale-orange very poorly sorted coarse-grained one.

Most of the interval assigned to the Chinle and Chugwater(?) Formations undivided is probably Chinle; the gritty nature of the red beds, even well above the top of the Precambrian rocks, and the occurrence of lenticular crossbedded "Gartra-type" grits, all in the lower half of the interval at the second locality, suggest this. The presence of at least some Chugwater is indicated by the outcrops of reddish-brown silty claystone interbedded with thin reddish-brown and lighter colored very fine grained sandstones near the middle of the interval at the first locality.

The Chugwater and, locally, the Chinle are nonconformable on the Precambrian. The contact of the Chinle and Chugwater Formations is not exposed in the area, but conglomeratic sequences in the lower part of the Chinle suggest an unconformity between the Chinle and the Chugwater.

The Chinle Formation is a water-laid deposit. The environment of deposition was probably that of a flood plain which, according to an interpretation by Ash (1967) of paleobotanical evidence from the Chinle had a humid climate. Baker, Dane, and Reeside (1936, p. 49-50) suggested a west or southwest source for the Chinle in the Four Corners region. The gritty nature of the siltstone and the abundant fragments of angular quartz and punky feldspar in conglomeratic sequences are evidence for a local source for much of the material of the Chinle in the map area.

The Chugwater is also a flood-plain deposit, but limestone tongues in the lower part of the formation in other areas indicate that marine incursions are a part of the depositional history of the formation.

Correlation and Age

No fossils were found in the rocks assigned to the Chinle and Chugwater(?) Formations undivided, and assignment to these formations is based on stratigraphic positions and lithology.

The Chugwater Formation on the east side of the Gore Range may be equivalent in part to the State Bridge Formation in the southwest corner of the area. F. G. Poole in Hail (1968) suggested that red beds between Chinle Formation equivalents and Precambrian rocks in the Gore Pass quadrangle may be equivalent to State Bridge Formation strata. In their unpublished measured sections of Jurassic and Triassic rocks in northern Colorado, G. N. Pipiringos, W. J. Hail, Jr., and G. A. Izett refer to the red beds immediately below the Chinle Formation as the Chugwater Formation where they occur on the east side of the range in the Gore Pass quadrangle and as "Chugwater equivalents, in part," near Radium and McCoy on the west side of the range.

The Chinle is generally regarded as Upper Triassic and the Chugwater as Permian and Triassic.

Jurassic Rocks

SUNDANCE FORMATION

Definition

N. H. Darton (1899, p. 387) used the name Sundance for marine Upper Jurassic rocks of the Black Hills of South Dakota and Wyoming. He applied the name to a series of fossiliferous sandstones and shales lying between red beds of the Triassic Spearfish Formation and the sandstones of the Upper Jurassic Unkpapa Sandstone.

In this report the Sundance Formation is applied to a sequence of light-colored sandstones and greenish-gray siltstones lying between variegated beds of the Upper Jurassic Morrison Formation and Precambrian crystalline rocks of the Precambrian or red beds of the Permian and Triassic State Bridge or Chinle and Chugwater(?) Formations undivided. This application of the Sundance Formation follows the usage of Pipiringos (1957) in the Laramie Basin, Wyo., of Hail (1965, p. 23-25; 1968) in western North Park and northwestern Middle Park, and of G. N. Pipiringos, W. J. Hail, Jr., and G. A. Izett in their study of the pre-Morrison marine and marginal marine Upper Jurassic rocks of northern Colorado.

The Sundance Formation of the Wyoming-Colorado region has been divided by various workers into several members (Darton, 1899; Imlay, 1947; Pipiringos, 1957). In the Laramie Basin of Wyoming, Pipiringos (1957; oral commun., 1967) recognizes seven members of the Sundance Formation. From bottom to top these members are the Canyon Springs Sandstone, the Stockade Beaver Shale, the Hulett Sandstone, the Lak, the Pine Butte, the Redwater Shale, and the Windy Hill Sandstone. According to G. N. Pipiringos, W. J. Hail, Jr., and G. A. Izett, all but two members, the Stockade Beaver Shale and the Hulett, are present in north-central Colorado. On the east side of the range in the map area, G. N. Pipiringos and the author measured a section of Sundance lying on Precambrian rocks and overlain by the Morrison Formation. In this section, Pipiringos recognized the Canyon Springs Sandstone, the

Pine Butte Member, and the Windy Hill Sandstone. In the map area on the west side of the Gore Range, the Sundance overlies the State Bridge Formation and includes beds formerly mapped as Entrada Sandstone by Steinbach (1956); it is probably composed primarily of beds of the Canyon Springs Member.

Distribution

Rocks of the Sundance occur in thin discontinuous northwest-trending bands on both flanks of the Gore Range. In the map area they are generally nonresistant and outcrops are poor. On the east side of the Gore Range and the north side of the Colorado River, a few exposures occur near the base of cuestas held up by Morrison limestones; on the south side of the river no definite Sundance exposures were seen. On the west side of the Gore Range, a Sundance Formation sandstone is exposed in a railroad cut north of the river and near the west portal of Gore Canyon (fig. 31).

Thickness

Owing to the nonresistant lithologies of the Sundance in this area, only one measured section suitable for obtaining a reasonably accurate thickness measurement was found in the map area. This section is north of the Colorado River in the NW¼ sec. 21, T. 1 N., R. 81 W., and is given at the end of this section of the report. At this locality the Sundance is exposed along an irrigation ditch, and the formation consists of 68 feet of sandstone and siltstone assigned to the Canyon Springs (48 ft), Pine Butte (13 ft), and Windy Hill (7 ft) Members of the Sundance Formation.

Sections of the Sundance Formation measured by G. N. Pipiringos, W. J. Hail, Jr., and G. A. Izett (unpub. data) and by Hail (1965, p. 22-23; 1968) north of the Colorado River along the east side of the Gore and Park Ranges show that this formation thickens in a northwesterly direction from the map area, although local exceptions to this thickening are not uncommon. In the Gore Pass quadrangle, G. N. Pipiringos and his

Survey party, including the author of this report, measured a total of 54 feet of Canyon Springs, Pine Butte, and Windy Hill Members near Tyler Mountain and 176+ feet near McMahon Reservoir. At the first locality, 33 feet of the total is Canyon Springs; at the second, 117 feet. Further north along the east flank of the Park Range, Hail (1968) reported that the lower part (Canyon Springs Sandstone) of the Sundance ranges from 166 to 63 feet and the upper part ranges from 60 to 44 feet.

The Sundance Formation is thin or absent in most of Middle Park basin east of Kremmling. Izett (1968) reported that in the Hot Sulphur Springs quadrangle in the central part of the basin the Morrison Formation directly overlies the Precambrian. East of Granby but west of Tabernash, rocks probably equivalent in part to the Sundance are locally exposed along the Fraser River and along U.S. Highway 40.

South of the Colorado River along the east flank of the Gore Range and up the Blue River drainage between Kremmling and Dillon, rocks with a stratigraphic position similar to that of at least part of the Sundance Formation are mapped locally as the Entrada Sandstone. Holt (1961, p. 15) observed Entrada outcrops west of Green Mountain, and further south he measured 120 feet on the east side of the Blue River 10 miles north of Dillon. The Entrada Sandstone is about 150-180 feet thick near Dillon (Holt, 1961, p. 14-15; Wahlstrom and Hornback, 1962, fig. 2).

The Sundance Formation or rocks in a similar stratigraphic position have been mapped on the west side of the Gore Range. Near the west portal of Gore Canyon, Steinbach (1956) measured 125 feet of Entrada which the author assigns to the Sundance. South of Gore Canyon in the Sheephorn Creek area, Parsons (1954) measured 38 feet of Entrada, and in the Radium area, Gates (1950) reported that the Entrada ranged from 45 to 102 feet. G. N. Pipiringos, W. J. Hail, Jr., and G. A. Izett (unpub. data) measured two sections south of Radium and recorded 96 feet of Sundance which included 67 feet of Canyon Springs (Entrada equivalent) at the base in one, and 156 feet of Sundance which included 116 feet of Canyon Springs at the base in the other.

Lithology

In general, the Sundance in the map area is a sequence of light-yellowish-orange, gray, and brown sandstone, light-greenish-gray sandstone and siltstone, and commonly subordinate amounts of greenish-gray, rarely red claystone. Lithologic units within the formation appear to be very lenticular.

A short distance north of the Colorado River on the east flank of the Gore Range, the Sundance is predominantly light-greenish-gray shaly sandstone to claystone and light-yellowish-brown to gray massive sandstone probably equivalent to the Canyon Springs Member, light-greenish-gray nodular-weathering and locally fossiliferous sandstone and siltstone probably equivalent to the Pine Butte Member, and pale-yellowish-orange ledgy ripple-marked sandstone probably equivalent to the Windy Hill Member. The sandstone is generally limy and commonly very fine grained and well sorted.

Farther to the north, the only rocks characteristic of the Sundance that crop out and have any lateral persistence are ripple-marked ledgy sandstone and greenish-gray shaly siltstone and sandstone beds. In the NE. cor. sec. 17, T. 1 N., R. 81 W., a section about 10 feet thick of thinly interbedded dark-red claystone and yellowish-gray very fine grained sandstone is near the base of a covered interval assigned to the Sundance Formation. The beds probably belong to the Canyon Springs Member, a conclusion first suggested by W. J. Hail, Jr., after a brief visit to the area in 1964.

South of the Colorado River no definite Sundance outcrops were seen, but some of the poorly exposed sandstones near the base of the Jurassic rocks in the San Toy Mountain area may belong to the Sundance.

On the east side of the Gore Range in the map area, the base of the Sundance Formation is generally covered by substantial amounts of colluvium. Shallow trenching by the author about 1½ miles northwest of the Colorado River exposed conglomeratic Sundance resting on deeply weathered Precambrian gneiss. The conglomerate fragments are locally derived angular quartz, punky feldspar, and gneiss in a matrix of very fine grained quartz sandstone. To the northwest near the edge of the area, a red-bed sequence, the Chinle and Chugwater Formations undivided, overlies Precambrian granodiorite, and the Sundance probably unconformably overlies the Chinle Formation. Farther northwest beyond the map area along the east flank of the Gore Range, the Sundance Formation overlies the Chinle Formation or the Chugwater Formation (G. N. Pipiringos, W. J. Hail, Jr., and G. A. Izett, unpub. data).

In the map area on the east side of the Gore Range, the Sundance Formation is conformably overlain by the Morrison Formation.

A measured section of the Sundance Formation follows. Stratigraphic correlation of rocks of this section to the Sundance and some of its members was made by G. N. Pipiringos.

Irrigation Ditch section

[North side of irrigation ditch in the NE¼NW¼ sec. 21, T. 1 N., R. 81 W., Kremmling quadrangle. Measured by G. N. Pipiringos and C. S. V. Barclay, June 1963.]

	Thickness (feet)
Morrison Formation (in part):	
16. Sandstone, grayish-orange to light-gray, thin-bedded; interbedded with gray clay shale; 2-ft bed of fresh-water limestone at top; thin conglomeratic sandstone bed in middle of unit contains fragments of limestone similar to bed at top; forms ledges and reentrants	20.0
15. Sandstone, grayish-orange, thin-bedded; interbedded with gray clay shale, claystone, and limestone; sandstone is similar to unit 11; forms ledges and reentrants	9.0
14. Claystone, greenish-gray and light-pinkish-gray; upper 0.5 ft is dense gray sandy limestone; forms soft slope capped by limestone ledge	1.5
13. Sandstone, grayish-orange to light-gray, very fine grained, slightly limy; interlayered with greenish-gray blocky silty claystone; appears transitional between unit 14 and unit 12; forms slopes and ledges	2.5
Partial thickness, Morrison Formation	33.0
Sundance Formation:	
Windy Hill Sandstone Member:	
12. Sandstone, pale-yellowish-orange, very fine grained, clean, well-sorted, slightly limy, ripple-marked; greenish-gray clayey shaly siltstone near middle of unit; sandstone forms ledges separated by siltstone reentrant	4.5

Irrigation Ditch section--continued

	Thickness (feet)
Sundance Formation--continued	
Windy Hill Sandstone Member--continued	
11. Sandstone, pale-yellowish-orange, very fine grained, clean, well-sorted, slightly limy, ripple-marked; light-gray shaly silty claystone in upper 0.5 ft; forms slope and ledge---------	2.5
Total thickness, Windy Hill Sandstone Member--	7.0
Unconformity.	
Pine Butte Member:	
10. Siltstone and very fine grained sandstone, light-greenish-gray, limy, clayey, micaceous; contains some bottom-dweller trails; middle part of unit forms ledges, rest of unit forms slopes--------	5.0
9. Sandstone, light-greenish-gray, very fine grained; contains casts of marine pelecypods and bottom-dweller trails; forms rounded ledge------------	2.0
8. Sandstone, light-greenish-gray, very fine grained, clayey; forms slopes and ledges----------------	6.0
Total thickness, Pine Butte Member-----------	13.0
Canyon Springs Sandstone Member:	
7. Sandstone, light-yellowish-brown, very fine grained, slightly clayey; basal 1 ft forms ledge, rest forms slope-----------------------	12.0
6. Bentonite, white, waxy, mixed with some light-greenish-gray silty sandstone and claystone; forms slope----------------------------------	1.0
5. Sandstone, light-yellowish-brown, very fine grained, clayey, locally limy, shaly; forms slope-------	2.0
4. Sandstone, light-yellowish-brown, very fine grained, well-sorted, fairly clean, massive; shale partings; grades laterally into shale; contains ripple marks and bottom-dweller trails and borings; forms rounded ledge-------------------	17.0
3. Siltstone, very light greenish gray, well-sorted, limy, slightly clayey; more clayey and shaly and contains some thin (¼-2 in.) lenticular brown limestone layers in upper part; forms slopes and ledges--	14.0
2. Partly covered; sandstone, light-gray, micaceous, limy, conglomeratic near base, thin-bedded; forms ledges and slopes------------------------------	2.0
Total thickness, Canyon Springs Sandstone Member	48.0
Total thickness, Sundance Formation--------	68.0

Unconformity.

1. Biotite gneiss and migmatite of Precambrian age.

Base of measured section.

Within the map area on the west side of the Gore Range, the Sundance Formation is represented by rocks which Steinbach (1956) mapped as the Entrada Sandstone. A section of these rocks is well exposed along the railroad tracks near Gore Canyon and consists of a lower massive crossbedded yellowish-orange sandstone and an upper sequence of evenly bedded yellowish- to grayish-orange sandstone which contains greenish-gray shaly partings. Sandstone of both the upper and lower parts of the section is commonly very fine grained to fine-grained and the cementing material is generally calcareous. The evenly bedded sandstone becomes silty toward the top. The evenly bedded sequence is thick bedded at the base to thin bedded and laminated at the top; the abundance of greenish-gray sandstone increases from bottom to top. The crossbedding in the lower unit is large scale and sweeping; in the upper unit it is small, medium scale, and tabular. Most of the beds exposed in this partial section are probably equivalent to the Canyon Springs Sandstone, although the uppermost part has lithologic aspects similar to the Pine Butte Member as well as to the Canyon Springs. These two members and the Windy Hill Sandstone Member have been described in sections to the west near Radium and McCoy by G. N. Pipiringos, W. J. Hail, Jr., and G. A. Izett (unpub. data).

Near the west end of Gore Canyon the Sundance lies unconformably on the State Bridge Formation. To the west toward Radium, the Sundance equivalents overlie the Chinle Formation.

The top of the Sundance Formation in the southwest corner of the map area was beveled during deposition of Quaternary gravel deposits (fig. 31); where it is present immediately to the west, it is overlain by the Morrison Formation.

In the Black Hills and in the Laramie Basin (Pipiringos, 1957), the Sundance Formation is marine and marginal marine. Fossil and lithologic evidence reported by Hail (1965, p. 24; 1968) and G. N. Pipiringos, W. J. Hail, Jr., and G. A. Izett (unpub. data) and seen by the author indicates a marine or marginal marine depositional environment for the Sundance in north-central Colorado. The Canyon Springs locally consists of massive sandstones with sweeping low-angle crossbeds and frosted quartz grains, features generally considered to be characteristic of eolian deposition. Elsewhere, it is chiefly composed of interbedded sandstones and shaly siltstones, lithologic sequences indicative of waterlaid deposits. The Pine Butte Member contains the fossil marine pelecypod Camptonectes (Hail, 1965, p. 24; 1968; G. N. Pipiringos, W. J. Hail, Jr., and G. A. Izett, unpub. data) in many nearby areas of North and Middle Parks. Hail reports fresh-water ostracods in beds intertonguing with Camptonectes-bearing beds of the Pine Butte Member, which suggests a delicate balance, at least locally, between marine and marginal marine conditions of deposition. G. N. Pipiringos (oral commun., 1967) has found that the Windy Hill Sandstone is widespread, bevels all lower Sundance members, and not uncommonly contains fragments of fossil marine shells; he believes that it is a bar deposit which encroached upon the Sundance sea.

Correlation

No fossils of stratigraphic significance were found in the rocks of the Sundance in the map area, and stratigraphic assignment is made on the basis of position, lithology, and field studies made by G. N. Pipiringos.

The Sundance Formation has been traced from the Laramie Basin through North Park into Middle Park (G. N. Pipiringos, W. J. Hail, Jr., and G. A. Izett, unpub. data). On the east side of the Gore Range in the map area, Pipiringos (oral commun., 1967) recognizes the Canyon Springs, Pine Butte, and Windy Hill Members. Pipiringos correlates the Canyon Springs Member of the Sundance Formation with the Entrada Sandstone of Late Jurassic age and the Pine Butte Member in which he and Hail have found the Late Jurassic fossil marine pelecypod Camptonectes (Hail, 1965, p. 24; 1968) with the Curtis Formation, also of Late Jurassic age.

MORRISON FORMATION

Definition

The first published use of the name Morrison in the stratigraphic nomenclature of the Rocky Mountain area was by Cross (1894); his use followed that of Eldridge (in Emmons and others, 1896) who had originally used the name for a sequence of rocks in the Morrison, Colo., area. The name is now applied to Upper Jurassic continental rocks above Upper Jurassic marine and marginal marine beds and below various rock units of the Cretaceous System in the Western Interior.

In the map area the Morrison Formation is a sequence of varicolored claystone to mudstone interbedded with sandstone and fresh-water limestone. These beds overlie the Sundance Formation and underlie the Dakota Sandstone.

Distribution

North of the Colorado River, Morrison exposures are limited to the east flank of the Gore Range, but south of the river exposures extend to a high shoulder and to the crest of the range.

Outcrops of the Morrison are few and small owing to the soft nature of the formation. The most extensive Morrison outcrops are thin fresh-water limestones which, together with local Morrison sandstones and (or) Sundance sandstones, hold up the first low cuestas east of the Precambrian rocks north of the river. Massive lenticular sandstones near the base of the Morrison locally form prominent outcrops on otherwise covered Morrison slopes.

Thickness

In general, thicknesses of the Morrison are difficult to determine because of poor exposures and the ill-defined contact with the underlying Sundance Formation and locally with the overlying Dakota Sandstone. On the basis of map computations and a series of partial measured sections, the Morrison is believed to be between 230 and 270 feet thick, with 250 feet a fair approximation. Richards (1941, p. 9) reported that the Morrison Formation is only 100 feet thick in the Gore Canyon area and he included all the rocks below the Dakota in the Morrison. Richards' thickness figure seems much too low, although it is conceivable that he may have obtained his thickness where there is considerable local relief on top of the Precambrian rocks.

Thicker sections of the Morrison have been reported to the north and west. Immediately north in the Pass Creek area, Miles (1961) measured more than 316 feet of strata between the Chugwater and Dakota Formations which he assigned to the Morrison Formation with the qualification that the basal 50 feet of light-colored siltstone could belong to the Entrada Sandstone, part of the Sundance Formation of this report. Farther north near the northwestern corner of Middle Park, Hail (1968) estimated that the Morrison could be more than 500 feet thick. In an area adjacent to the southwest corner of the map area, Steinbach (1956) reported 292± 50 feet of Morrison strata between the Entrada and the Dakota sandstones, and in the Radium area farther to the southwest Gates (1950) reported 400-450 feet in the same stratigraphic interval.

The Morrison thins to the east toward the west flank of the Front Range (Tweto, 1957, p. 20) and to the southeast along the east flank of the Gore Range toward Dillon. In the Hot Sulphur Springs quadrangle, Izett (1968) measured 210 feet of Morrison strata in a well-exposed but faulted section overlying Precambrian rocks at the east end of Byers Canyon. Southeast of Kremmling, Tweto (1957, p. 20) estimated 200 feet of Morrison strata near Green Mountain on the east flanks of the Gore Range, and Howard (1966, p. 1253) estimated 75 feet in the Williams Fork Mountains to the east. Farther southeast near Dillon, Wahlstrom (1966, p. 728) measured 226 feet of Morrison lying between the Entrada and the Dakota.

Lithology

The Morrison Formation within the map area is a poorly exposed sequence of claystone to siltstone which contains a few beds of limestone and sandstone. Owing to the poor exposures, it is lithologically imperfectly known in this area but what is known is characteristic of the Morrison Formation as reported from other areas of Middle and North Park (Tweto, 1957; Izett and Barclay, 1964; Hail, 1965, 1968; Wahlstrom, 1966; Izett, 1968).

The lower two-thirds to three-fourths of the Morrison within the map area is best exposed in southwest-facing slopes north of Gore Canyon. It is composed of variegated commonly nonfissile claystone to siltstone which contain subordinate beds of thin light-brownish-gray dense limestone, thin slabby pale-yellowish-orange fine-grained sandstone, and locally toward the base very thick massive lenticular yellowish-orange fine- and medium-grained sandstone. The claystone to siltstone is reddish brown, dusky to grayish red, greenish to light olive gray, red and greenish gray mottled, and, much less commonly, dusky yellow. Weathering characteristics of some of the rocks indicate an abundance of the swelling clays. The massive sandstone near the base shows fluvial-type crossbedding and locally contains granule- to pebble-size rounded fragments of gray clay or pits where clay pellets have weathered out. Sandstone and siltstone are commonly calcareous, a characteristic of most beds of the lower part of the Morrison in the nearby Hot Sulphur Springs quadrangle and in the Dillon area. The limestone beds are of fresh-water origin. The weathered tops of some of the limestone beds show conspicuous "mats" of stubby carbonate-replaced plant stems.

A thin section of a sample from the stem-matted top of a limestone bed was studied under the microscope. In cross section an individual stem is composed of a central calcite-filled tube in a cluster of much smaller calcite-filled tubes. The average cross sectional diameter of the stems in the slide examined is about 0.8 mm. The stems are in a calcite and black clay matrix.

The upper part of the Morrison is generally in landslides with the overlying Dakota Sandstone and rarely crops out within the map area. The thickest interval of the upper part of the Morrison seen is on the east side of Beaver Dam Gulch in sec. 26, T. 1 N., R. 81 W. At this place is a 65-foot sequence composed of greenish-gray claystones to siltstones and a few thin resistant ledges of brown siltstone. This sequence is overlain by the basal chert-pebble conglomerate of the Dakota and the contact is well exposed. The claystone to siltstone rocks of this sequence are generally noncalcareous, locally contain an abundance of the swelling clays, and are commonly laminated but nonfissile. Discontinuous red and orange oxidized bands in greenish-gray silty claystones are within a few feet of the base of the Dakota and some irregular orange staining is below that. Some of the claystone has abundant coarse silt to very fine grained sand-size angular quartz fragments which impart a "tapioca" texture to the claystone. The resistant brown ledges present in the 65-foot interval are principally light-yellowish-brown hard slightly and irregularly calcareous siltstones, but one 5-foot series of resistant ledges and subordinate interbeds of greenish-gray silty claystone contain some hard pale-brown silty carbonate-rich rock. In a few places in the area, small outcrops of resistant very fine grained yellowish-orange to brown irregularly iron-oxide-stained siliceous thin-bedded sandstones occur near the base of the upper part of the Morrison Formation.

The only outcrop of the Morrison and Sundance contact is along an irrigation ditch in the northern part of sec. 21, T. 1 N., R. 81 W. There the contact is conformable; variegated claystones to siltstones and thin limestones of the Morrison intertongue over a stratigraphic interval of several feet with thin sandstones typical of the Windy Hill Member of the Sundance. The same relationship in parts of Middle and North Parks has been reported by Hail (1965, 1968) and G. N. Pipiringos, W. J. Hail, Jr., and G. A. Izett (unpub. data). In the San Toy Mountain area and along the top of the south wall of Gore Canyon, the Sundance may not be present and the Morrison may lie directly on Precambrian rocks, a situation similar to that in the Hot Sulphur Springs quadrangle (Izett and Barclay, 1964; Izett, 1968).

The lithologies characteristic of the Morrison in the map area and lithologic and fossil evidence found in the Morrison elsewhere suggest that the environment of deposition was that of a broad flood plain. The thin limestone beds in the formation probably represent lakes, the thick lenticular sandstones which show fluvial-type crossbeds represent water courses. No fossils were found in the Morrison in the map area, but in nearby areas of North and Middle Parks, Beekly (1915, p. 27), Izett (1968), and Hail (1965, 1968) among others, have reported fossil ostracods, reptilian bones, fresh-water molluscs, and land plants in Morrison beds.

Much of the material in the Morrison Formation may have had a volcanic source. Wahlstrom (1966, p. 737-738), in a study of the mineralogy and petrology of the Morrison near Dillon, Colo., concluded that the upper noncalcareous part of his section contained material derived from a distant volcanic source and that some of the material in the lower noncalcareous part might have had a similar origin. Pervasive silica cement and, locally, yellow bentonitic laminae in the claystones to siltstones of the upper part of the Morrison and the abundant occurrence of swelling clays in claystone to siltstone lithologies in all parts of the formation in the map area suggest that Wahlstrom's conclusions in the Dillon area might be applied here.

Partial sections of the Morrison follow.

Partial sections of the Morrison and Sundance Formations and the Chinle and Chugwater(?) Formations undivided. Measured by C. S. V. Barclay, June 1965.

Location 1

[West slope of low ridge in W½ sec. 33, T. 1½ N., and NE¼NE¼ sec. 4, T. 1 N., R. 81 W.]

	Thickness (feet)
Ridge top.	
Morrison Formation (in part):	
22. Covered except for a few large slabs of chert-pebble conglomerate similar to that found at base of Dakota Sandstone in nearby areas, at top may be nearly in place	20.0

Location 1--continued

Morrison Formation (in part)--continued	Thickness (feet)
21. Covered; area littered by chert-pebble conglomerate; slope break at top----------------------------------	15.0
20. Covered; at top, first float of chert-pebble conglomerate of Dakota Sandstone------------------------	117.0
19. Mostly covered; sandstone slabs weather out in a discontinuous band across slope; sandstone, grayish-orange (generally weathers grayish orange, locally yellowish gray); fine sand-size quartz grains are predominant; well-sorted, abundant limonite grains, very calcareous, irregularly very thin bedded, very faintly and thinly laminated---------------------	5.0
18. Covered, locally dug out; probably mostly claystone, light-olive-gray, derived soil yellowish-gray, slightly silty, calcareous; montmorillonitic "popcorn" crust on derived soil; forms slope, shallow reentrant between limestone ledge below, sandstone ledge above; slope change at top 15° above, 30° below--	10.0
17. Poorly exposed; limestone, similar to unit 15; nodular-weathering; forms discontinuous ledge--------------	0.5
16. Covered, locally dug out; mostly claystone, light-olive-gray (weathers yellowish gray), calcareous, silty; forms shallow reentrant--------------------	4.0
15. Limestone, light-brownish-gray (weathers light gray), dense; irregular 6-in. and 2-in. beds in upper part; 1-ft bed in lower part; slabby (upper) to blocky weathering; forms ledge; bench on top--------------	3.0
14. Varicolored siltstone interbedded with subordinate amounts of claystone and a few thin sandstone beds. Siltstone, dusky-yellow, yellow-green to grayish-yellow-green, pale-greenish-yellow to dusky-yellow, yellowish- to greenish-gray, light-yellowish-orange, light-olive-brown, dark-reddish-brown, dusky- to grayish-red, and red and greenish-gray mottled; calcareous, commonly clayey, locally arenaceous with a tapioca texture, and, rarely, conglomeratic near top with granule-size quartz; commonly laminated and locally slightly shaly. Claystone, most abundant in upper part, grayish-red, dark-reddish-brown, medium-greenish-yellow, greenish-gray, pale-olive, light-olive-brown mottled, and grayish-yellow-green; silty, calcareous. Sandstone, abundant near middle, grayish-yellow-green, very fine grained, silty, calcareous, thinly laminated. Whole unit forms moderately steep slope----------------------------	35.0

	Thickness (feet)
Morrison Formation (in part)--continued	
13. Partially covered; sandstone, yellowish-gray, very pale orange, grayish-orange, to locally dark-yellowish-orange (weathers medium yellow), very fine grained, subrounded quartz grains, limonitic and calcareous cement, friable, locally silty with tapioca texture, irregularly thin bedded and laminated; commonly forms smooth steep slope but thin hard sandstone locally present at base; forms ledge. Some orange arenaceous siltstone at top; angular very fine sand-size grains of quartz in cōarse silt matrix; weathers in angular chips and fragments. Interval forms moderate slope----------	15.0
12. Siltstone, mostly covered by sandstone colluvium from above, dark-reddish-brown to pale-olive to grayish-yellow-green, and mottled reds and greens, argillaceous, very calcareous; forms slope----------------	6.0
Partial thickness, Morrison Formation------------	230.5
Sundance Formation(?):	
11. Sandstone, poorly exposed, medium-yellow to dark-yellowish-orange (locally weathers grayish orange), very fine sand-size subangular quartz grains predominant, limonitic grains abundant, well-sorted, very calcareous, friable, irregularly laminated and massive; commonly forms steep slope with slight bench at top; locally forms ledge------------------	3.0
10. Sandstone, top and bottom covered, pale-orange, grayish-orange, pale-yellowish-orange, and grayish-yellow (locally weathers light olive gray to yellowish gray to light gray), fine sand-size subrounded to subangular quartz grains predominant, some silt-size limonitic grains, well-sorted, very calcareous, friable, massive; forms smooth steep slope or rounded ledge with bench at top. Base of this unit marks slope change from less than 20° below to 30° and steeper above--------------------------	7.0
9. Covered slope; contact of Sundance and Chinle probably in lower part of interval-------------------------	97.0
Total thickness, Sundance Formation(?)------------	107.0[1]

[1] See footnote, page 104.

	Thickness (feet)
Chinle and Chugwater(?) Formations undivided:	
8. Covered slope with sandy soil in about lower third and sandstone and grit outcrop at base. Sandstone, coarse-grained, and grit, dark-yellowish-orange (weathers grayish orange), locally conglomeratic, poorly sorted, subangular to subrounded clasts; predominantly of quartz but some fragments of partially decomposed pink potash feldspar and smaller fragments and lesser amounts of white plagioclase. Conglomeratic fragments are granule- to pebble-size subrounded to subangular quartz and rare pink feldspar; very calcareous cement; friable. Bedding indistinct; some discontinuous and irregular very thin beds; thin laminations and low-angle wedge cross-laminations locally distributed. Forms a 3-4-ft rounded ledge in roadcut, locally slumped----------------------------	35.0
7. Mostly covered; siltstone, dark-reddish-brown, clayey, calcareous; forms slope----------------------------	5.0
6. Mostly covered; siltstone, red, calcareous; irregularly laminated with orange and greenish-gray arkosic grits; forms slope--	5.0
5. Covered slope--	15.0
4. Siltstone, red, calcareous; contains some irregularly distributed quartz and feldspar granules and decomposed greenish-gray pebble-size granodioritic fragments; forms slope--	2.0
3. Siltstone; very irregular grayish-red to very dusky red to locally grayish-orange and pink layers about 1 in. thick; calcareous. Irregularly distributed; quartz and feldspar clasts and lithic fragments of pegmatite and grayish-green "rotten" granodiorite; all fragments subrounded to angular, most about 1 in. in diameter. Arkosic "grit" at base 1-2 in. thick, contains red siltstone lenses 1-2 in. long. Forms slope----------	0.9
Total thickness, Chinle and Chugwater(?) Formations undivided--	62.9[1]
Boulder Creek Granodiorite:	
2. Granodiorite, deeply weathered, crumbly surface; feldspar, partially decomposed; alteration of mafics to iron oxides widespread and yellowish-brown and orange-stained surfaces abundant----------------------------	3.0
1. Covered--	7.0

Base of section at stream level.

[1] The thickness of the Sundance Formation is probably between 68 and 107 feet, and the thickness of the Chinle and Chugwater(?) Formations is probably between 63 and 97 feet.

Location 2

[Southeast of location 1 and small fault; offset on thin limestone. Unit 17 of location 1 is unit 1 of location 2.]

	Thickness (feet)
Morrison Formation (in part):	
10. Ridge top, mostly covered; sandstone rubble caps ridge locally; sandstone, fine-grained, siliceous, irregularly iron stained, thin-bedded, slabby weathering--	9.4
9. Mostly covered to covered slope. From top to bottom: silty claystone and siltstone, light-reddish-brown and dark-reddish-brown to dusky-red to grayish-red and greenish-gray, and mottled red and greenish-gray, calcareous. Claystone, mottled very dusky red to dark-reddish-brown and greenish-gray, silty, calcareous. Siltstone, grayish-red, argillaceous, calcareous. Near top of lower third of interval is a thin bed of dense light-olive-gray (weathers olive gray) limestone and at least one thin bed of very fine grained grayish-orange to dark-yellowish-orange to pale-orange very calcareous very thin bedded slightly limonitic sandstone. Locally, float of light-olive-gray nodular-weathering arenaceous very limy irregularly bedded siltstone which has a "tapioca" texture is commonly associated with the limestone and sandstone outcrops. Forms slope-------	37.6
8. Sandstone, yellowish-gray and dark-yellowish-gray, fine- to very fine grained, very calcareous; subrounded quartz grains predominant; thinly and very thinly bedded and laminated; slabby and blocky to rough platy weathering; forms resistant ledge locally--	1.0
7. Mostly covered slope. In upper, thicker part, claystone, mottled dark-reddish-brown to dusky-red and greenish-gray, slightly silty, very calcareous; siltier and more greenish at top than bottom. In lower part, sandstone, dark-yellowish-orange, very fine grained, very silty--	4.7
6. Covered slope--	9.4
5. Covered slope; float is yellow sandstone similar to unit 19 at location 1------------------------------	18.8
4. Sandstone, pale-greenish-yellow to yellowish-gray to almost white (weathers yellowish and dark gray), very fine grained, very calcareous; hard, forms resistant ledge; blocky weathering----------------------------	1.0
3. Covered slope--	1.5

Location 2--continued

	Thickness (feet)
Morrison Formation (in part)--continued	
2. Mostly covered; claystone, dusky-yellow-green to greenish-gray (weathers pale olive to light gray), slightly silty, montmorillonitic------------------	4.7
1. Limestone, light-brownish-gray (weathers light gray), irregularly very thinly bedded and laminated; forms resistant ledge------------------------------------	0.5
Partial thickness, Morrison Formation-----------	88.6

Correlation

Assignment of beds to the Morrison Formation is made on the basis of lithology and stratigraphic position. The age of the Morrison is generally regarded as Late Jurassic, but W. J. Hail, Jr. (1968) suggested that locally the Morrison may be conformable with the Dakota and may be Early Cretaceous in part.

Cretaceous Rocks

DAKOTA SANDSTONE

Definition

Meek and Hayden (1861, p. 419-420) applied the name Dakota to a 400-foot sequence at the base of the Cretaceous series composed of sandstones, locally interbedded with claystones and lignites, exposed near Dakota, Nebr. Since 1861, the name has been variously used by geologists as a formation name, a group name, and a much-restricted formation name. A recent and extensive study of rocks mapped as Dakota in Colorado was made by Waagé (1955, 1959) along the eastern flank of the Front Range. He used Dakota as a group name, as did Lee (1925; 1927, p. 17-23), and divided the rocks into two new formations: Lytle, the lower formation, and South Platte, the upper.

Lithic equivalents, but not the boundaries, of Waagé's two formations can be recognized within the map area and, therefore, the name Dakota Sandstone is applied to the sequence of conglomerates and sandstones, siltstones, and sandstones between variegated Morrison beds and the lowest overlying beds which contain fish scales assigned to the Benton Formation.

Distribution

Within the map area, beds of the Dakota Sandstone are exposed in a northwest-trending belt along the east flank of the Park Range and, south of Gore Canyon, at the crest and on a small bench west of the crest. The sandstones are resistant and locally form bold cliffs, extensive dip slopes, and in the San Toy Mountain area, mountain peaks. Because of landslides, outcrops of the Dakota are not abundant; the best outcrops are near the east end of Gore Canyon where the Dakota hogback is breached by the Colorado River (fig. 33). Strike valleys in the Morrison have accentuated the bold Dakota cliffs.

Thickness

Ill-defined poorly exposed contacts with the overlying Benton Formation, with the underlying Morrison Formation, and landsliding make thickness determinations difficult in most of the area. Except for the beds near the contact of the Benton and Dakota, the Dakota is well exposed and its thickness is easily measured just northwest of the east end of Gore Canyon (fig. 33); there the Dakota is about 225 feet thick. Richards (1941, p. 10-11) measured about 210 feet and Miles (1961, p. 74-75) measured more than 203 feet in the Gore Canyon area.

In surrounding areas the Dakota is 100-300 feet thick. To the north, Jenkens (1957, p. 52) measured 296 feet in the Red Dirt Creek area; Hail (1968) measured only 120 feet near Red Dirt Creek and 140 feet about 6½ miles north along Muddy Creek. In the Hot Sulphur Springs quadrangle, G. A. Izett, A. A. Wanek, and the author measured 230 feet below the Williams Fork Reservoir Dam. At the east end of Byers Canyon,

FIGURE 33.--The Dakota Sandstone on north side of Colorado River near east end of Gore Canyon in sec. 23, T. 1 N., R. 81 W. Beds dip northeasterly. At some places the top of the cliff is probably within 10 feet of the base of the Benton Shale. Line of small scattered evergreens in middle of cliff marks interval of siltstones and sandstones at top of lower part of the Dakota Sandstone.

Izett (1968) reported 185 feet for the Dakota. Further east in the Fraser area, Tweto (1957, pl. 21) found the Dakota to be nearly 400 feet thick. In the Mount Powell quadrangle, which straddles the Gore Range south of the Kremmling quadrangle, Taggart (1963) measured 200 feet of the Dakota. At Green Mountain Dam in the same quadrangle, Tweto (1957, p. 21) reported that a 152-foot section of the Dakota was cored. On the west side of the Gore Range, Steinbach (1956) measured 198 feet and 227 (250?) feet. Parsons (1954) measured 201+ feet between the map area and Radium, and Gates (1950) measured 200-250 feet near Radium.

Lithology

In the map area, the Dakota Sandstone can be divided into two parts. A lower nonmarine part, lithogenetically related to the underlying Morrison Formation, is composed of lenticular conglomerate, conglomeratic sandstone, sandstone, and variegated siltstone and claystone. An upper more evenly bedded marginal marine and marine(?) part, lithogenetically related to the overlying Benton Shale, consists of sandstone and subordinate siltstone. Figure 33 shows the topographic expression of this two-fold division.

The lower part of the Dakota typically has a basal sequence composed of chert-pebble conglomerate, fine-grained to locally coarse grained and conglomeratic quartz sandstone and, rarely, thin claystone to siltstone. This basal sequence of beds is overlain by thin-bedded fine- and very fine grained sandstones irregularly interbedded with variegated siltstones and claystones.

Chert-pebble conglomerate characteristically forms the base of the formation, but it also occurs as thin lenses within the associated sandstone. Locally the basal conglomerate is absent. The conglomerates and associated sandstones are light gray, pale orange, grayish orange, or yellowish orange and are lenticular, locally crossbedded, and commonly form a massive cliff.

In a few places claystone or siltstone occurs as lenticular beds within the massive sandstone and conglomerate of the basal sequence. A 3-foot greenish-gray claystone containing uraniferous coaly carbon lenticles is in chert-pebble conglomerate and sandstone near the base of the Dakota scarp in sec. 26, T. 1 N., R. 81 W. A thin slightly arenaceous and pebbly greenish-gray claystone is in basal massive sandstone just north of the Colorado River. In the SW¼ sec. 33, T. 2 N., R. 81 W., at the north edge of the area, a hint of a thick red siltstone or mudstone in a mostly covered zone occurs between basal chert-pebble conglomerate and a very thick massive crossbedded sandstone.

The sandstone and interbedded siltstone and claystone overlying the conglomerate and massive sandstone characteristic of the base of the Dakota are commonly poorly exposed, generally forming a steep reentrant talus-covered slope between the lower and upper cliffs of the Dakota. In the few outcrops studied, the sandstones of this interbedded sandstone, siltstone, and claystone sequence are thinly and evenly bedded, and are more irregularly colored and finer grained than the sandstone of the basal sequence. The siltstone and claystone are red and greenish gray, variegated, nonfissile, locally siliceous, and locally arenaceous.

The base of the Dakota rarely crops out in the map area, and the contact relation of the formation to the underlying Morrison is not clear. South of the Colorado River the contact is locally well exposed on the west side of the Dakota hogback. South of the adit in sec. 26, T. 1 N., R. 81 W., chert-pebble conglomerate overlain by sandstone lies directly on a slightly wavy or undulating surface on top of locally oxidized red and greenish-gray claystone of the Morrison, and the contact is sharp and appears to be unconformable (fig. 34). North of the Colorado River a similar contact appears to be present in the vicinity of the measured section in sec. 22, T. 1 N., R. 81 W. At other places the contact between the two formations is not marked by a sharp lithologic boundary and is difficult to determine. Near and to the north of the adit in sec. 26, T. 1 N., R. 81 W., massive sandstone appears to be present on both sides of the contact, although it is possible that all

FIGURE 34.--Contact of the Dakota Sandstone and the Morrison Formation in sec. 26, T. 1 S., R. 81 W. Head of geologic pick at base of chert-pebble conglomerate of the Dakota; Geiger counter is at base of outcrop of Morrison claystone.

the sandstone exposed there represents a Dakota channel in the Morrison and the Dakota and Morrison contact is somewhere below. North of the measured section in sec. 22, T. 1 N., R. 81 W., the projected position of the contact is at the base of a sequence of evenly bedded well-sorted fine- and medium-grained sandstones thinly interbedded with brownish-red siltstones and at the top of greenish-gray siltstones and mudstones or claystones. At this last locality the contact of the Dakota and Morrison appears to be conformable.

The upper part of the Dakota is the thickest, best exposed, and seemingly the most lithologically persistent part of the Dakota in the area. The most complete exposures are in the segments of the Dakota hogback near the east end of Gore Canyon. There, well-bedded sandstone of the upper part forms bold cliffs that rest and locally slightly overhang softer beds at the top of the lower part. The contact between the upper and lower parts is sharp, gently undulating or wavy, and may be unconformable. Most of the upper part is grayish or pale-yellowish-orange thin- and thick-bedded siliceously cemented quartz sandstone which has small-scale tabular crossbedding, "worm" burrows, and ripple marks locally abundant. The sandstone is slabby, blocky weathering, fine grained, and locally slightly conglomeratic. Associated with the sandstone beds are partings and thin beds of light-gray claystone and siltstone, and locally thick and very thick moderately shaly clayey siltstone to silty sandstone which are locally interbedded with thin beds of light-brown or gray very fine grained siliceous sandstone. The upper 15-30? feet of the upper unit is a light-gray locally iron-stained irregularly thin- and very thin bedded flaggy siliceous very fine grained sandstone. Locally it contains silicified plant fragments, wood molds, and sand-size black carbonaceous fragments. Some bedding-plane surfaces are ridged with ripple marks and commonly have interference ripple marks. Small-scale low-angle wedge and tabular cross-laminae sets are locally abundant.

The contact of the Dakota with the overlying Benton Shale is generally covered in the area but seems to be a conformable and gradational sequence of interbedded platy sandstone to shaly claystone that spans the transition from a marginal marine to a marine depositional environment. The contact was arbitrarily drawn above the highest flaggy siliceous sandstone and below the lowest gray platy siliceous siltstone containing fish scales. Locally, a light-gray siliceous massive claystone which contains a few fish scales occurs at the contact. The claystone represents the transition from marginal marine to marine conditions; it is nonresistant and in mapping it was included with the Benton Shale. A few inches of pebble conglomerate are present at the upper surface of the highest bed of Dakota Sandstone found in the arroyo that cuts across the C SE¼ sec. 31, T. 1 N., R. 81 W. The highest sandstone of the Dakota found in the NW¼ of the same section is also locally conglomeratic with chert, claystone, and quartzite pebbles and granules. Similar occurrences of conglomerate at the top of the Dakota are reported by Waagé (1955, p. 33) who believed that they represented local "winnowing" at the top of the Dakota.

Section of Dakota Sandstone near C W½ sec. 23 and center of east edge of sec. 22, T. 1 N., R. 81 W. (fig. 33); measured by C. S. V. Barclay, assisted by A. M. Thompson, June 30, 1964.

	Thickness (feet)
Benton Shale (in part):	
13. Dip slope covered with colluvium and landslide deposits which contain fragments of very thin bedded gray, rust-weathered siliceous siltstone containing fish scales. Contact with Dakota is probably high on dip slope.	
Dakota Sandstone (in part):	
Upper member (in part):	
12. Sandstone, light-gray, siliceous, very fine grained; very thin bedded and laminated and locally cross-laminated in low angle; wedge-shaped and tabular sets; black shale(?) and (or) coaly(?) fragments, 1 mm in largest dimension, common in some laminae; flaggy. Some beds of fine-grained locally ferruginous commonly red- and orange-stained sandstone in uppermost part; slabby----------------------	14.5

Section of Dakota Sandstone in secs. 23 and 22--continued

	Thickness (feet)
Dakota Sandstone (in part)--continued	
Upper member (in part)--continued	
11. Sandstone, very pale yellowish and pale-yellowish and dark-yellowish-orange, irregularly iron-oxide stained; composed of fine-grained siliceously cemented subangular to angular quartz, locally contains granule- to pebble-size fragments; contains abundant borings of soft-bodied organisms and ripple marks; irregular very thick, thin, and medium beds; thin greenish-gray siltstone to claystone partings locally present. Approximately 8 ft from base, 1-2 ft of very thinly interbedded greenish-gray siltstone and sandstone or, locally, a chert-pebble conglomerate lens. Forms massive cliff, recessed at base; contact with next lower unit sharp, slightly irregular, wavy-------------	92.0
Partial thickness, upper member----------------	106.5
Lower member (in part):	
10. Claystone, greenish-gray; some silt and subrounded very fine sand-size quartz grains; hard, siliceous; forms reentrant----------------------	1.5
9. Sandstone, medium-light-gray, locally stained black by manganese oxide; composed mostly of fine-grained quartz but contains some medium-grained and abundant very fine grained phenoclasts; siliceous cement, very thin cherty zones common; irregularly very thin and very thick bedded; forms very thick massive weathered ledge---------	7.5
8. Sandstone, pale-yellowish, grayish- and dark-yellowish-orange; irregularly iron-oxide stained; composed of fine- to very fine-grained subangular to angular quartz; siliceous; irregularly thin and very thick bedded with silty partings; forms massive ledge------------------------------------	8.0
7. Sandstone, thinly interbedded with subordinate siltstones; sandstones are very light and pinkish gray, very pale orange and grayish orange pink (weather brown and orange); composed of very fine grained quartz, siliceously cemented; thin-bedded; forms ledges in lower two-thirds of interval. Siltstones, greenish-gray, dusky-red-mottled, clayey, locally slightly arenaceous and "tapioca" textured; form reentrants--------------	5.0

	Thickness (feet)
Dakota Sandstone (in part)--continued	
Lower member (in part)--continued	
6. Claystone, medium-dark-gray, very dusky red, mottled; contains some subrounded very fine sand-size quartz; siliceous, hard; no bedding planes; slickensides; forms reentrants----------	1.0
5. Sandstones and interbedded subordinate siltstones; sandstones, light-brown, dark-yellowish-orange, grayish-orange, pink and light- to medium-light-gray, irregularly stained brown and orange; composed of very fine angular and subangular quartz, some fine subangular and subrounded quartz, and siliceous locally ferruginous cement; thinly bedded; forms ledges. Siltstones, light-, medium-light-, and light-greenish-gray, dusky-red, moderate-reddish-brown, and red and greenish-gray mottled; quartzose; irregularly clayey and slightly sandy; locally ferruginous; form very thin reentrants. Topmost sandstone ledge has abundant clayey and limonitic laminae and an irregular top; local unconformity?-------	9.5
4. Sandstone, very light gray and pale-yellowish-orange; dark-yellowish-orange where iron-oxide-stained; quartz sand, siliceously cemented; contains lenses of chert-pebble conglomerate and conglomeratic coarse-grained sandstone; very thick bedded; small- and medium-scale sets of low-angle wedge-shaped and lenticular cross-laminae; forms massive cliff-------------------	65.0
3. Conglomerate, orange, grayish-orange (dark-yellowish-orange where iron-oxide-stained); composed predominantly of granule- to pebble-size well-rounded fragments of medium- to light-gray and light-brown chert in a matrix of fine- to coarse-grained, angular to subangular quartz and siliceous locally ferruginous cement; also contains well-rounded fragments of light-colored very fine grained siliceous sandstones and light-grayish-yellow cherty claystone; much less commonly, near the base are relatively soft angular fragments of greenish-gray claystone as large as 2 ft long and 4 in. thick, and smaller silicified more rounded fragments of similar material; lenticular; very thick bedded; forms massive cliff------------------------------------	12.0[1]
Partial thickness, lower member---------------	109.5[1]

[1] See footnote, page 116.

Section of Dakota Sandstone in secs. 23 and 22--continued

	Thickness (feet)
Dakota Sandstone (in part)--continued	
Partial thickness, Dakota Sandstone-------	216.0[1]
Morrison Formation (in part):	
2. Covered slope; contact of Dakota and Morrison is probably in upper 3 ft------------------------------	8.1[1]
1. Mostly covered slope; claystone, medium- and slightly greenish gray, irregular and thinly laminated, shaly; contains some thin yellowish bentonitic laminae and at least one thin bed of light- to greenish-gray clayey very fine grained ledge-forming sandstone-----	5.0
Partial thickness, Morrison Formation--------------	13.1

Base of section covered.

Partial section of Dakota Sandstone, sec. 34, T. 1½ N., R. 81 W.; measured by C. S. V. Barclay.

[Section is top of large glide block. The beds of this partial section appear undisturbed.]

	Thickness (feet)
Benton Shale (in part):	
10. Mostly covered. Ground littered by siltstone, gray (weathers rust), siliceous, laminated (1/8-½ in.), flaggy; fish scales on bedding planes; forms gentle northwestward-dipping slope at top of slide block contact--	5.0-10.0
Benton Shale and Dakota Sandstone undivided:	
9. Mostly covered slope; claystone float, gray, light- to very light-gray (locally stained dark orange brown), siliceous "domino" weathering claystone; no fish scales. Near top are a few flagstones of fine- to medium-grained orange-brown (weathers darker) very siliceous hard siltstone; forms slope--------------	15.0-20.0
Dakota Sandstone (in part):	
Upper member (in part):	
8. Sandstone, light-gray (weathers grayish orange, darker orange and brown where limonitic stained), fine- to very fine-grained, siliceous, very hard, irregularly thin bedded (2-4 in.), slabby; forms ledge in reentrant slope-----------------------	4.0

[1] Some of both units 2 and 13 are Dakota; the upper and lower members of the Dakota are each probably 5 ft or more thicker, and the total thickness of the Dakota is probably near 225 ft.

Partial section of Dakota Sandstone, sec. 34--continued

	Thickness (feet)
Dakota Sandstone (in part)--continued	
Upper member (in part)--continued	
7. Mostly covered; locally a few thin ledges indicate that it is thin-bedded sandstone like unit 6; forms slope	2.0
6. Sandstone, mostly light tan and grayish orange (weathers dark yellowish orange, dark orange, or brown), fine-grained, subangular and angular quartz, siliceous, very hard; beds 4 in.-4 ft, mostly 1-4 ft; some thin laminations and shaly partings between thick beds; tabular small-scale crossbedding; some ripple marks; blocky and slabby weathering; forms cliff	35.1
5. Covered steep slope; light-gray claystone float	3.0
4. Sandstone, light-gray and light-tan (weathers light to dark brownish orange, locally limonitic stained to yellowish orange), fine- to very fine-grained, siliceous, hard; beds 1-4 ft thick; slabby and blocky weathering	8.2
3. Siltstone, arenaceous, light-gray, irregularly orange stained, very thinly laminated; at middle and top grades to light-gray and light-tan (dark-orange and brown weathering) very fine grained thinly and irregularly bedded sandstone; forms slope	7.0
2. Covered slope	3.0
1. Sandstone, light-tan and light-gray (weathers grayish orange brown), very fine grained, siliceous, hard; worm trails; thin- and very thinly bedded; flaggy; bedding-plane surface weathers irregular and rough. Interbedded with arenaceous siltstone, colors similar to sandstone but commonly limonitic stained, siliceous, friable, laminated and thinly laminated, wavy laminations, slightly shaly weathering. Unit forms series of ledges with thin reentrants	15.0-20.0
Partial thickness, upper member of Dakota Sandstone	77.3-82.3

Base covered; colluvial and landslide debris.

Correlation

On the basis of stratigraphic position and lithology, the Dakota Sandstone of the map area is correlated with the Dakota Sandstone mapped by Izett and Barclay (1964) and Izett (1968) in the Hot Sulphur Springs area and with Waagé's (1955) Dakota Group of the foothills along the east side of the northern part of the Colorado Front Range.

The lower part of the Dakota of this report and the basal Lytle Formation of Waagé's Dakota Group are probably equivalent, not only on the basis of stratigraphic position but because of the distinctive chert-pebble conglomerate and associated sandstone and variegated beds which are characteristic of both. The upper part of the Dakota is probably equivalent to Waagé's South Platte Formation, although the small number of exposures in the map area did not reveal the abundant marine shales and siltstones nor the definite members of Waagé's South Platte Formation.

Although no diagnostic fossils were found in the Dakota Sandstone, an Early Cretaceous age is proposed for this formation on the basis of Waagé's (1955, p. 27) Early Cretaceous age for the Lytle Formation and the generally accepted Early Cretaceous age for the lower part of the overlying Benton Shale.

BENTON SHALE

Definition

The name Fort Benton was originally used by Meek and Hayden (1861, p. 419, 420-422) for the lower part of their Colorado Group which lies above the Dakota Group and below the Montana Group in Montana, Wyoming, South Dakota, and Nebraska.

In this report the term Benton Shale follows the usage of Izett and Barclay (1964) and Izett (1968) in the Hot Sulphur Springs quadrangle and is applied to the marine shale, sandstones, and limestones between the stratigraphically highest quartzitic sandstone of the Dakota and below the limestone and thinly interbedded shale of the Fort Hays Limestone Member of the Niobrara Formation.

Distribution

The Benton Shale is exposed in a northwest-trending belt on the lower sage-covered slopes of the east flanks of the Gore Range. Outcrops of the formation are generally small and scattered owing to its composition largely of nonresistant shales and to landsliding. The best outcrops are in the southeastern part of the area; they belong to the sandstone and limestone member at the top which locally with the overlying Fort Hays Limestone Member of the Niobrara form the crest and dip slopes of low cuestas.

Thickness

The thickness of the Benton in the map area is estimated to be between 330 and 350 feet. A partial section measured south of State Highway 11 totaled more than 320 feet of Benton, and less than 10 feet of the uppermost part of the Benton may be missing. Estimates based upon map relations in the same area generally fall within the range of 320-400 feet, with the best approximations about 365 feet or less; some estimates are as high as 495 feet. Estimates based on a drill log (Voegeli, 1965, p. 46) of a well near C NE¼ sec. 30, T. 1 N., R. 80 W., range from 443 to 457 feet. All these estimates are probably less reliable than the measured section because of structural complexities in the area.

Richards (1941) reported a 300-foot section south of Wolford Mountain near Kremmling. Howard (1966, fig. 3), in a study of the Williams Range thrust fault along the Blue River valley and in the Kremmling area, uses a thickness of 300 feet for the Benton. Holt (1961, p. 20), working further south in the Blue River valley, reported 340 feet near Dillon.

Maximum thickening of the Benton Shale is to the north. Miles (1961, p. 78-79) reported 370 feet in the Pass Creek-Wolford Mountain area; Jenkens (1957, p. 52) reported 418 feet in the Red Dirt Creek area; and Hail (1965, p. 40; 1968) measured more than 500 feet along Muddy Creek near the northwest corner of Middle Park.

To the west and southwest, Steinbach (1956, p. 30) measured 453 feet in the Azure area, and Parsons (1954, p. 50-53) reported 419 feet in his Gore Canyon area. To the east, Izett (1968) estimated that the Benton is 400 feet thick.

Lithology

The Benton Shale of the map area can be divided informally into a lower siliceous shale member, 70-90 feet thick, a middle calcareous shale member, 195-215 feet thick, and an upper interbedded sandstone, limestone, and subordinate shale member, 45-50 feet thick. Owing to poor exposures of the formation, the members could not be mapped separately, and the thickness and lithologic character of each is only approximately known.

The lower member is known only from float and a few small widely scattered outcrops. It consists principally of dark-gray to almost black, locally slightly brownish- or olive-gray fissile to subfissile noncalcareous claystone. It is locally silty, especially near the base where it commonly contains a few thin yellowish-brown siltstone laminae. Ironstone concretions are locally abundant; most are small (less than 2 in. in diameter) and round, but the author found a kidney-shaped concretion 1 foot long and 4 inches thick.

The character of the beds of the lower member and the contact of the Benton and the Dakota are not well known in the map area, for this part of the section is almost invariably obscured by colluvial or landslide cover. Meager evidence indicates that the contact in the map area is generally conformable and gradational although local unconformities, marked by evidence of winnowing at the top of the Dakota, may be present (p. 124). Lovering and Goddard (1950, p. 39) near Dillon and Parsons (1954, p. 50-53) southwest of Gore Canyon reported conglomerate at the base of the Benton and suggested at least a local unconformity between the Benton and the Dakota. The only place in the map area that the contact crops out is at the measured section (p. 123) in the southeastern part of the area. There, dark-gray clay-shale is in sharp contact with locally conglomeratic quartzitic sandstone of the Dakota. In other parts of the map area the topmost sandstone of the Dakota is commonly covered by a zone in which there is abundant float of gray, rust-weathering platy siliceous siltstone which contains fish scales on bedding planes. In some areas, notably in sec. 3, T. 1 S., southwest of San Toy Mountain, and in sec. 3, T. 1 N., and sec. 34, T. 1½ N., gray siliceous claystone that contains rare fish scales and weathers into domino-shaped fragments is interlayered between slabby quartzitic sandstones of the Dakota and platy siliceous fish-scale-bearing siltstone. At one place at the north edge of the area, the gray siliceous claystone was estimated to be as much as 15-20 feet thick. The zone that contains claystone, siltstone, and shale at the base of the Benton was estimated to be as much as 35-40 feet thick in the southern part of the area. It is a transition sequence between marginal marine sandstones of the Dakota and the marine silt- and clay-shales of most of the lower part of the Benton.

The middle member of the Benton is predominantly gray to olive-gray very calcareous slightly silty clay-shale. Very thin beds and laminae of pale-yellow bentonite and olive- to brownish-gray clastic recrystallized locally fossiliferous limestone, which commonly has a fetid odor, are numerous in the lower 70 feet. A few disc-shaped pods and thin lenticular beds of gray, yellowish-gray-weathering dense limestone were seen in the upper part. The contact with the lower member was seen only in the section measured in the NE¼SE¼ sec. 31, T. 1 N., R. 80 W., where the lower member becomes irregularly and slightly calcareous and then more calcareous, more fissile, more resistant, and lighter colored over an interval of about 5 feet. The contact was arbitrarily selected at the base of a 1-foot bed of sticky bentonite at about the middle of the 5-foot interval. The contact with the upper member was locally well exposed by digging along the west side of the cuesta capped by Fort Hays Limestone north of the road. The contact was picked where shale abruptly grades to a less calcareous very silty ferruginous and subfissile to nonfissile claystone.

The upper member is predominantly a series of ledge-forming sandstone and clastic limestone beds interbedded with reentrant-forming siltstone and shale. The lower third consists of a basal irregularly calcareous to noncalcareous silt-shale to massive sandy siltstone which grades to a well-bedded very fine grained calcareous sandstone. Carbonaceous matter is in all the lower third but is more abundant in the basal part. It occurs as black to brown films on bedding planes and in woody molds, black silt- to sand-size grains, and, rarely, irregular masses as much as a few millimeters across and several millimeters thick. Some fragments of an irregular mass which had an asphaltic texture were placed in a solution of organic solvents, acetone and alcohol, and some were placed in a 6 normal sodium-hydroxide solution. The organic-solvent solution showed no discoloration after application of heat. The NaOH solution turned brown, indicating the presence of humates and coaly rather than petroliferous material. The middle part of the upper member consists of very thinly and thinly bedded laminated brownish- to olive-gray, brown-weathering recrystallized clastic limestone interbedded with yellowish-gray very fine grained sandstone and, near the base, lesser amounts of fine-grained recrystallized clastic limestone, locally containing the fossil pelecypod *Inoceramus perplexus*. The brown-weathering limestone contains abundant fossil fragments, principally *Inoceramus* valves, scaphitoid ammonites, and shark teeth; it has a very strong fetid odor even on weathered surfaces and wavy or crinkly laminations. The upper part of the upper member is not generally as well exposed as the lower parts. It appears to be composed chiefly of thin beds of brown recrystallized petroliferous limestone in a soft nonresistant sequence of gray silty clay-shale.

Partial section of Benton Shale in NW¼SE¼ sec. 31, T. 1 N., R. 80 W.; measured by C. S. V. Barclay, June 1964.

	Thickness (feet)
Benton Shale (in part):	
Upper and middle members undivided (in part):	
7. Covered. Top is dip slope which has a few slabs of brown-weathering fossiliferous recrystallized clastic limestone common to uppermost part of Benton. Base of light-gray blocky limestone of Fort Hays Member of Niobrara Formation is exposed down dip slope and may be within 10 ft of top of section; interval forms slope of 30°-40° in upper 30 ft---	76.3
Middle member (in part):	
6. Partially covered. Clay-shale, similar to unit 5 but siltier, less fissile. Within 6 ft of top, lenticular beds, 6 in. thick and as much as 5 ft long, of medium-gray, grayish-orange-weathering limestone; irregularly bedded 1-4 in.; forms 25°-30° slope broken by a few discontinuous limestone ledges. Locally at base, dense slightly silty limestone in concretionary pods 4 in. thick and 3 ft in diameter----------------------------	24.5
5. Partially covered clay-shale, similar to unit 4, but thin laminae of light-colored siltstone common in upper half. Some limestone similar to that in unit 4 but in much thinner (1/8 in.) beds. At least two bentonite beds, one 5 in. thick 58 ft from base, another 3 in. thick 28 ft from base. Forms slope of 25°, lessening to 10° in basal 15 ft-----	78.5
4. Clay shale, olive-gray (weathers medium gray to light olive gray), calcareous, silty. In upper half, several thin (¼-2 in.) lenticular beds of limestone, light-olive and medium- to brownish-gray (weathers yellowish gray), clastic, very slightly silty, very finely recrystallized; fossiliferous (mollusc fragments); fetid odor. At least three bentonite beds, 2-8 in. thick. At base, bentonite, very pale orange, wet, sticky, deeply weathered, 0.5-1.0 ft thick. Forms steep slope, maximum 50°-55°----------------------------------	59.0
Partial thickness, middle member---------------	162.0

Partial section of Benton Shale in sec. 31--continued

	Thickness (feet)
Benton Shale (in part)--continued	
Lower member:	
3. Clay shale, dark-gray (weathers medium gray and locally pale yellowish brown), noncalcareous to slightly calcareous, more calcareous, and slightly less fissile in uppermost 3 ft, thin-bedded and laminated; forms gentle (15°-20°) slope---------	33.0
2. Covered except for basal few inches which is clayey siltstone, pale-yellowish-brown, siliceous and hard, thin-bedded and laminated, platy to shaly weathering; contains irregularly distributed thin dark-gray silt laminae (weathers dark to olive gray); basal 5 ft of overlying colluvial cover is largely composed of silt- to clay shale (weathers medium gray), noncalcareous to very slightly and irregularly calcareous. Forms very gentle (5°-10°) slope---	49.0
Total thickness, lower member------------------	82.0
Partial thickness, Benton Shale------------	320.3
Dakota Sandstone (in part):	
1. Sandstone, yellowish-gray to very pale orange (weathers very pale orange to pale yellowish orange), irregularly iron-oxide-stained, fine-grained, very siliceous and hard, very thin- and thin-bedded; local pockets of chert-pebble conglomerate 4-6 in. thick at top; top forms floor of modern stream channel-------------	0.5-1.0
Covered.	

Composite partial section of the Benton Shale in SW¼ sec. 30, T. 1 N., R. 80 W.; measured by C. S. V. Barclay, June 1964.

	Thickness (feet)
Niobrara Formation (in part):	
Fort Hays Limestone Member (in part):	
11. Limestone, light-gray, dense, hard, thin- and thick-bedded, blocky; very thin darker gray clayey and shaly partings. Forms crest and dip slope of ridge; thickness estimated----------------------	12.5
10. Mostly covered steep slope; predominantly medium-gray to medium-light-gray calcareous silty clay shale; silt-size grains mostly quartz, some black carbonaceous? matter; thin yellow bentonite at base. Some of interval may be shale of the Benton Shale slope------------------------------	8.0
Benton Shale (in part):	
Upper member (in part?):	
9. Mostly to partially covered steep slope broken by resistant ledges of limestone, brownish-gray, olive-gray, and medium- to medium-dark-gray (weathers dark yellowish brown), clastic, recrystallized, very fossiliferous, fetid odor, irregularly laminated and thinly bedded; some thinly interbedded limy and muddy sandstone with wavy laminations similar to limestone--	7.0
8. Covered, steep slope. Shale?----------------------	10.0
7. Limestone as in unit 9; forms ledge----------------	1.2
6. Partially to mostly covered steep slope broken by some thin resistant ledges of sandstone and limestone. Sandstone, grayish-orange (weathers yellow gray), noncalcareous to irregularly calcareous, very fine grained. Limestone, medium-light-gray, slightly sandy and silty, clastic. Thinly interbedded and laminated with grayish-black irregularly "rusty" silty very fine grained sandstone which contains some black shale partings. Black coaly(?) grains and (or) shale fragments locally abundant. One limestone ledge contains cast of <u>Inoceramus perplexus</u> (identified by W. A. Cobban). Along strike, upper parts may contain brown-weathering limestone like units 7 and 9--------------------	7.0
5. Sandstone, medium-light- to light-gray (weathers grayish orange and irregularly darker gray and orange), very fine grained, locally silty or muddy, very calcareous with visible crystalline carbonate cement to locally and irregularly slightly calcareous, hard; locally contains small (maximum 2x1x¼ in.) lustrous black coaly chips, woody molds,	

Composite partial section of the Benton Shale in sec. 30--continued

	Thickness (feet)
Benton Shale (in part)--continued	
Upper member (in part?)--continued	
5.--continued *Inoceramus* fragments, and black shale chips; thinly and very thinly bedded and laminated; some wavy and irregular laminae; very thin black shale films 1/16 in. thick on some laminae surfaces. Forms ledges-----------------------------------	2.6
4. Sandstone, yellowish-gray (weathers orange), very fine grained, calcareous. Upper 4 in., irregularly colored, muddy, irregularly calcareous, wavy and irregularly laminated, similar to sandstone in unit 3. Basal 2 in., evenly bedded, contains "worm" trails on bedding planes, similar to sandstone in unit 5. Forms ledge----------------------------	0.5
3. Sandstone, irregularly colored, grayish-black, dark-gray, olive-black, light-brown to dark-yellowish-orange where limonitic stained (weathers lighter grays and blacks, very fine grained, silty (muddy?), irregularly very slightly calcareous to noncalcareous, massive and irregularly and crudely bedded and laminated, nodular-weathering where locally exposed; some irregular very thin (1/16 in.) discontinuous black shale laminae; lower 4 ft covered. Forms steep slope; rounded ledge at top--	6.5
2. Mostly covered. Silt-shale, olive-black (weathers olive gray), very clayey, slightly sandy, slightly calcareous to locally noncalcareous toward top; irregular laminations ½ in. and less; tends to be subfissile. Forms steep slope------------------	5.0
Partial thickness, upper member----------------	39.8
Middle member (in part):	
1. Mostly covered. Clay-shale, olive-gray to dark-olive-gray to olive-black (locally weathers dark to light medium gray), very calcareous, irregularly rust stained on bedding planes near top; irregularly distributed, very calcareous light-colored laminae, some as thick as 1 in. Zone 3 ft thick of very closely spaced discontinuous thin laminae of very limy silt or silty limestone 17-20 ft from base of section locally forms ledgy outcrop. Most of interval forms steep slope----------------------	108.0
Base of section covered(?).	
Partial thickness, middle member--------------	108.0
Partial thickness, Benton Shale-----------	147.8

Correlation

The Benton Shale of the map area is equivalent to the Benton Shale of the Hot Sulphur Springs area of central Middle Park as mapped by Izett and Barclay (1964). It correlates with the Benton Shale of the east side of the Front Range and of northwestern Middle Park and western North Park, as described by Hail (1965, p. 40-48; 1968).

The lower member of the Benton contains beds at the base equivalent to the Mowry Shale of eastern Wyoming. The platy siliceous fish-scale-bearing siltstone, generally seen as float near the base of the Benton in the map area, is characteristic of this part of the Benton in the Hot Sulphur Springs area. Izett (1968) correlated beds in the lower Benton with the Mowry Shale of Albian age on the basis of fossil fish-scale collections.

The Benton Shale is correlated with parts of the Graneros Shale of Albian and Cenomanian age, the Greenhorn Limestone of Cenomanian and Turonian age, and the Carlile Shale of Turonian age as these units and their correlatives are described by Scott (1963, p. 94-97) in the Kassler quadrangle near Denver and by Hail (1965, p. 47-48; 1968) and Izett (1968) in western North Park and Middle Park. The lower member of the Benton in the map area is approximately equated with the Graneros of the Kassler quadrangle on the basis of contained fossil fish scales in the lower part and abundant ironstone concretions in soft shales of the upper part. Scott's description of the basal Lincoln Limestone Member of the overlying Greenhorn Limestone, shale interbedded with very thin fetid calcarenite layers and having a bentonite marker at or near the base, would be reasonably accurate for the lower part of the middle member of the Benton. The middle part of the middle member is generally covered, and the presence of beds equivalent to stratigraphically higher strata of the Greenhorn Limestone could not be ascertained. The upper part of the middle member is approximately equated to the basal Fairport Chalky Shale Member, and the basal 5-9 feet of the upper member is approximately equated to the middle Blue Shale Member of the Carlile Shale of the Kassler quadrangle. The interbedded sandstone, petroliferous limestone, and shale sequence of the middle and upper parts of the upper member is thought to contain beds equivalent to what Scott in the Kassler quadrangle originally called the Codell Sandstone of the Carlile, but which he now (oral commun., 1967) equates with the Juana Lopez, a member of the Mancos Shale of southern Colorado and northern New Mexico. W. A. Cobban of the U.S. Geological Survey is quoted in Hail (1968) and Izett (1968) as believing that both Codell and Juana Lopez equivalents are present in the upper part of the Benton Shale of North and Middle Parks. In northwestern Middle Park, Hail (1968; oral commun., 1967) found a stratigraphic break between the 16 feet of sandstone and the overlying 40 feet of limestone and sandstone of his uppermost Benton: he believes that the 16 feet of sandstone is the Codell equivalent and the overlying sandstone and limestone, the Juana Lopez equivalent of Cobban's usage. In the map area of this report, the sandstone in that part of the upper member between the Blue Hill Shale equivalent and the middle part of the upper member is probably equivalent to the Codell Sandstone and the overlying sandstone, limestone, and shale sequence to the Juana Lopez.

NIOBRARA FORMATION

Definition

Meek and Hayden (1861, p. 419, 422) originally used the name Niobrara for the limestone and overlying chalky-weathering marl which lies between the Fort Benton and the Fort Pierre and comprises the upper part of the Colorado Group.

The Niobrara Formation is here applied to the sequence of limestones, shales, and clayey chalks between the Benton and Pierre Shales; this follows the usage of Izett and Barclay (1964) and Izett (1968) in the Hot Sulphur Springs area and Hail (1965; 1968) in the northwestern Middle Park and western North Park areas. In the map area the Niobrara consists of two members, the Fort Hays Limestone Member and the overlying Smoky Hill Shale Member.

Distribution

The Niobrara is exposed in a northwest-trending belt at the base of the east flank of the Park Range. Outcrops of the formation are chiefly restricted to limestone ledges of the Fort Hays at the base and, less commonly, to the limestones and very limy shales in the upper part of the Smoky Hill. The Fort Hays Limestone generally forms the resistant cap of the dip slope of Benton cuestas; the limestones, limy shales, and chalks of the upper part of the Smoky Hill Member form the last low cuestas at the west edge of Middle Park basin; and the soft shales of the lower part of the Smoky Hill form the strike valley between. The best exposures and the locations of the measured sections of the Niobrara are along the Blue River in sec. 32, T. 1 N., R. 80 W. (figs. 35-38).

Thickness

A poorly defined gradational contact between the Niobrara Formation and the overlying Pierre and generally poor exposures near the contact prevent precise thickness determinations. Niobrara exposures on the east side of the Blue River in the southeast corner of the area total 645-681 feet. Most of the upper 275-305 feet was measured across a covered area near a monoclinal warp and may be in error by more than 60 feet. G. A. Izett measured a section in the same area and obtained a thickness of about 450 feet; map relations in the area give thicknesses from 600 to 800 feet; most thicknesses fall between 600 and 700 feet.

Thickness values reported from the map area and other areas of Middle Park indicate that the Niobrara is probably about 600 feet thick in this area and that it thickens to the north and northwest. In the Kremmling-Blue River valley area, Howard (1966, p. 1253) reported 500 feet for the Niobrara in his study area, and farther south, Holt (1961, p. 22) measured 455 feet near Dillon. Between Kremmling and Wolford Mountain, Richards (1941) measured a 500-foot section of Niobrara. In sec. 32, T. 1 N., R. 80 W., G. A. Izett (oral commun., 1967) obtained a thickness of less than 450 feet for the Niobrara but believed this value to be too small. To the east in the Hot Sulphur Springs quadrangle, Izett (1968) measured 545 feet in a surface section but estimated from well data an average thickness of 500 feet. Tweto (1957, p. 21) reported 400 feet for the Fraser area. To the north, Miles (1961, p. 80-81) measured 525 feet in the Pass Creek area, and Jenkens (1957, p. 53) measured 410 feet in the Red Dirt Creek area. In most of northwestern Middle Park and southwestern North Park, Hail (1968) estimated the Niobrara to be 700-730 feet on the basis of well data and surface studies, but he believed as much as 800 feet may be present in the westernmost part of the area.

The basal Fort Hays Limestone is almost constant in thickness. In the map area, the Fort Hays ranges in thickness from 12 to 16 feet, depending upon the thickness of shale at the base. Elsewhere in Middle Park, Howard (1966, p. 1253) reported 20 feet of limestone at the base of the Niobrara, Holt (1961, p. 22) reported 12-18 feet, Richards (1941) reported 15 feet, Izett (1968) reported 15-20 feet, Jenkens (1957, p. 53) reported 14 feet, and Hail (1968) reported 15-23 feet. In northwestern North Park, Hail (1965, p. 49) found 17 feet of limestone at the base of a 720-foot section of Niobrara. The Fort Hays Limestone seemingly persists to the west because Steinbach (1956) reported 17.5 feet near the east end of Blacktail Gorge in his Azure Station area, and Parsons (1954) measured 11 feet in the same general area.

Lithology

The Fort Hays Member commonly consists predominantly of 12-16 feet of evenly and thinly and very thinly bedded medium-gray to light-brownish-gray, yellowish-gray-weathering limestone (fig. 35). The limestone is dense and very hard and weathers into blocks. Shaly partings and very thin interbeds of dark-gray very calcareous very hard irregularly shaly argillaceous limestone to shaly claystone are present within the sequence.

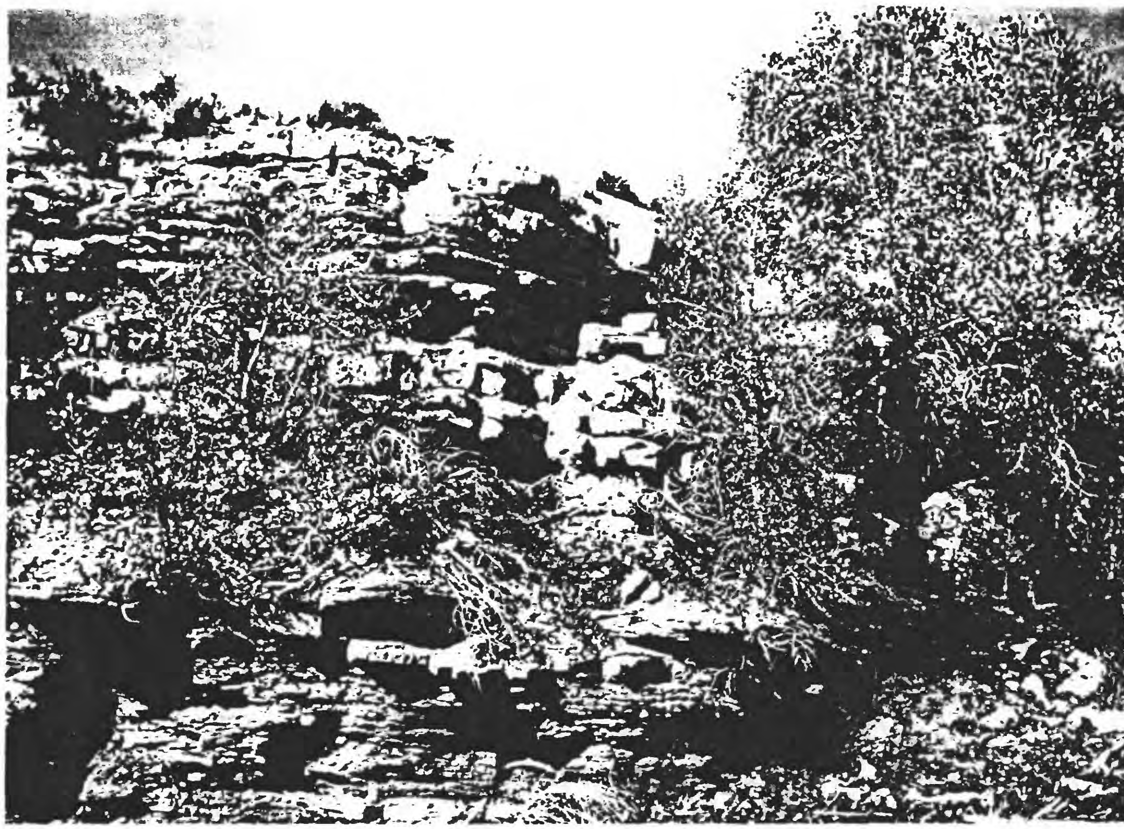

FIGURE 35.--Beds on both sides of the contact of the Niobrara Formation and the Benton Shale, on the west side of the Blue River in the SW¼NE¼ sec. 32, T. 1 N., R. 80 W. Contact is in covered area about middle of scarp.

Thin-section study of a sample of the blocky limestone typical of the Fort Hays revealed clastic, locally bioclastic carbonate rock which has been irregularly and very finely recrystallized. The rock is composed of numerous tests and test fragments of planktonic Foraminifera and a few calcite spines in a cryptocrystalline matrix of carbonate and clay. Pyrite in veinlets and small irregular blebs in fine-grained matrix material and pyritic replacement of Foraminifera tests are common.

For mapping purposes, the boundary between the Niobrara and the Benton was drawn at the base of the lowest limestone of the Fort Hays Limestone Member. Actually, the contact generally occurs within a shale sequence less than 1 to more than 8 feet thick which is commonly present between the highest petroliferous limestone of the Benton and the lowest light-gray limestone of the Fort Hays Member of the Niobrara. At a locality on the west side of Blue River in the SW¼NE¼ sec. 32, T. 1 N., R. 80 W., this shale interval is 5 feet thick (fig. 35). The beds in the lower 2 feet are dark-gray irregularly shaly to subfissile calcareous claystone and are lithologically more similar to the Benton than to the Niobrara; the beds in the upper 3 feet are medium-gray to medium-light-gray very calcareous and hard clay-shale, and they grade into the shaly partings at the base of the lowest limestone bed of the Fort Hays. Within 100 yards to the west, a covered zone which represents the whole shale interval is less than 1 foot thick and appears to be occupied by the gradation from shale to shaly limestone common to the base and partings within the limestone sequence of the Fort Hays. The shale interval is 7-8 feet thick in a section (p. 161) measured just north of State Highway 11 in the SW¼ sec. 30, T. 1 N., R. 80 W. There, fissility, color, and hardness are approximately intermediate between shales typical of the upper member of the Benton and shales typical of the Fort Hays, and the contact is placed at the base of a thin bentonite at the bottom of the interval on the basis of reports of bentonite in the Fort Hays (Scott and Cobban, 1964, p. 7).

The contact of the Fort Hays Member with the Juana Lopez equivalent at the top of the Benton appears to be unconformable. Data presented in the foregoing paragraph suggests that the Fort Hays beveled the uppermost shales of the Juana Lopez and filled shallow irregularities in the beveled surface with clayey material--reworked Benton Shale--to form an irregularly distributed basal shale. A disconformity between the Benton and the Fort Hays Member of the Niobrara in eastern Colorado was reported by Johnson (1930) and was later supported by faunal and stratigraphic studies by Cobban and Reeside (1952, chart 10b), Scott (1963, p. 95, pl. 3), and Scott and Cobban (1964, p. 8, 95).

The Smoky Hill Member consists of a lower unit of calcareous shale and subordinate chalky argillaceous limestone and an upper, thicker unit of chalky-speckled shale and subordinate limestone.

The lower unit of the Smoky Hill is approximately 177 feet thick and consists predominantly of medium-gray very calcareous fissile to subfissile nonresistant claystone (fig. 36). Laminae and very thin beds of yellowish-orange bentonite, nodules of concretionary argillaceous limestone which have iron-sulfide cores, and very chalky argillaceous limestone layers are scattered throughout the unit. The chalky argillaceous limestone beds are fairly abundant in a fossiliferous part of the lower unit about 25 feet above the Fort Hays (fig. 37). Thicker, locally very fossiliferous chalky argillaceous limestone beds are in the shale in the upper 34 feet and become increasingly more abundant toward the top.

Thin-section studies of four samples from the lower unit of the Smoky Hill Member were made. Two of the samples were taken from subfissile claystone of the basal 150 feet, one from an argillaceous limestone at the base of the upper 27 feet (fig. 36) and one from subfissile claystone 10-25 feet below the top of the lower unit. The samples are characterized by numerous fragments of calcite tests of Foraminifera (mostly Heterohelicidae--chiefly _Heterohilix_?) and spines in a cryptocrystalline carbonate-clay matrix. Irregularly shaped pyritic replacement blebs are numerous in the matrix and selective pyritic replacement

FIGURE 36.--Lower part of the Niobrara Formation exposed on the east side of the Blue River in the NW¼SE¼ sec. 32, T. 1 N., R. 80 W. Beds dip northeasterly 15°-20°. Light-colored beds that form the few scarps above water near the lower left corner belong to the Fort Hays Limestone; up-section to the right, strata of the lower part and the basal beds of the upper part of the Smoky Hill Shale are exposed. The top of unit 7, the base of unit 6--the base of the upper part of the Smoky Hill, and the base of unit 4 of the measured section of the Niobrara (p. 142) are approximately indicated. A Quaternary Blue River terrace gravel of the 40- to 50-foot level is pictured above the lower part of the Smoky Hill in the middle of the photograph.

FIGURE 37.--The Fort Hays Limestone Member and the basal portion of the Smoky Hill Shale Member of the Niobrara Formation, east side of the Blue River, NW¼SE¼ sec. 32, T. 1 N., R. 80 W. The light-colored beds that form the low ledgy scarp in the left middle ground are the limestones of the Fort Hays. The shales and chalky argillaceous limestones above the Fort Hays are the basal beds of the Smoky Hill. Beds dip northeasterly 15°-20°. Fossil sample V-76-64 collected near the base of the relatively resistant beds near base of Smoky Hill (forked limb points to sample locality); fossil sample V-77-64 collected in about middle of shale interval pictured.

for Foraminifera tests is common. Differential thermal analyses for carbonate content of fragments from the four samples are shown in table 4.

The upper unit of the Smoky Hill Member is predominantly dark-gray to medium-dark-gray, light-gray, and locally yellowish-gray, grayish-orange, or very pale orange weathering chalky speckled shale. The shale is platy and brittle and forms a moderately resistant unit (fig. 38). Thin beds of medium-light-gray limestone similar to the Fort Hays limestones are interbedded with the shale in decreasing abundance from bottom to top of the basal 27 feet of the upper unit (fig. 39). Thin yellowish bentonite layers, small round iron-sulfide[1] nodules, and thin layers of Ostrea fragments and Inoceramus prisms are present.

The depositional environment of the Niobrara is established by its rich marine fauna. The most abundant megafossils found in the formation in the map area include the sedentary clams belonging to the genus Inoceramus and oysters belonging to the genus Ostrea. J. F. Mello (written commun., March 10, 1965), after a study of the Foraminifera in eight samples collected by the author from the base of the Fort Hays to the top of the lower shale and chalky argillaceous limestone units of the Smoky Hill, concluded:

> "(1) The presence of at least a few specimens of two or more bottom-dwelling species in each sample indicates normal marine bottom conditions.
>
> "(2) The presence of planktonic specimens in all samples indicates that the water mass was of normal salinity and not turbid.
>
> "(3) The large proportion of specimens of planktonic species suggests water depth equivalent to that over the outer continental shelf today (200-400 ft). However, it should be pointed out that this proportionality is only approximately true even for the Recent and, therefore, for the Cretaceous it would probably be best to say that deposition was probably in water of moderate depth."

The chalky shale of the upper part of the Smoky Hill is characterized by fine white specks, which are spindle shaped and chalky in texture. Speckled shales are characteristic of the Niobrara and its equivalents over side areas of the Western Interior. Goodman (1951)

[1]Pyrite identified in X-ray diffractometer study of one nodule.

TABLE 4.--Differential thermal analyses showing calcium-carbonate content of samples from the lower part of the Smoky Hill Shale Member of the Niobrara Formation.

[Measured on east side of Blue River in the SE¼ sec. 32, T. 1 N., R. 80 W. Analyses by W. N. Lockwood, U.S. Geological Survey.]

Sample No.	Location in section[1]	Lithologic description	Percent calcium carbonate by DTA
V-85-64	Composite sample, unit 4.	Subfissile claystone.	27
V-834-64	Basal 10-12 in. of unit 4.	Resistant ledge of chalky argillaceous limestone.	56
V-767-64	Composite of samples taken 24 and 64 ft from base of unit 3.	Shale to subfissile claystone: in fossiliferous zone; forms relatively resistant ledgy outcrop locally.	25
V-75-64	Composite sample, unit 3.	Shale to subfissile claystone.	29

[1] Unit 4: 150-167 ft from base of Smoky Hill Shale Member.
Unit 3: basal 150 ft of Smoky Hill Shale Member.

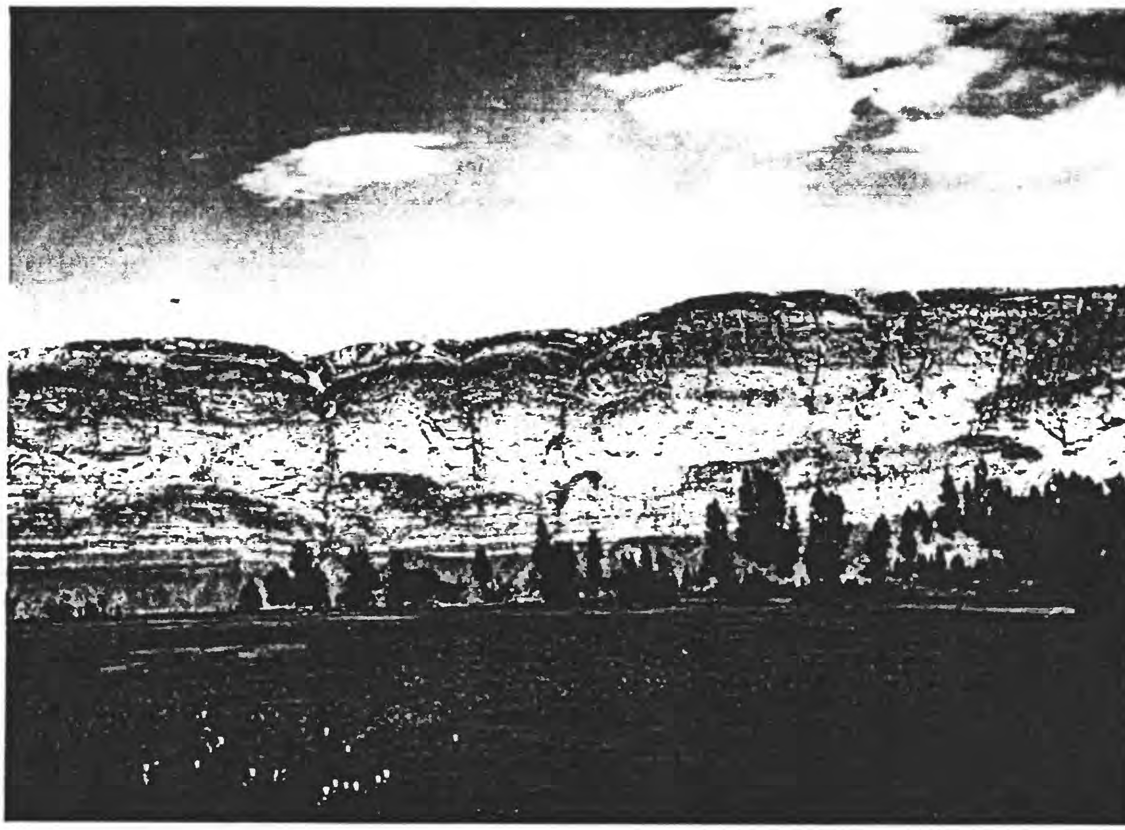

FIGURE 38.--A cliff of the upper part of the Smoky Hill Shale Member of the Niobrara, in the SE¼ sec. 32, T. 1 N., R. 81 W. The uppermost shale beds of the less resistant lower part of the Smoky Hill are exposed at the base of the cliff on the west side of the Blue River.

FIGURE 39.--Basal beds of the upper part of the Smoky Hill Shale Member of the Niobrara in the NW¼SE¼ sec. 32, T. 1 N., R. 80 W., east side of Blue River. The base of the scarp is the base of unit 6 of the measured section (p. 141) and the base of the upper part of the Smoky Hill Member. Basal limestone beds and shales of the lower part of unit 7 are shown.

made a study of specks in the Colorado Shale, which includes the Niobrara Formation at the top, and determined the presence of coccoliths, planktonic algae.

Measured sections of the Niobrara are presented on the following pages. Table 5 is a list of fossils which were collected at the measured sections and identified by W. A. Cobban and J. F. Mello of the U.S. Geological Survey.

Section of Niobrara Formation exposed from west to east from east bank of Blue River in the NW¼SE¼ sec. 32 to east side of State Highway 9 near west edge of sec. 33, T. 1 N., R. 80 W. (figs. 36-39). Measured by C. S. V. Barclay, assisted by A. M. Thompson, June 1964.

	Thickness (feet)
Pierre Shale (in part):	
Basal shale member (in part):	
12. Shale, olive-gray to light-olive-gray (weathers drab, mostly olive grays and browns, locally olive yellow); irregularly noncalcareous to slightly calcareous at top to irregularly moderately to very calcareous at bottom; 2-in. layer of reddish- to yellowish-brown thinly laminated calcareous siltstone at top; bentonite layers (weather dark yellowish orange) 1-2 in. thick at base and at 9+, 13+, 17+, and 26+ ft above base of unit; shale in lower half is irregularly and sparsely speckled. Soft flaky-weathering smooth slopes----------------------------------	29.5
Niobrara Formation:	
Smoky Hill Shale Member:	
Upper unit:	
11. Shale, speckled chalky-medium-gray and slightly bluish (weathers lighter gray, locally tannish); very calcareous platy weathering; forms slope----------------------------------	10.0-15.0
10. Covered; chalky speckled shale?; forms slope--	20.0

Note: Unit 11 and at least part of unit 10 may be a part of the Pierre or a Pierre Shale and Niobrara transition unit.

	Thickness (feet)
Niobrara Formation--continued	
Smoky Hill Shale Member--continued	
Upper unit--continued	
9. Covered (80 percent) to well exposed (10 percent). Where exposed, shale, speckled chalky-medium-gray (weathers slightly bluish gray, locally tannish), thinly bedded and laminated; hard flakes and plates; tannish-weathered beds more calcareous, more resistant than bluish-gray beds. Forms slope----------------------	310.0
8. Shale, speckled chalky-dark-gray to medium-dark-gray (weathers very light gray to slightly bluish light gray), also locally tannish, yellowish-gray, grayish-orange, and very pale orange; irregularly thin bedded and thinly laminated; commonly weathers into hard brittle plates and flakes with a hackly fracture; contains sparse irregularly distributed _Inoceramus_ prisms and a few small red iron-stained nodules of pyrite; a few thin (3 in.) yellowish-orange layers which contain bentonite and granular calcite; a few resistant ledges, commonly about ½ in. thick, composed of _Ostrea_ fragments and _Inoceramus_ prisms cemented with calcite and having a fetid odor in upper 65 ft, most abundantly in uppermost 5 ft. Forms steep slopes or cliffs---------	118.5
7. Shale and subordinate shaly limestone. Shale, speckled chalky-dark-gray to medium-dark-gray (weathers medium light gray, locally grayish orange), hard, brittle, flaggy. A few beds, 4-18 in. thick, of medium-light-gray hard limestone like unit 6 at top and in lower 6 ft; shaly-weathering at top and bottom of beds; blocky. Unit contains _Inoceramus_ prisms and pyrite "stems" (1/8 in. in diameter, 3 in. long). Forms resistant ledges and steep slope or ledgy cliff (figs. 36, 39)----------------	21.5
6. Limestone, medium-gray and slightly brownish or olive (weathers medium light gray), locally grayish orange and chalky textured, dense, clastic, locally finely crystalline with sparry calcite blebs, very hard, conchoidal fracture, thin-bedded (2 in.-1½ ft), slabby and blocky weathering; shaly partings and very thin beds of chalky limestone to chalky shale between hard limestone beds; shaly plates are hard and	

Section of Niobrara Formation--continued

	Thickness (feet)
Niobrara Formation--continued	
Smoky Hill Shale Member--continued	
Upper unit--continued	
6.--continued brittle and have hackly fracture. Small spheroids and stems of pyrite and, less commonly, fragments of large Inoceramus valves. Forms ledgy cliff or very steep ledgy slope (figs. 36, 39)------------------	7.0
Total thickness, upper unit of Smoky Hill Shale Member---------------------------	487.0-492.0
Lower unit:	
5. Limestone, medium-dark-gray (weathers lighter gray), argillaceous, chalky; interbedded with very limy shale to subfissile claystone like unit 3. Limestone is in beds 3-10 in. thick, separated by and gradational with enclosing shale; thickest shale interval is 3-4 ft, most are 1 ft or less. Dark-yellowish-orange bentonitic layers, 2 in. thick. Small pyrite nodules and fragments of large Inoceramus valves. Limestone forms ledges; shale forms slight reentrants; unit forms ledgy cliff (figs. 37, 38)----------------------------	10.0
4. Shale to subfissile claystone like unit 3; small pyrite spheroids and fragments of large Inoceramus common; forms very steep slope. At base, chalky argillaceous limestone bed, 10-12 in. thick, medium-dark-gray (weathers medium light gray, locally grayish orange); very fossiliferous; small pyrite spheroids and abundant Inoceramus fragments; forms ledge gradational with enclosing shale (fig. 36)---	17.0
3. Shale to subfissile claystone, medium-gray (weathers slightly lighter), very limy, soft, locally nodular and harder; a few thin (1-3 in.) bentonitic layers, yellowish-orange-weathering; a few thin light-gray-weathering chalky argillaceous limestone ledges; rare limestone nodules that have a pyrite core, and, more abundantly, ovoid iron-oxide and clay masses derived from similarnodules?; unit forms steep slopes covered by shaly debris (figs. 36, 37)---------------------------------------	150.0
Total thickness, lower unit of Smoky Hill Shale Member--------------------------	177.0
Total thickness, Smoky Hill Member----	664.0-669.0

Section of Niobrara Formation--continued

	Thickness (feet)
Niobrara Formation--continued	
Fort Hays Limestone Member:	
2. Limestone, medium-gray to light-brownish-gray (weathers yellowish gray, light gray, and locally a chalky very pale orange), dense, clastic, slightly chalky, hard, conchoidal fracture; in thin (4 in.-1½ ft) blocky-weathering beds; numerous very fine sparry calcite blebs. Thinly interbedded and laminated with very limy medium-dark-gray shale (weathers light olive gray); occurs as a few very thin partings in upper part and very thin beds as much as 4 in. thick in lower part. Unit forms low ledgy cliff with reentrants where shaly partings and beds are present (fig. 37)-------------------------------	12.0
1. Mostly covered; top 6 in. is very limy shale to argillaceous shaly limestone at base of basal limestone ledge of unit 2; forms reentrant------	4.0
Total thickness, Fort Hays Limestone Member---	16.0
Total thickness, Niobrara Formation------	680.0-685.0

Base of section just above water level of Blue River.

Note: Slabs of petroliferous brown limestone of the Benton Shale are at base of above section. These slabs are not in place but are thought to be nearly so, and the top of the Benton is probably at or within a few feet of the base of the section.

Section across contact of Niobrara and Benton, west side of Blue River in the SW¼NE¼ sec. 32, T. 1 N., R. 80 W. Measured by C. S. V. Barclay, June 1964 (fig. 35).

	Thickness (feet)
Quaternary terrace deposit: unconsolidated sand and gravel.	
Unconformity.	
Niobrara Formation (in part):	
Fort Hays Limestone Member:	
4. Limestone, light-gray, especially at shaly partings, dense hard conchoidal fracture, fossiliferous, thinly (6 in.-2 ft) and evenly bedded; shaly partings in upper part to shaly argillaceous limestone beds as thick as 4 in. in lower part; blocky weathering; forms ledgy scarp-------------	12.0
3. Claystone to limestone, medium-gray to medium-light-gray (weathers light gray), shaly, argillaceous toward top, very limy; similar to shaly partings in unit 4; forms steep slope; grades into limestone ledge within a few inches of top--	3.0
Benton Shale (in part):	
2. Claystone, dark-gray, subfissile to fissile, very limy, very thinly and irregularly bedded, fossiliferous; forms steep slope-------------------------------------	2.0
1. Limestone in upper part, brownish-gray (weathers brown), clastic, recrystallized; slimy fetid odor on fresh surface; mostly Inoceramus fragments; thin-bedded, slabby. Lower 6 ft (variable) is very thin bedded and laminated and more of a very limy sandstone, a true calcarenite. Forms ledgy scarp-----------(approx.)	10.0

Base of section is covered by Quaternary alluvium of Blue River flood plain.

Correlation

A Late Cretaceous age for the Niobrara was established in the field on the basis of stratigraphic position. The age and correlation of the Niobrara of the map area was confirmed by fossil collections identified by W. A. Cobban and J. F. Mello from material collected by the author (table 5).

In the map area that part of the Niobrara referred to the Fort Hays Limestone Member is restricted to the basal limestone and subordinate interbedded shale sequence. Fossil evidence, however, indicates that not only these beds but also the lowest part of the lower shale sequence of the Smoky Hill Member contain faunal elements characteristic of the Fort Hays east of the Colorado Front Range. According to J. F. Mello (written commun., 1965), preliminary research on Foraminifera of Upper Cretaceous rocks of the Western Interior suggests that the fossil Foraminifera species Eouvigerina genae Morrow is found only in the Fort Hays; Globorotalites subconicus (Morrow) is confined to the Fort Hays in the Western Interior (though it ranges into rocks as young as Early Campanian in the Gulf Coast area); and Buliminella carseyae Plummer and Gyroidina nitida (Reuss) have been reported only from the Fort Hays. Mello found Eouvigerina genae Morrow and Globorotalites subconicus (Morrow) in samples collected 25 and 65 feet, respectively, above the top of the highest typical Fort Hays Limestone. He tentatively identified Buliminella carseyae Plummer and (or) Gyroidina nitida (Reuss) in several samples collected from shales just below the base of the lowest Fort Hays Limestone bed to beds near the top of the lower shale and the subordinate chalky argillaceous limestone unit of the Smoky Hill. In the Eouvigerina genae Morrow samples taken 25 feet above typical Fort Hays Limestone, W. A. Cobban (written commun., 1964) identified Inoceramus erectus Meek which, he stated, "* * * is common in the Fort Hays Limestone Member along the Front Range."

In the Pueblo area on the east side of the Front Range, Scott and Cobban (1964, table 2) divided the Smoky Hill Shale Member into units, the chief of which are, from bottom to top: a shale and limestone unit (20 ft), a lower shale (56 ft), a lower limestone (38 ft), a middle shale (283 ft), a middle chalk (28 ft), an upper chalky shale (264 ft), and an upper chalk (8 ft). Although exposures in the area are not adequate to attempt correlation with these units, it is interesting to note that alternation of nonresistant shale and resistant limestone and chalk units from the top of the Fort Hays to the Pierre Shale is present in both areas. The strongest possibility of correlation of divisions of the Smoky Hill in the two areas is in the limestone and interbedded shale zone at the base of the upper unit (fig. 38) of the Smoky Hill in the map area and the lower limestone unit of Scott and Cobban. The position of each above soft shale units, their similar thicknesses, and the distinctive cyclic repetition of shale and limestone beds in each suggest such a correlation.

PIERRE SHALE

Definition

Meek and Hayden (1861, p. 419, 424) gave the name Fort Pierre to the lower formation of the Montana Group of the western plains. In the plains area and in some of the first ranges of the Rockies, the term Pierre Shale is now used for approximately the same marine sequence lying conformably between the Niobrara and a redefined Fox Hills Sandstone.

In the map area the name Pierre Shale is applied to the poorly exposed drab marine shales and sandstones which lie above the Niobrara along the east edge of the map area.

Distribution

Except for the northeast corner, only a lower nonresistant shaly part of the Pierre is exposed within the map area. It floors part of the west edge of Middle Park basin and forms the gentle first slopes of the Gore Range. In the northeast corner, the lower beds of the upper sandy part of the Pierre crop out and farther east and south form the prominent cliffs, locally called Muddy Buttes, north of Kremmling.

Thickness

The thickest interval of Pierre Shale in the map area is in the northeastern part of the area. G. A. Izett (oral commun., 1968) estimated that the exposed thickness of the Pierre in that area is 1,500-2,000 feet. Pierre exposures continue to the east where Richards (1941) put together a 4,939-foot composite section from partial sections measured near Coal Mountain and between Wolford Mountain and Kremmling. To the south, Holt (1961, p. 23) measured 5,844 feet on the west side of Ute Peak in the Williams Range Mountains some 3 miles northwest of Dillon. None of these sections represent the total original Pierre thickness for the area. In Middle Park, the Fox Hills Sandstone has not been found, and Upper Cretaceous(?) and lower Cenozoic beds of the Middle Park Formation locally bevel the Pierre.

Lithology

All but approximately the upper 400 feet of that part of the Pierre Shale exposed in the map area consists of black to dark-olive-gray, light-olive- and brownish-gray-weathering calcareous and noncalcareous soft clay shales and subfissile silty claystone. Some rusty-weathering hard limy clayey siltstone pods and lenticular beds and, less commonly, thin beds of limy arenaceous siltstone that contains *Inoceramus* fragments are present.

The contact of the Smoky Hill Member with the overlying Pierre is conformable and gradational where it is exposed in the measured Niobrara section (p. 140), in sec. 32, T. 1 N., R. 80 W. There the contact is drawn in the middle of a 30-foot sequence in which the brittle more resistant limy slightly bluish-gray speckled platy shale of the Niobrara grades up into soft nonresistant irregularly limy and speckled flaky olive-gray shale of the Pierre. This transitional zone is marked by a slight topographic break near the measured section and, therefore, in areas without continuous exposures the contact was placed at the topographic break between definite Niobrara and Pierre lithologies.

In the extreme northeastern part of the map area, a total of approximately 400 feet of sandstone interbedded with subordinate shale and a few limestone beds is discontinuously exposed along the ridge between U.S. Highway 40 and Muddy Creek. This interval overlies the thick basal shale interval of the Pierre and is the basal part of the upper sandy portion of the Pierre (G. A. Izett, oral commun., 1968). The lowest 125 feet or so of this sandy sequence was studied in some detail. Most of this interval is light-olive to yellowish-gray to pale-yellowish-brown, yellowish-brown to yellowish-gray-weathering very thin bedded laminated and, locally, cross-laminated very fine grained well-sorted very calcareous hard ledgy sandstone. The sandstone is composed predominantly of subangular to subrounded quartz grains but contains some very small grains of feldspar, biotite, and carbonaceous(?) matter. The sandstone is very thinly interbedded with olive-gray shale. Locally near the base there is a 6-foot ledge of irregularly thick- and thin-bedded light-brownish-gray, yellowish-orange-weathering dense nodular lenticular limestone and dolomite?. There are also a few thinner lenticular very limy mudstone beds which have numerous fine coaly fragments and are similar in color and weathering characteristics to the limestones in the lower part of the interval. Fragments of I. subcompressus (W. A. Cobban, oral commun., 1967) were collected locally in both the sandstone and mudstone.

Within the map area various portions of the Pierre are overlain by Quaternary landslide, terrace, and alluvial deposits.

Correlation

Stratigraphic position and abundant faunal evidence in lithologically similar rocks mapped as Pierre in adjacent areas establish the age of beds of this formation as Late Cretaceous. The U.S. Geological Survey regards the Pierre Shale as including rocks of middle and early Campanian age.

TERRACE DEPOSITS

Terrace deposits of Pleistocene to Holocene age occur at various levels within and along the sides of the valleys of the Colorado and Blue Rivers and Muddy Creek. Except for some of those whose upper surfaces are close to the modern flood plain, these deposits consists predominantly of sand and gravel and lesser amounts of finer grained material. Most of the gravels--those associated with the Colorado and, not as commonly, with the Blue River drainages--contain some small boulders. Roundstones of Precambrian crystalline rocks and Mesozoic sandstones are common to gravels of all the deposits and comprise the bulk of the material of most. Estimated thicknesses for most of the deposits range from 10 to 20 feet, but some are less than 5 feet and some may be more than 50 feet thick.

The upper plane surfaces of the various deposits occur at levels from 10 to 20 feet to more than 350 feet above the modern flood plains of the associated drainages. Those below the 30- to 40-foot level are generally associated with deposits that consist predominantly of sand and silt and are believed to be Holocene in age. These fine-grained deposits of low-level terraces were mapped with the Quaternary alluvium. Beginning at the 30- to 40-foot level, the deposits of the various levels were mapped separately. No attempt was made to precisely correlate the many terrace levels mapped and, therefore, none of the terrace deposits were assigned stratigraphic rank. Altitude of the tops of the various levels as given in this report was based for the most part on map study and is only approximate.

The Colorado River terrace deposits are well exposed near Kremmling and just west of the west entrance to Gore Canyon (fig. 2). Some of these are more than 50 feet thick. Boulders of Precambrian gneiss 3 feet and more in largest dimension are in a few of the deposits. Most roundstones are Precambrian gneiss but some Mesozoic sandstones are present. East of Gore Canyon well-developed terrace levels occur at

30-40 feet, 80-85 feet, and 185-205 feet. These levels are exposed on a high hill in a bend in the Colorado River in the S½ sec. 13, T. 1 N., R. 81 W. The town of Kremmling is built on the two lower levels. The lowest terrace level at Kremmling appears to be cut on Quaternary gravel for, according to a well log in a report by P. T. Voegeli, Sr., a 60-foot well on the 90-foot level in the NE¼SE¼ sec. 8, T. 1 N., R. 80 W., bottomed in gravel. Richards (1941) described prominent terrace levels at 40, 90, and 120 feet above the Colorado River in the Kremmling-Troublesome Creek area. He assigned the 40-foot level to the latest period of Pleistocene glaciation of the area. Izett (1968) reported a very prominent terrace level 80 feet above the Colorado River in the western part of the Hot Sulphur Springs quadrangle; he assigned all Colorado River terrace levels above and beginning with a 50-foot level to the Pleistocene. Near the west end of Gore Canyon, the top of a Colorado River terrace deposit, which is approximately 25 feet thick and consists predominantly of rounded boulders and cobbles of Precambrian gneiss and sand, occurs approximately 220-240 feet above the Colorado River (fig. 31). This level could not be correlated with terrace levels in the map area east of the canyon, but G. A. Izett (oral commun., 1968) reported terrace deposits of Pleistocene age at approximately 220 feet above the Colorado River in the eastern part of the Kremmling quadrangle. The 220-to 240-foot terrace level at the west end of Gore Canyon appears to be locally beveled by a pediment surface. Near the mountain front this surface carries thick (more than 25 ft) deposits of silty sand with lenses of angular and subangular Precambrian gneiss fragments of cobble size.

The Blue River terraces are similar in general composition and thickness to the Colorado River terraces, and at their confluence they have many levels in common. A distinctive feature of the Blue River terraces, at least the lower ones and the modern flood plain, is the abundance of fine-grained porphyritic rocks of the Green Mountain laccolithic complex (trachyte-latite porphyry: Holt, 1961, p. 42). In addition to distinct terraces at levels above the modern Blue River flood plain coincident with those of the Colorado River, there is a poorly preserved one at the 110- to 120-foot level and there are two prominent high levels, one about 300 feet and the other more than 350 feet, above the Blue River flood plain. The one at 300 feet can also be considered a Colorado River terrace. It is well displayed in sec. 20, T. 1 N., R. 80 W., at the high point on the northwest-trending ridge between the Colorado and Blue Rivers and is approximately equidistant above each of their respective modern flood plains. Holt (1961, p. 39) reported three persistent terrace levels at 90, 140, and 200 feet above the modern flood plain of the Blue River downstream from Green Mountain. He also described a 40-foot level which he believed might be related to the last glaciation of the area.

The gravel deposits along Muddy Creek range in thickness from 5 to 15 feet. They contain a large proportion of fine material--sand, silt, and clay, because much of the drainage basin of Muddy Creek for some distance north of Kremmling is floored with Cretaceous marine shale and soft Tertiary siltstone and sandstone. The gravel is largely pebbles and small cobbles of sandstone, siltstone, and basalt, the latter from the Tertiary volcanics in the upper reaches of its basin. Precambrian crystalline roundstones are also present but commonly very subordinate. Not enough of the terrace deposits of the Muddy Creek drainage were mapped to be able to relate the small terraces of the area to definite levels; there seem to be three to five levels between 30 and 120 feet.

The outline of a pediment surface in the northeastern part of the area is shown in figure 40. In most areas the pediment is cut on Pierre Shale, and the associated deposits are a few inches of Pierre colluvium topped by a thin soil. In some areas the surface is stripped to the cut surface and there is no deposit. In the SE¼ sec. 11, T. 1 N., R. 81 W., the surface bevels deposits which consist of iron-oxide-stained angular fragments of Dakota Sandstone as large as small boulder size. For mapping purposes these deposits were treated as normal colluvial deposits of Dakota Sandstone, but they could be very early landslide

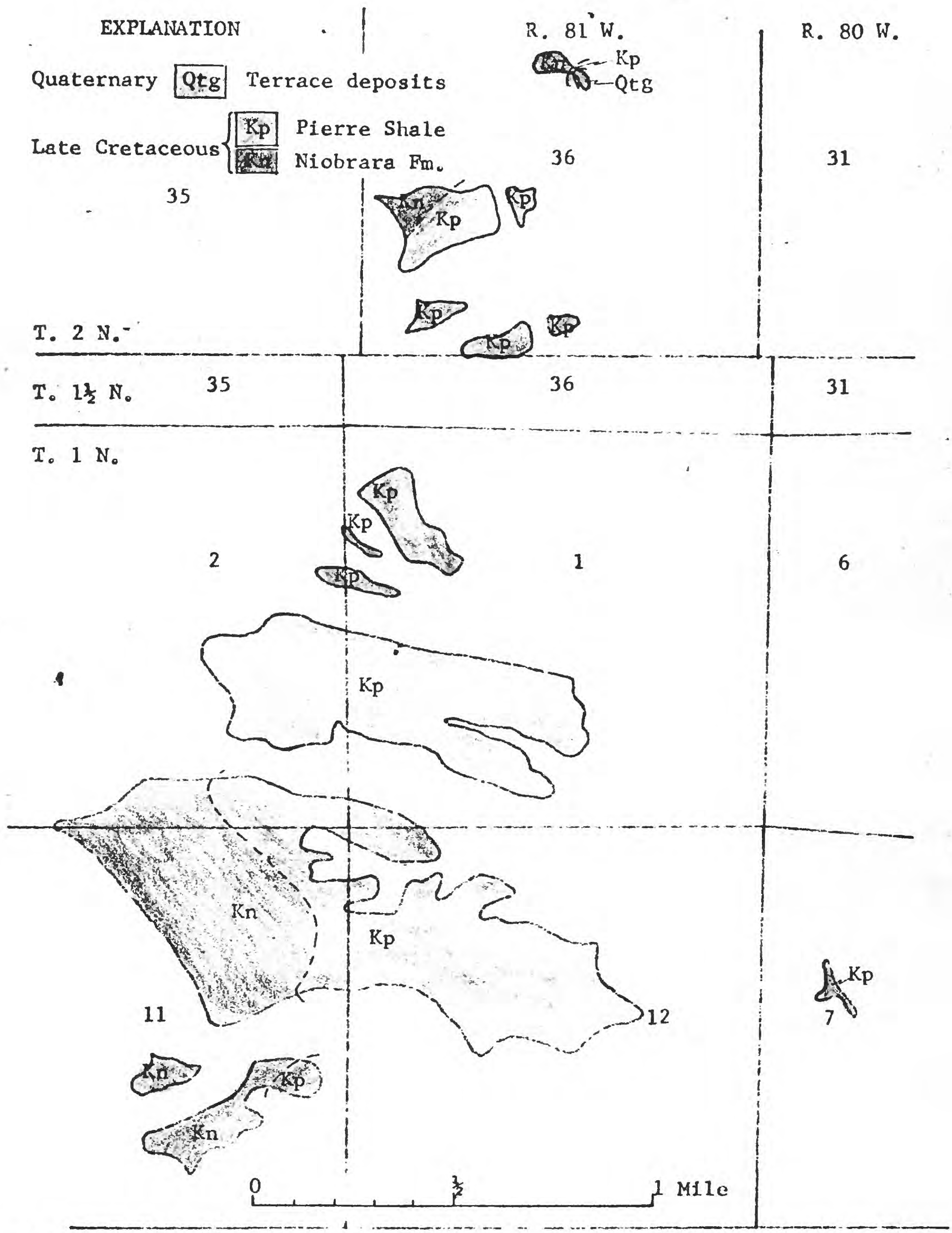

Figure 40.--Sketch map that shows a dissected pediment surface in the northeastern part of the area and some of the formations it beveled.

deposits. The smallest pediment surface remnant, shown in the SE¼ sec. 11 as having been cut on Niobrara, is cut on one of these ancient landslide(?) deposits and has been overrun by--and involved in--more modern landslides.

The pediment surface is probably late Pleistocene in age. In the W½ sec. 7, T. 1 N., R. 81 W., this surface bevels the Pierre Shale in outcrops near and at elevations above the 80-foot terrace level of the Colorado River. In the same area, this surface is just below an isolated terrace which contains material characteristic of the terraces up the Muddy Creek drainage and which is at about the 120-foot level, a level present along the Blue River and reported by Richards (1941) to be present along the Colorado River. In sec. 36, T. 2 N., R. 81 W., this pediment surface cuts a terrace level at about the 120-foot level above Muddy Creek.

LANDSLIDE DEPOSITS

Extensive landslide deposits occur along the east flank of the Gore Range, both north and south of the Colorado River, and locally are made up of rocks of Precambrian through Quaternary age. The principal types of landslide deposits within the area are block glides, slumps, debris slides, and earthflows as defined by Varnes (1958). The most common type of landslide deposit is composite slump and earthflow. Crescent-shaped scarps and hummocky locally potholed terrain are widespread and distinct. Classic examples are on the north fork of Sheep Creek and in the Beaver Dam Gulch area. Block glides of Dakota Sandstone on clayey Morrison strata are in the large area of landslide deposits north of the Colorado River; they are a characteristic feature of tilted Dakota and Morrison rocks to the northwest toward Rabbit Ears Pass (W. J. Hail, Jr., oral commun., 1967). Debris slides are common at the foot of cliffs on the south side of San Toy Mountain and along the base of the scarp face of the Dakota hogback on either side of the Colorado River near the east end of Gore Canyon. Deposits of debris slides of Precambrian gneiss talus between joint ribs in Gore Canyon, of soil falls in the alluvium along the Colorado River, and of rock falls along the scarp face of the Dakota hogback and among the cliffs and spires of Precambrian gneiss in Gore Canyon were not mapped.

The various parts of a landslide have been named and described by Varnes (1958, pl. 1). Some of these features were mapped (fig. 2) by the author to show the internal structure of the various deposits. Mapping was done on aerial photographs at a scale of 1:20,000 and 1:40,000 and transferred to the topographic base.

Structural features mapped are slump scarps, longitudinal faults, transverse ridges and cracks, radial cracks, and large glide and slump blocks. The very large glide blocks such as the one that covers large parts of secs. 34 and 35, T. 2 N., R. 81 W., and sec. 34, T. 1½ N., R. 81 W., might better be called slip sheets (de Sitter, 1956, p. 274). The transverse ridges, the longitudinal "faults" between adjacent landslide deposits, and some of the long ridge-forming rotated glide or slide blocks are noteworthy, for in many cases their pattern reveals something of the kinematics of their formation. The flow pattern of transverse elements, including "drag" configurations of transverse elements along boundary longitudinal faults, is unmistakable.

The best and most extensive exposures of landslide deposits are north of the river where an area more than 4.5 x 2.5 miles in maximum dimensions and more than 5 square miles in extent is covered by a series of overriding glide and slump blocks and coalescing slumps and earthflows, made up of rocks of the Morrison through the Niobrara Formations and, along its east edge, a pediment deposit of Quaternary age. Figure 41 illustrates some of the structural elements of the deposits shown on figure 2. In addition, it displays the sequence and pattern of surficial deformation in the southern part of the large deposit. This part of the deposit is dominated by a sinuous semicircular train of ridges that form an arc open up-slope to the west. The ridges are long rotated joint blocks of Dakota Sandstone which were shed from the topographic and probable slight structural high near and (or) to the south and west of

FIGURE 41.--Aerial photograph of the composite landslide deposit in the northern part of the map area. Some large-scale features of the composite deposit and directions of movement in various parts of the deposit are shown on the accompanying overlay.

S→ Direction of movement of slip sheet

→ Direction of movement of rotated glide block

→ Direction of earthflow

⌒ Head of slide, hachures on downthrown side

the corner of sec. 16, T. 1 N., R. 80 W. These large rotated glide blocks and the larger more cohesive slip-sheets of Dakota Sandstone which are characteristic of this and nearby areas may be detached portions of folds and the upper joint- and fault-segmented plates of bedding-plane faults or slips which formed in response and parallel to Pleistocene(?) uplift along the Park Range. Some of the Dakota glide blocks appear to have detached themselves near the Dakota and Morrison contact (southeastern arc); others, at the soft clayey siltstone zone at the top of the Lytle equivalent (northeastern arc). Some shift along longitudinal or east-northeast breaks and transverse rumpling indicates that the plates of strata below the planes of detachment of the rotated blocks have also moved, mostly east-northeast. Secondary surficial deformation includes slumping and earthflow and is widespread, especially along joint-controlled scarps of the lower Dakota plate toward the back of the slide and at the oversteepened slope at the front of the slide.

Some control of the pattern of "fractures," which bound the variously sized slide units, by the bedrock fracture pattern is demonstrated in this area. East-northeast and northeast, and to a lesser extent, north-northwest bedrock fractures serve as channels for the movement of meteoric water and groundwater and, subsequently, as planes or zones of weakness for the detachment of blocks, initiation of slumps, and landslide boundaries.

A more precise age assignment than Quaternary for the landslide deposits is not possible. Some of the slides are quite recent and parts of many are still active. During fieldwork the author witnessed movement in slumps and earthflows in the slide areas in the western portions of secs. 31 and 11, T. 1 N., R. 80 W. Evidence of much older slides is present elsewhere. North of the river in sec. 11 the east edge of an extensive slide overruns a Pleistocene(?) pediment (fig. 30) and part of the pediment itself might have been cut on deposits of an older slide. Some of the oldest landslide deposits are probably the large blocks in the extensive slide area north of the river which may have been detached during Pleistocene(?) uplift. A few of the major slumps and flows might have been initiated during periods of heavy precipitation or melt-water runoff associated with Pleistocene glaciation.

Landslides in the Kremmling area are a source of continuing economic loss. During field investigation the author saw the railroad tracks in Gore Canyon blocked by debris slides of Precambrian talus and a portion of State Highway 11 in the SW¼ sec. 31, T. 1 N., R. 80 W., covered by earthflows in the Benton Formation.

The Kremmling city reservoir in the SE¼ sec. 10 and the NE¼ sec. 15, T. 1 N., R. 81 W., is on the lower plates of detached Dakota Sandstone glide blocks (or slip sheets) and is behind a ridge formed by a line of rotated glide blocks. Although the author did not make an engineering study of the reservoir site, the existence of such a structure in this type of terrain should be considered a geologic hazard.

ALLUVIUM

Flood-plain deposits of Holocene age are mapped as alluvium in the valleys of the Colorado and Blue Rivers and Muddy Creek and part way up some of their tributaries. The material of those deposits is sand, silt, clay, and subordinate gravel. A few terrace deposits which have tops less than 30 feet above the present flood plain have been mapped with the alluvium along the Colorado and Blue Rivers and some of these are chiefly composed of gravel. Mapped with the alluvium are the distal ends of some of the alluvial fans which spread onto the flood plains.

The thickness of the alluvial deposits in the various drainages is unknown but an estimate for the deepest portions would be nearly 70 feet for the Colorado River, nearly 50 feet for the Blue River, and nearly 30 feet for Muddy Creek. A water well at the edge of the modern flood plain near the Engle Ranch buildings in sec. 20, T. 1 N., R. 81 W., was bottomed in alluvium at 36 feet (Voegeli, 1965, p. 46, table 8). Richards (1941) indicated that there is approximately 80 feet of unexposed Quaternary fill, which includes Pleistocene gravels, in the Colorado River valley near Kremmling.

Structure

REGIONAL SETTING

The Gore Canyon-Kremmling area contains parts of four north- to northwest-trending regional structural features and lies west of a fifth. From east to west they are the North-Middle Park basin, the Park Range uplift, the Gore fault, and the Central Colorado trough; the Williams Range thrust fault is exposed just east of the area. The Gore Canyon-Kremmling area also appears to lie in a regional zone of northeast faults, some of which appear to offset the north- to northwest-trending regional structures; some of the regional structures which form the tectonic framework for the Gore Canyon-Kremmling area are shown on figure 1.

The eastern part of the area lies along the east flanks of the Park Range uplift and along part of the west edge of Middle Park of the Middle-North Park basin, a broad northward-trending structural depression of Laramide age. Middle Park, the south half of the basin, is topographically separated from North Park by the Rabbit Ears Range, a short east-west mountain range composed of lower Tertiary sedimentary rocks and middle Tertiary intrusive and extrusive rocks. The eastern part of the area is occupied by northeast-dipping Late Paleozoic and Mesozoic sediments which are locally beveled by Quaternary terrace gravels along the Colorado and Blue Rivers and Muddy Creek. The Mesozoic rocks were deformed during the Laramide orogeny and by post-Laramide movement in late Tertiary time. Deformation resulted principally in northeast to east-northeast faults and related monoclinal flexures and in a few small folds due to vertical movements along the northward-trending axis of the Park Range uplift. Extensive landsliding occurred during the Quaternary and may have been induced by continued uplift during that time.

The Williams Range fault, a north-northwest-striking east-dipping to nearly flat thrust whose trace extends from the Breckenridge area almost to the Rabbit Ears Range north of Kremmling, lies just to the east of the area. It is well exposed at Wolford Mountain where Precambrian crystalline rocks have been thrust on Pierre Shale. The fault seemingly had several periods of recurrent movement during Laramide time (G. A. Izett, oral commun., 1967).

The Park Range and Front Range uplifts follow part of the west and east edges of the ancient Front Range highland of Colorado, a positive element (Lovering and Johnson, 1933, p. 371-373), which had origins in the Precambrian (Ver Wiebe, 1930, p. 768-769), was prominent in the Paleozoic, was covered by the Late Cretaceous sea and was uplifted and separated into the Park and Front Range uplifts by the formation of North-Middle-Park basin during the Laramide. The axis of the Park Range uplift trends approximately north-northwest to north-south through the center of the western part of the area where it is topographically expressed as the crest of the Gore Range. The core of the uplift exposed in Gore Canyon is predominantly composed of high-rank Precambrian paragneiss intruded by Boulder Creek Granodiorite, rocks which are common to the Precambrian terrain of the Front Range. The Precambrian rocks show evidence of having been both plastically and cataclastically deformed during Precambrian time. These Precambrian deformations and the probable order of their occurrence, oldest to youngest, are: (1) plastic deformation about a north-northwest to northwest fold axis; (2) plastic deformation about a northeast to east-northeast fold axis accompanied by intrusion of the Boulder Creek Granodiorite and, in its later stages, by cataclasis in zones parallel and subparallel to the general trend of the folding; (3) north-northwest fracturing--including faulting, some dilation and filling of north-northwest fractures by granophyre or quartz, and renewed movement and minor epidote veining in old northeast- to east-northeast cataclastic zones.

The Gore fault bounds the Park Range uplift on the west for more than 40 miles from south of Vail Pass northward to the Colorado River (Tweto and Sims, 1963, pl. 1). North of the Colorado River the uplift broadens and segments of the Gore fault appear to cut deeply into its western flanks. The Gore fault is a north-northwest to northwest-striking vertical to high-angle reverse fault which had origins in the

Precambrian and recurring movements as late as the Laramide and perhaps as late as the late Tertiary. The Gore fault may be segmented by northeast faults northwest of the Colorado River.

The southwest corner of the area extends beyond the Gore fault, which breaks the margin of the Late Paleozoic and Early Mesozoic State Bridge Formation which is locally unconformably overlain by Jurassic rocks in the map area and Triassic rocks to the west. The Paleozoic and Mesozoic strata thicken abruptly to the west beyond the map area.

The Gore-Canyon-Kremmling area lies within a region which displays the scars of several periods of deformation. Various rock units within the area show evidence of Precambrian and Laramide (latest Cretaceous and early Tertiary) deformations; in other parts of the region more recent deformations have been reported (Lovering and Goddard, 1950). The Precambrian rocks contain evidence of both plastic and nonplastic deformations, the details of which have been discussed in the section on Precambrian rocks. Precambrian deformation for which there is a record proceeded from plastic to nonplastic with the passage of time, which suggests that deformation took place at progressively higher levels in the crust. Movements in the Gore fault zone may have been initiated during the later stages of Precambrian deformation.

No direct evidence of deformation during the Paleozoic was found. Movement probably did occur along the Gore fault zone, at least during the Late Paleozoic, for during that interval most of the area was part of the Front Range highland and was rising while the Central Colorado trough was being depressed to receive more than 15,000 feet of sediment (Lovering and Goddard, 1950, p. 57).

The Laramide orogeny in this region began with arching and uplift of the Front and Park Ranges during latest Pierre time (Lovering and Goddard, 1950, p. 58; Tweto, 1957, p. 28) or later near the end of the Mesozoic era. During the Laramide, the region was subjected to a northeasterly-southwesterly compression according to Lovering and Goddard (1950, p. 63) and Badgley (1960, p. 167) and, at various intervals during the Laramide, late Tertiary, and early Pleistocene, to uplift along northward-trending axes (Lovering and Goddard, 1950, p. 63). In the Gore Canyon-Kremmling area, vertically directed stress was relieved principally along the north-northwest to northwest-striking Gore fault zone. Regional compressive stress, which may have been only a component of vertical stress (Tweto, 1957, p. 29), probably initiated faulting transverse to the Park Range uplift along old Precambrian shear zones parallel and subparallel to the regional northeasterly foliation in the Precambrian rocks. Subsequently, vertical movements occurred along these fault planes in response to continued uplift and, possibly, to some accompanying longitudinal stretching. During later stages of uplift, bedding-plane slip in directions away from the axis of uplift and the formation of folds subparallel to the axis of the uplift occurred on the east flank of the Gore Range in the sedimentary section. Uplift and some bedding-plane slip probably continued into Pleistocene time and may have led to the formation of slip sheets, the oversteepening of folds, and the subsequent detachment of glide bocks, all near surface deformations similar to those described by de Sitter (1956).

FAULTS

Northeast Faults

Faults with northeast to east-northeast strikes are herein termed northeast faults. Included within this northeast system of faults are the west-northwest faults in sections 4, 5, and 29, T. 1 N., R. 81 W., and the San Toy Mountain fault. Northeast faults are in all parts of the map area but are most conspicuous along the crest and east flank of the Park Range uplift where they are transverse to the general axial trend of the uplift. The linear traces of most and fault-plane exposures along some of the northeast faults indicate that fault plane dips along northeast faults probably range from 70° to 90°. The San Toy Mountain fault near the south edge of the area is considered to be a northeast fault, but its sinuous trace and the decrease in slope of the fault scarp at inflections of the fault trace indicate local fault-plane dips of less than 60° S.

Poor exposures prevented accurate measurement of direction and amount of displacement along most faults. General field relations suggest that most of the movements along northeast faults are normal. However, some direct evidence of strike-slip movement was found along the fault which cuts the trace of the Dakota and Morrison contact north of the top of San Toy Mountain and the center of sec. 35, T. 1 N., R. 81 W. This fault strikes N. 70° E. and dips 65°-75° NW. Throw, south side down, was estimated at 25 feet. There are also slickensides on at least one exposure of the fault plane and these plunge about 10° S. 63° W., and the base of the Dakota scarp is offset along the fault plane about 70 feet in a right lateral sense. The monoclinal flexure in the southeast corner of the area suggests that the normal fault mapped on line to the west may also have a right lateral component. High-angle reverse movement may have occurred along northeast faults: some movement along the northeasterly projection of the Cattle Drive fault of the northeastern part of the area is thought to have been in this sense (cross section A-A', fig. 2). Estimated amounts of displacement along some of the northeast faults that cut Mesozoic rocks indicate that most of these faults have throws of less than 100 feet. The two short parallel faults that break the contact of the Benton and the Niobrara in the S½ sec. 30, T. 1 N., R. 80 W., have displacements of less than 10 feet each. However, at least four faults have estimated maximum throws in excess of 100 feet. Three of these are, from north to south, the Sheep Creek fault, the Cattle Drive fault, and the San Toy Mountain fault. Maximum estimated apparent throw on each of these faults as determined by approximate map measurements of offsets of the contact between Precambrian crystalline rocks and the overlying sedimentary rocks is nearly 1,300, 650, and 700 feet, respectively. The fourth fault with a throw in excess of 100 feet is the Trough fault which is east of the San Toy Mountain and which appears to intersect the San Toy Mountain fault at a small angle south of the map area within the general vicinity of W½ sec. 2, T. 1 S., R. 81 W. The Trough fault may have more than 400 feet of throw where its trace crosses the SE¼ sec. 36, T. 1 N., R. 81 W.

Movements along northeast faults appear to have originated in the Precambrian basement rocks. Several of the northeast faults can be traced into the Precambrian rocks exposed high on the flanks of the Park Range uplift and some cross the crest line of the uplift. To the east in the sedimentary rocks the northeast faults, where they could be traced, invariably die out in Upper Cretaceous shales or are represented by monoclinal flexures in Cretaceous or even older strata. The Sheep Creek fault, which has several hundred feet of throw near the west end of its trace in the area, has a maximum throw of 75 feet and is accompanied by subparallel folding at the contact of the Niobrara and the Benton and appears to die out into a monoclinal flexure in the Pierre Shale. Laramide or post-Laramide(?) movements on the east-northeast faults which break and brecciate Precambrian rock in the E½ sec. 17, T. 1 N., R. 81 W., only bend Morrison sandstones and limestones just to the east along strike. Displacement along the Trough fault near the SE. cor. sec. 36, T. 1 N., R. 81 W., appears to be near 400 feet; on strike to the east, no trace of a fault with a displacement of this magnitude could be found along exposures of the contact of the Niobrara and the Benton in the SE¼ sec. 30 and the NE¼ sec. 31, T. 1 N., R. 80 W.

Many of the northeast faults are of ancient origin and of more than one age. Cataclasis partially obscured by shearing superposed during a later Precambrian and (or) Laramide deformation is present in northeast to east-northeast zones in Precambrian rocks, and some of these zones can be traced into faults or the axial trace of monoclinal flexures in Mesozoic rocks. The best evidence of recurrent movement along northeastward Precambrian structures is to be found in the zones which cut the Boulder Creek Granodiorite border in secs. 5, 8, and 17, T. 1 N., R. 81 W. The Cattle Drive, Sanitarium, and Sheep Creek faults and the small unnamed faults in the same area, all of which break or warp Mesozoic rocks, can be traced into zones in which the Boulder Creek shows Precambrian cataclastic structures, is locally petrologically dominated by a late potash-rich (leucoquartz monzonite) phase, and contains superposed Precambrian shear structures. The Precambrian shear structures in these zones locally include granulation and mylonitization, shear foliation, brecciation, and slickensided sheeting, accompanied by epidote and (or) quartz veining and pervasive alteration--sausseritization of plagioclase, chloritization and epidotization of mafics, and kaolinization of microcline. Some of these shear structures are similar to the type cited by Tweto and Sims (1963, p. 998) as being typical of Precambrian deformation within and in areas adjacent to the Colorado Mineral Belt, but some of the brecciation and sheeting could be post-Precambrian.

Northeast Precambrian faulting along the east flank and across the crest of what is now the Park Range followed cataclastic zones probably formed during the later stages of that deformation marked by east-northeast to northeast-folding of the biotite gneiss and the synkinematic intrusion of the Boulder Creek Granodiorite. Movement along many of these north-easterly faults occurred again during the Laramide orogeny and (or) the late Tertiary. Northeast faults of Laramide and post-Laramide time formed transverse to the Park Range uplift, perhaps first in response to northeast-southwest to east-northeast to west-southwest horizontal stress and then in response to continued vertical stress and some attendant longitudinal stretching.

Northwest Faults

Faults with northwest to north-northwest strikes are termed northwest faults. Northwest faults are parallel or subparallel to the general trend of the axis of the Park Range uplift; they are most conspicuous on the west side of the Gore Range. Northwest faults are more variable in dip than are the northeast faults; vertical and near-vertical dips are common but shallower dips also occur. Almost all these faults are in Precambrian rocks and displacement was generally impossible to determine. Most of the faults appear to be normal or high-angle reverse faults.

One of the few northwest faults observed in the post-Precambrian rocks cuts the contact between Jurassic sedimentary rocks and Precambrian biotite gneiss in sec. 17, T. 1 N., R. 81 W. Its fault plane is nearly vertical and displacement is estimated to be about 25 feet in the Precambrian, less in the Jurassic sedimentary rocks which are dragged into steep (more than 70°) dips along the fault trace.

The major north-northwest fault of the area is the Gore fault. This fault is actually a zone of multiple faulting locally accompanied by extensive cataclasis, mylonitization, and (or) brecciation. The fault zone (fig. 2) is about 500 feet wide where it cuts Precambrian crystalline rocks and the State Bridge and Sundance Formations at the west end of Gore Canyon. The best exposures of the Gore fault zone are along the railroad tracks north of the river. There, the east boundary of the Gore fault zone is a fault in biotite gneiss. The fault is a brecciated zone from 6 inches to 3 feet wide between shear planes that trend N. 3° W. and dip 55° E. and N. 10° E. and dip 60° SE. The biotite gneiss on the west side of the shear planes appears to be dragged up, and the relative direction of movement is east side up. In addition to being the east boundary of the Gore fault zone, this fault appears to be the principal fault of the zone in this area. West of the bounding fault, the rock is highly fractured and pervasively sheared, brecciated, and gougey. A few vertical faults that trend N. 25° E. offset, east side up, red beds of the State Bridge Formation and brecciate Precambrian gneiss. Farther west, a railroad cut shows the State Bridge Formation beveling Precambrian gneiss that contains a gougey shear zone which is approximately 1 foot thick and is subparallel to the fault that bounds the Gore fault zone on the east (fig. 32). Farther west, the first exposures of massive Jurassic sandstone show some evidence of shearing, but beyond, stratigraphically higher beds are relatively undeformed and outcrops of the underlying Precambrian rocks show little shear deformation. On the south side of the river to the southeast of the railroad-cut outcrops, bedrock exposures which would reveal the Gore fault zone are covered by Quaternary terrace deposits and colluvium. Further south beyond the map area, the fault trace is at the base of the steep west slope of the Gore Range and the fault offsets Late Paleozoic and Mesozoic sediments on the west against Precambrian biotite gneiss on the east. North of the railroad, the fault zone projects into terrain occupied by generally poorly exposed Boulder Creek Granodiorite. In this area shearing seems to be less intense and restricted to a few narrow zones. In upper Canyon Creek beyond the map area, the Gore zone may be a series of shears en echelon to the northeast.

A zone in which shear deformation of Precambrian rocks is conspicuous is exposed along the railroad cut between the Gore fault zone and the adit mapped at the east edge of sec. 32, T. 1 N., R. 81 W. Abundant shear surfaces and some narrow intervals of breccia and gouge are widespread in this zone but alteration and fracturing of the rocks are not as pervasive as in the Gore fault zone. This shear zone east of the Gore fault appears to trend generally north-northwest, and shear surfaces and gougey intervals of this zone are exposed up and along the east side of the Canyon Creek drainage to the north and, more abundantly, in the Inspiration Point area south of the river. The more westerly of the two faults mapped in this shear zone east of the Gore fault is a near-vertical fault which has a strike of about N. 15° W. and on the east side of Canyon Creek north of the railroad has a breccia zone 10 feet wide. This fault and its northward projection are subparallel to the granophyre dikes and quartz veins mapped in the area. This fault may be the north end of the central segment of the Gore fault as shown on regional tectonic maps (Oriel, 1954; Osterwald and Dean, 1957), and the shear zone in which it is located may be the attendant shear zone.

Attitudes of faults, gouge, breccia zones, slickensides, and epidote- and quartz-encrusted fracture surfaces in the biotite gneiss and granodiorite of the southwestern part of the area (fig. 20) were measured in the field, and their poles were plotted and contoured on an equal-area projection of the lower hemisphere of a Schmidt net (fig. 42). The strong maxima which represent near-vertical shear systems at N. 25° E. and N. 40° W. and the weaker one at N. 60° W. illustrate the general

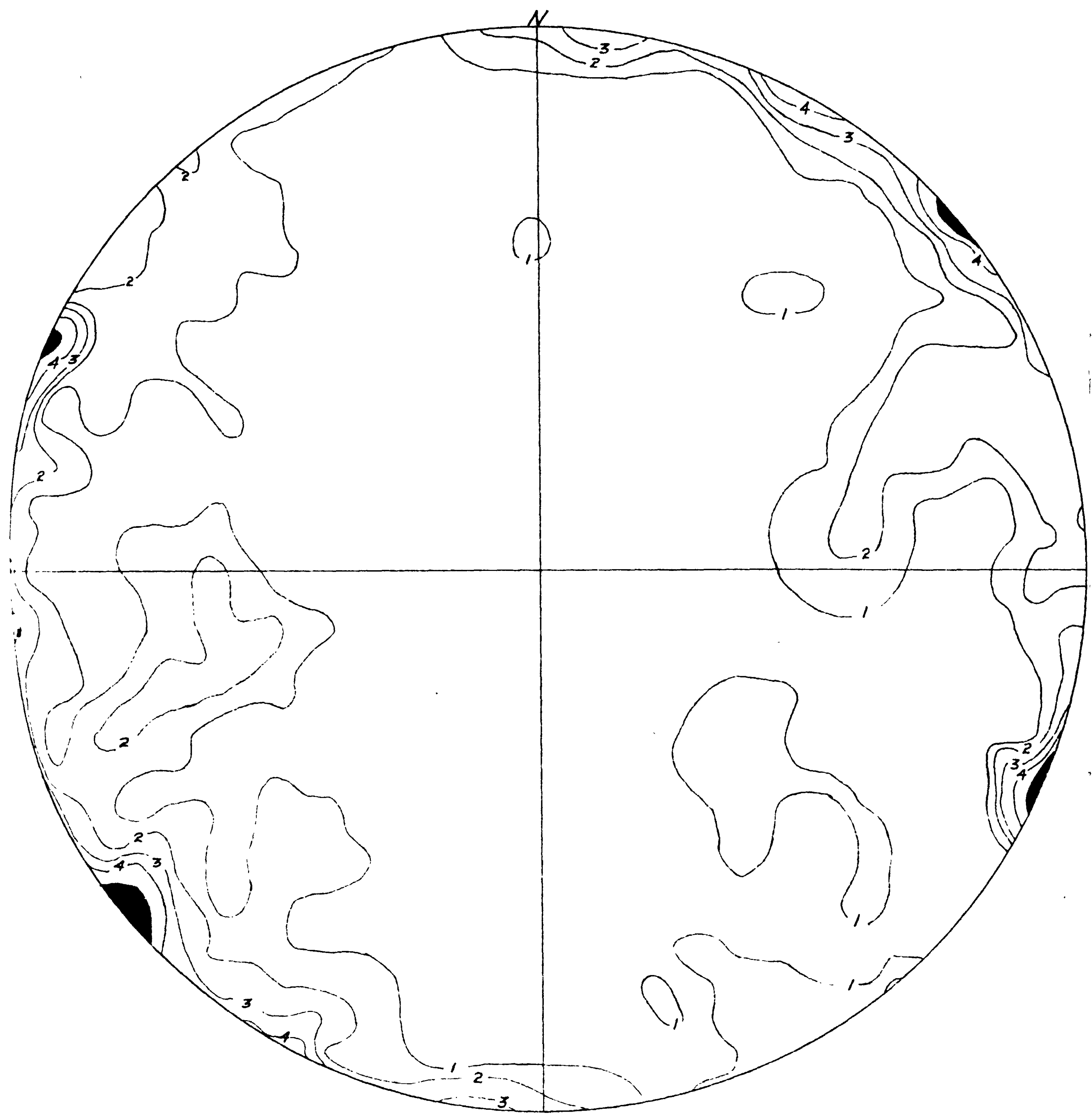

Figure 42.--Shear surfaces within the biotite gneiss and the Boulder Creek Granodiorite of the southwestern part of the area. Contour diagram of lower hemisphere of Schmidt equal-area projection of 226 poles. Contours, in percent: 1, 2, 3, 4

Legend (black box): Area containing over 5 percent of pole projections northeast-northwest shear pattern seen in outcrop in the southwestern part of the area. The higher concentration of poles in the northeast and southwest quadrants is a reflection of the Gore fault zone. Most of the faults that have extensive development of breccia or gouge are represented by weak maxima of poles of north-northwest planes and show a considerable dip-value spread. Most of the epidote-encrusted shears are represented by pole concentration in the northwest and southeast quadrants.

The Gore fault has been a zone of weakness and recurring movement at various intervals from Precambrian time to the Laramide orogeny. The regional evidence for the antiquity of this fault zone has been summarized by Tweto and Sims (1963, p. 1005-1006). Within and adjacent to the map area, ample evidence supports the long history of movement along the fault. Some of the structures within the Precambrian rocks shown on the geologic map (fig. 2) and represented on the plots of lineation data within the biotite gneiss (figs. 21, 22) are interpreted as drag or drag-related structures and suggest that the Gore fault zone was a zone of movement at least as early as the later stages of the Precambrian deformation that produced the northeast fold system. These drag or drag-related structures are (1) a general swing in the strike of foliations and the trend of lineations to a more southerly course as the Gore fault is approached from the northeast (figs. 2, 21, 22); (2) an increase in the percentage of southwest-plunging lineations in going from the northeastern to the southwestern part of the biotite gneiss unit (figs. 2, 21, 22); and (3) an apparent increase in the abundance of A lineations of the northeast fold system in the southwestern part of the area, a factor which suggests a deflection or shortening of the axis of a proposed northeastward-trending antiform.

There is also evidence of post-Boulder Creek Precambrian movement along the fault. Within the Gore fault zone and the bordering shear zone to the east, granulated and mylonitized biotite gneiss along northwest- to north-trending shears is taken as evidence of Precambrian movement (Tweto and Sims, 1963, p. 998). Evidence which also tends to support post-Boulder Creek Precambrian movement is an outcrop (fig. 35) within the Gore fault zone which shows a northeastward-dipping mylonitic shear zone within Precambrian rocks beveled by red beds of the Late Paleozoic and Mesozoic State Bridge Formation (fig. 32).

No record of movement during the Paleozoic was seen in the area, but abrupt thinning and wedging out of thick Late Paleozoic Central Colorado trough formations as the Gore fault is approached indicate a fault-line scarp along the Late Paleozoic Front Range highland (Tweto and Sims, 1963, p. 1006). Similar stratigraphic evidence in Triassic rocks suggests that the scarp persisted into the Mesozoic.

Most of the observable displacement along the Gore fault occurred during Laramide and later(?) time. The Gore Range is a Laramide and post-Laramide feature of considerable relief and it is bounded along most of its west side by the Gore fault. The Laramide and post-Laramide(?) Park Range uplift produced more than 2,000 feet of structural relief across the Gore fault zone in the area of the west portal of Gore Canyon. Within the fault zone itself, beds of the State Bridge Formation are broken and displaced, east side up and several tens of feet, in more than one place.

FOLDS

The dominant fold structure of the region is the broad north- to north-northwest-trending anticlinal arch of post-Precambrian sedimentary rocks over the Precambrian core of the Park Range uplift. In the map area the axis of this uplift lies generally along the crest of the Gore Range. In addition to this regional structure, outlined by the opposing regional dips of the Late Paleozoic and Mesozoic sedimentary rocks on either side of the Gore Range, folds of much smaller amplitude occur in the sedimentary rocks on the east flanks of the Gore Range (fig. 2).

Most of the folds along the east flank of the Gore Range appear to be folds associated with faults, chiefly the northeast faults described in a previous section of this report. These fault-related folds are proximate and parallel to faults or fault projections and are most commonly monoclinal warps. The best exposed of these folds are the monocline in sec. 32, T. 1 N., R. 80 W., and the monocline in sec. 11, T. 1 N., R. 81 W. Each of these two folds appears to be on the upthrown or in the eastward displaced block of a fault projected from the west. The clearest illustration of a fault-related fold is the monoclinal flexure along the northwest side of the Sheep Creek fault in the northern part of the area.

Three small anticlinal folds and one small syncline were mapped south of the Colorado River. Another small inferred anticline is north of the river and is shown only on cross section A-A' (fig. 2). All these folds plunge generally north-northwest, north-northeast, or southeast and have crest lines or trough lines subparallel to the axis of the Park Range uplift. These folds are shallow warps and buckles formed during Laramide and late Tertiary(?) tilting of the sedimentary section on the east flank of the Park Range uplift. At least two of these folds, those shown on cross sections A-A' and B-B' on figure 2, may have been initiated by movements along northward-trending faults and their amplitudes increased by bedding-plane slip down the flanks of the uplift.

JOINTS

Joint attitudes were measured in the biotite gneiss and the Boulder Creek Granodiorite in all areas of their outcrop and in the Dakota Sandstone along the hogback which extends from the south edge of sec. 15, T. 1 N., R. 81 W., on the north side of the Colorado River to the north edge of secs. 2 and 3, T. 1 S., R. 81 W., on the south side of the river. The poles of joints of the biotite gneiss units in the northeastern and southwestern portions of the outcrop area and of joints in the Boulder Creek Granodiorite were plotted on three separate projections of the upper hemisphere of a Schmidt equal-area net and the plots were contoured; the poles of all the Dakota joints were plotted and contoured on a fourth projection. The joint plots are shown in figures 43-46; the data-collection area for each plot of joints in Precambrian rocks is shown in figure 20.

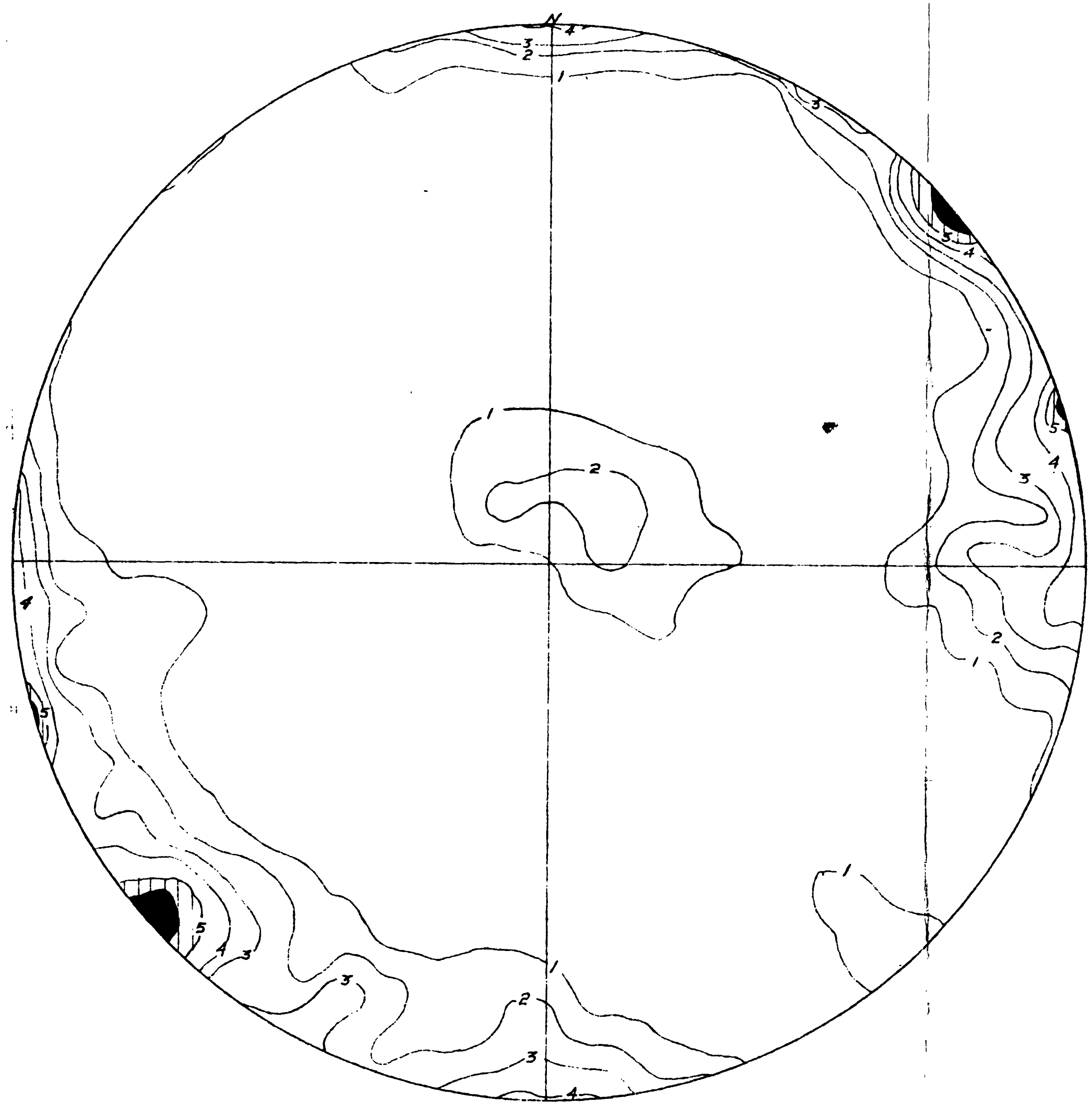

Figure 43.--Joints of the biotite gneiss unit in the northeastern part of its outcrop area
Contour diagram of upper hemisphere
Schmidt equal-area projection of 610 poles
Contours, in percent: 1, 2, 3, 4, 5

Area containing 5-6 percent of pole projections

Area containing over 6 percent of pole projections

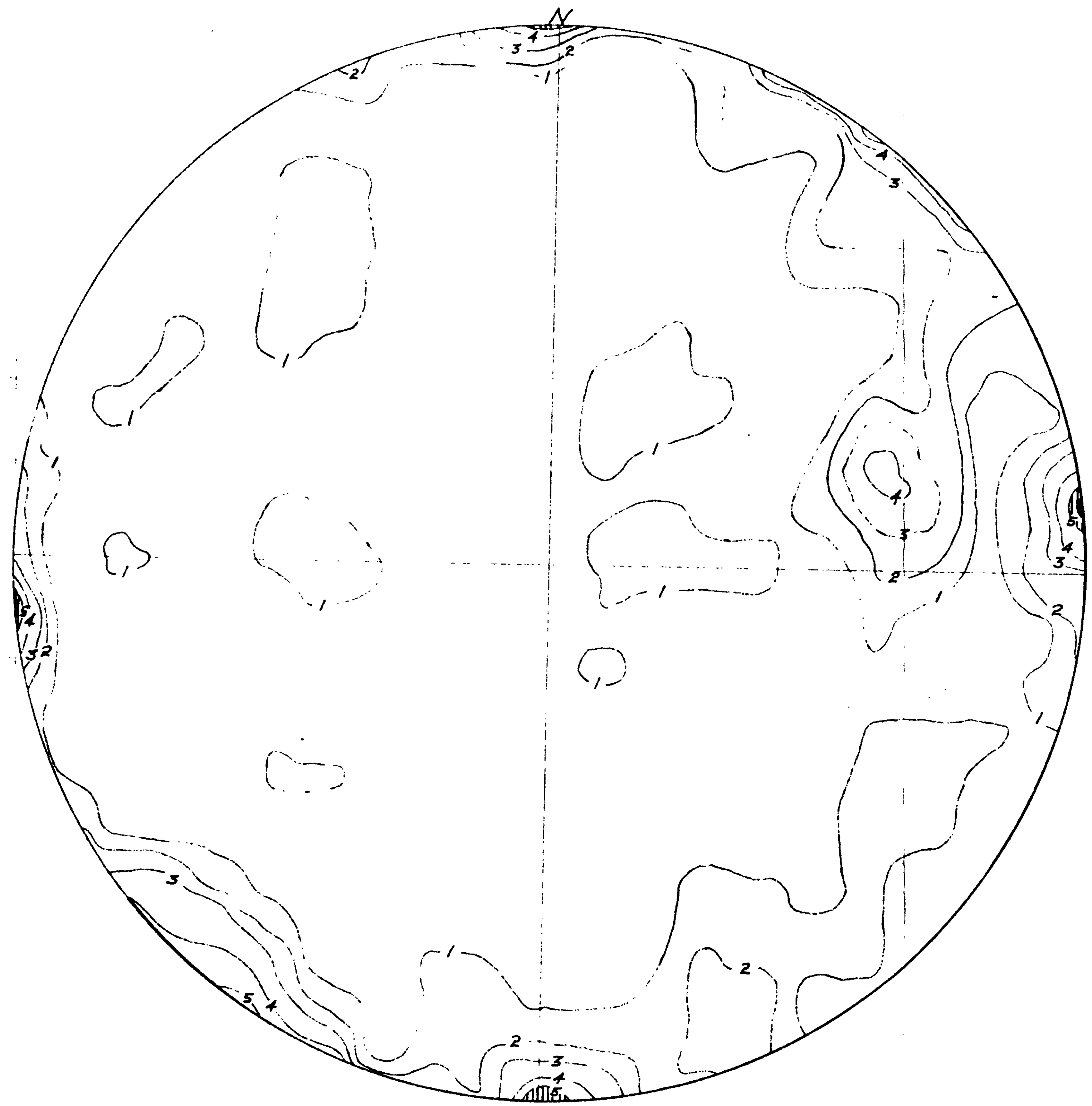

Figure 44.--Joints of the biotite gneiss unit in the southwestern part of its outcrop area. Contour diagram of upper hemisphere Schmidt equal-area projection of 250 poles. Contours, in percent: 1, 2, 3, 4, 5

Area containing 5-6 percent of pole projections

Area containing over 6 percent of pole projections

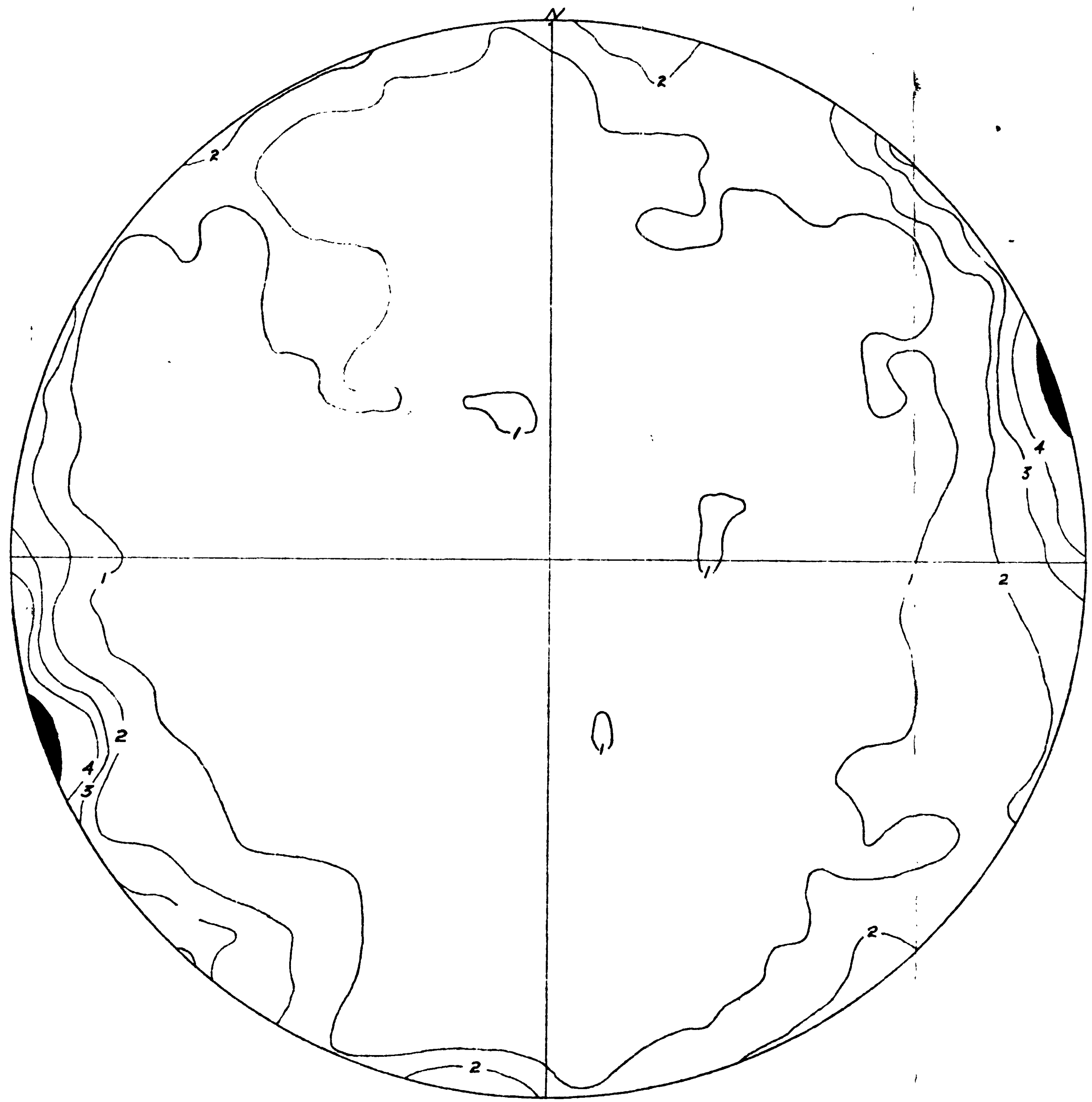

Figure 45.--Joints in the Boulder Creek Granodiorite. Contour diagram of upper hemisphere of Schmidt equal-area projection of 784 poles. Contours, in percent: 1, 2, 3, 4

Area containing over 5 percent of pole projections

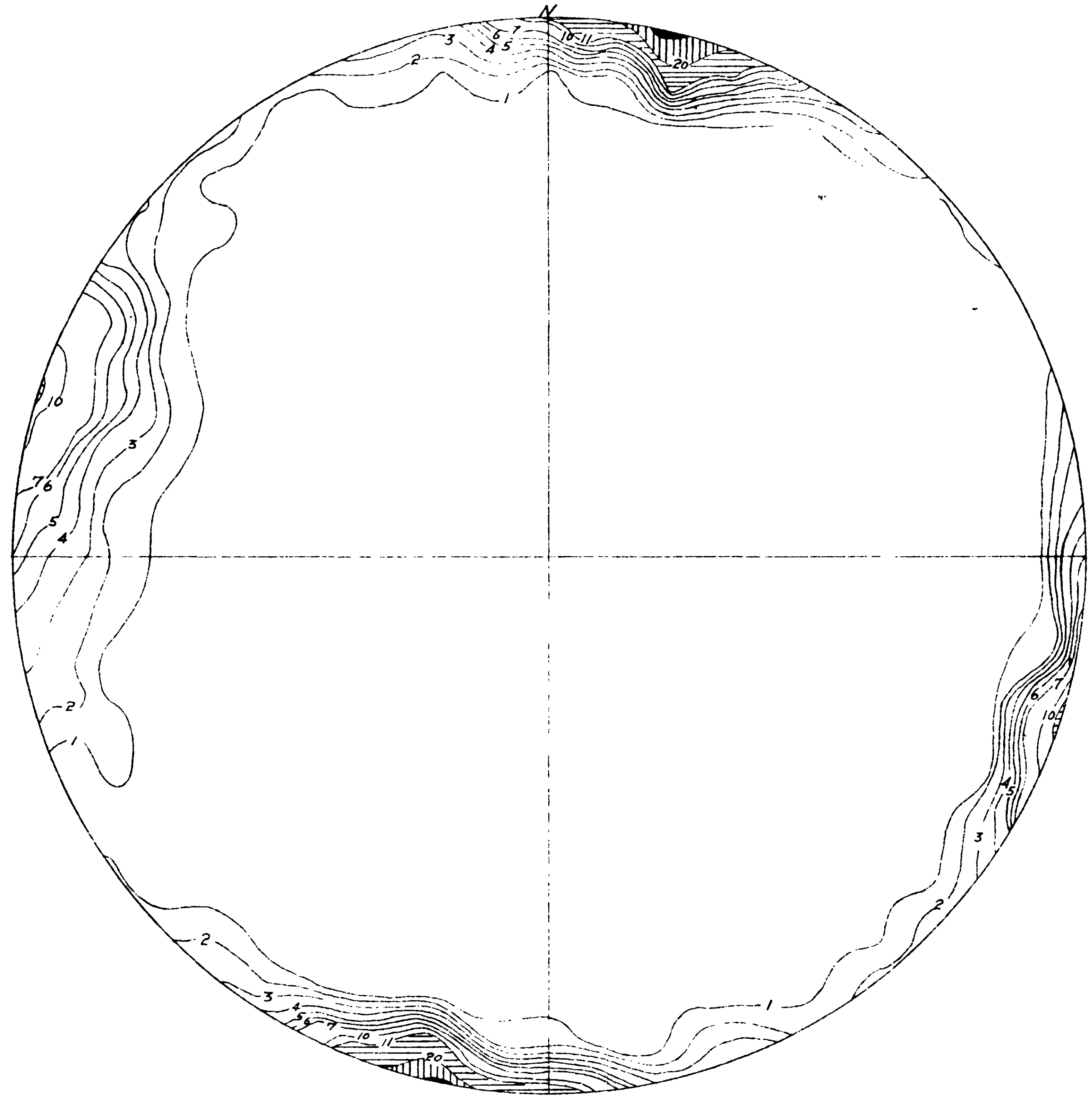

Figure 46.--Joints of the Dakota Sandstone.
Contour diagram of upper hemisphere of Schmidt equal-area projection of 635 poles.
Contours, in percent: 1, 2, 3, 4, 5, 6, 7, 10, 11, 20

Area containing 11-20 percent of pole projections

Area containing 20-30 percent of pole projections

Area containing over 30 percent of pole projections

Joints of Precambrian Rocks

Interpretation of the Precambrian joint data is difficult owing to the complex history of tectonism in the rocks, but a few generalizations are given below.

The plot of joints measured in the northeastern outcrop area of the biotite gneiss (fig. 43) shows a strong maximum representing a near-vertical N. 17° W. joint set, a weak maximum representing a steep nearly east-west joint set, and a strong maximum representing a near-vertical N. 42° W. set.

In the southwestern biotite gneiss unit (fig. 34) all the joint sets present in the northeastern part of the biotite gneiss unit are represented; there are a strong maximum representing a near-vertical set that strikes N. 7° W. and two weaker maxima representing near-vertical sets which strike N. 88° E. and N. 55° W. In addition, there is a weak maximum representing a N. 14° W. - 50°-55° E. joint set.

The contour diagram for joints in the Boulder Creek Granodiorite (fig. 45) shows a strong maximum in the position of a near-vertical N. 19° W. set and a weaker maximum in the position of a N. 50° W. set.

Most of the joint sets in Precambrian rocks are near-vertical and strike northwest to north-northwest. Joints included in these sets are cross joints perpendicular to the regional foliation and B lineations of a northeast Precambrian fold system and joints related to the uplift of the Park Range and the concomitant fracturing and faulting subparallel to the Gore fault.

Joints in the Dakota Formation

A plot of poles of joints measured in the Dakota Sandstone show maxima at N. 18° E. and N. 78° W. and dips within 5° of the vertical (fig. 46). The set at N. 18° E. is at a small angle to the axis of the Park Range uplift and is a longitudinal joint set that probably formed during uplift of the Gore Range. Dips of the joints indicate that there was rotation of previously formed joint planes as uplift continued. The N. 78° W. joint set are probably cross joints formed at approximately right angles to the axis of the uplift. Field observations along the Dakota hogback near Gore Canyon revealed that some surfaces with attitudes near the orientation of the N. 78° W. joint set served as planes of movement for Laramide and later(?) fault movements.

GEOLOGIC HISTORY

The geologic history of the area begins in Precambrian time with the deposition of a thick sedimentary sequence consisting chiefly of slightly pelitic clastic rocks--probably sandstone, siltstone, and shale--and minor amounts of interbedded impure carbonate rocks. A few basalt sills and flows may have been intercalated with the sedimentary pile. This sequence of rocks was regionally metamorphosed into a series of high-rank biotite gneisses and associated amphibolitic rocks which are similar to gneisses found in the Front Range and other parts of Middle Park and were referred to in the past as the Idaho Springs Formation. The gneisses were deformed under catazonal conditions into northwest- to north-northwest-trending folds. Continued tectonism--or a later separate period of tectonism--produced northeast- to east-northeast-trending folds. During the later stages of the formation of northeasterly folds, the biotite gneisses were synkinematically invaded by granodioritic to quartz monzonitic rocks similar to the Boulder Creek Granodiorite of the Front Range. Retrograde metamorphic effects were superposed on the gneiss, and deuteric alteration occurred in the granodiorite-quartz monzonite. Some cataclasis and later shearing and associated rock alteration occurred in zones parallel to the regional northeasterly foliation. Drag structures preserved in the Precambrian rocks northeast of the Gore fault suggest that there may have been some movement along the Gore fault before the end of the Precambrian deformation that produced the northeast fold system.

The metamorphism, folding, and plutonism is correlated with the Boulder Creek orogeny of Hutchinson and Hedge (1967). They have dated the orogeny in the Front Range as beginning about 1.74 billion years ago and ending at about 1.69 billion years.

Additional deformation appears to have occurred in Precambrian time subsequent to the emplacement of the Boulder Creek Granodiorite. This later deformation consisted of northwest to north-northwest faulting--principally within and immediately east of the Gore fault zone--, dilation and intrusion of granophyre or quartz along northwest to north-northwest fractures on the east and upthrown side of the Gore fault zone, and northeast- to east-northeast shearing. The radiogenic age of the granophyre associated with this post-Boulder Creek deformation is 1.13$\pm$ 0.15 billion years, and the emplacement of the granophyre may be related to the Pikes Peak Plutonic Event according to C. E. Hedge (written commun., 1967).

During most of the Paleozoic the area east and northeast of the Gore fault zone from Vail Pass on the south to beyond the Colorado River was part of the Eront Range highland (Lovering and Johnson, 1933). The area to the southwest and west was the site of the northern part of the Late Paleozoic Central Colorado trough. On the east side of the Gore Range, red beds which may be of later Permian age in part are present on the Precambrian in the northern part of the area and thicken irregularly to the north. Thin deposits of similar red beds are locally present on the Precambrian in other areas of Middle Park. Evidently the Front Range highland had been worn down sufficiently by latest Permian time to permit at least local deposition of flood-plain deposits on an irregular Precambrian surface. On the west side of the Gore Range, the featheredge of a red-bed formation which is Late Permian and perhaps also Early Triassic laps onto the Precambrian gneiss and is overlain by Late Jurassic marginal marine rocks. To the west this formation thickens abruptly and is underlain by Pennsylvanian rocks and overlain by Upper Triassic rocks. Abrupt thinning and wedging out of Paleozoic formations as the Gore fault zone is approached from the west indicates that the west side of the Paleozoic highland was steep. Tweto and Sims (1963, p. 1006) suggested that a scarp parallel to the Gore fault zone was present along at least part of the west side of the Front Range highland.

By the beginning of Mesozoic time marine deposition in the Central Colorado trough had ceased. The Front Range highland was considerably worn down but still probably a much dissected positive area so that Early Triassic flood-plain deposits and Late Triassic flood-plain and stream-channel deposits are more irregularly distributed and generally much thinner where they occur below Jurassic rocks on the old highland than they are to the west.

The Early and Middle Jurassic time is not represented in the depositional history of the area, but the Late Jurassic time brought the incursion of the Sundance sea from the north and west. During Sundance time, thick marginal marine and marine sandstones and siltstones were deposited on the west side of the old highland while similar but thinner and more irregularly distributed deposits formed on the old highland itself. The deposits related to the Sundance sea are everywhere blanketed by Late Jurassic continental deposits of the Morrison Formation. In many areas east of the old scarp line of the Front Range highland, the Morrison lies directly on the Precambrian, which suggests that positive areas were still in existence on the highland at the beginning of Morrison time. The variegated claystones to siltstones, thin fresh-water limestones, and lenticular sandstones of this formation suggest a swampy flood plain or lake-dotted savannah cut by meandering channels. Pyroclastic material has been reported (Wahlstrom, 1966) in beds of the upper part of the Morrison and is evidence of volcanism during Morrison time.

Continental deposition--but with a much greater abundance of high-energy deposits--continued into the Early Cretaceous with deposition of the conglomerate, sandstone, and subordinate siltstone of the lower part of the Dakota Sandstone. A shift to marginal marine conditions began with the deposition of the evenly bedded siltstone and sandstone of the upper part of the Dakota Sandstone, and the Cretaceous sea was introduced into the area. Marine siltstone and shale of the lower part of the Benton Shale of Early and Middle Cretaceous age were conformably deposited on the Dakota Sandstone, although there is local evidence for some "winnowing" on top of the Dakota preceding deposition of the Benton. Beginning with the Benton Shale, the record of marine deposition in the region is uninterrupted until latest Cretaceous time and is represented by approximately 6,000 feet of shale which contains subordinate beds of siltstone, sandstone, and limestone, and near the top thick sandstone sequences. Some shoaling of the Cretaceous sea occurred in Middle Cretaceous time as evidenced by the presence of sandstone and recrystallized arenaceous clastic limestone near the top of the Benton Shale and in Late Cretaceous time as evidenced by thick sandstones in the upper part of the Pierre Shale.

Regionally, Laramide deformation began by the end of Pierre deposition (Lovering and Goddard, 1950, p. 58) or in post-Pierre latest Cretaceous time (G. A. Izett, oral commun., 1967) and lasted into the Eocene. The Laramide in this region was marked by uplift of the Park and Front Ranges, formation of the synclinal depression known as Middle-North Park basin, intrusion of small hypabyssal plugs, and filling of the basin with several thousand feet of coarse clastics of the Middle Park Formation and, in North Park, of the Coalmont Formation. In the area of this report none of the deposits of this tectonically active time are present, and the record of the Laramide orogeny is displayed only in the faulting, tilting, and folding of the flanks of the Gore Range.

Regional uplift along the Park and Front Ranges and faulting occurred again in the Late Tertiary and was accompanied in some areas by volcanism and deposition of epiclastic volcanic rocks. During this time the topographic North and Middle Park basins were formed by volcanic construction of the Rabbit Ears Range. No rock record of these events is preserved in the report area but it is abundant to the east (Izett, 1968). In response to continued uplift near-surface deformation of Mesozoic rocks--chiefly the Dakota Sandstone--may have been initiated along the east flank of the Gore Range at this time and probably included bedding-plane slip and shallow folding.

Uplift of the Park and Front Ranges probably continued into the Pleistocene (Lovering and Goddard, 1950, p. 63), and near-surface and surface (landslide) deformation of sediments along the east flanks of the Gore Range was probably widespread. No evidence of glaciation is in the area but evidence of alpine and valley glaciation is locally abundant to the north and south along other segments of the Park Range. Several terrace levels in the valleys of Muddy Creek and the Colorado and Blue Rivers and a pediment surface in the Muddy Creek drainage can be correlated with Pleistocene glacial deposits to the south.

Post-Pleistocene time is represented by low terraces and flood-plain alluvium along the major drainages and by extensive landslide deposits, some of which were probably formed during the Pleistocene.

ECONOMIC GEOLOGY

Geologic investigations in the southwestern part of the Kremmling quadrangle were done as part of a larger mapping program to furnish a basis for classification of land withdrawn for coal. No coal beds were seen in the map area nor is the Middle Park Formation--the coal-bearing formation of the eastern part of the quadrangle--exposed in the area. The only coaly material seen was in thin discontinuous seams of carbon trash in a clay lens near the base of the Dakota Sandstone.

Gold

Several abandoned prospect pits, a shallow prospect shaft, and a short caved prospect adit are located along some of the northwest to north-northwest fracture zones within the Precambrian rocks of the area. Commonly, the prospected fracture zones contain indirect evidence of possible metal mineralization. This evidence consists of clay alteration, silicification, and iron-staining of the crystalline rocks. Direct evidence of mineralization was seen only in the fracture zone occupied discontinuously by quartz veins in secs. 17, 20, and 29, T. 1 N., R. 81 W.

The fracture zone or quartz vein along the crest of the Gore Range has been extensively prospected by shallow pits and, in the SE¼ sec. 20, T. 1 N., R. 81 W., by a shallow (approximately 15 ft deep) shaft where the zone contains thick quartz veins. Part of the fracture zone in the SE¼ sec. 20 and the NE¼ sec. 29, on either side and including the area of the shaft, was covered by two unpatented lode claims, the Blue Monday(?) claims, in May 1961. No evidence of assessment work on the claims in the area was seen by the author since June 1963, and the claims have probably lapsed. Two samples were taken from the quartz veins exposed in the shallow shaft in the SE¼ sec. 20. Each sample was crushed in a jaw crusher, ground on ceramic plates to 80-100 mesh, and panned. The 6- to 7-pound sample yielded no gold; the 2- to 3-pound sample yielded a flake of gold less than 0.1 mm across.

In June 1965 a placer operation on a gravel fan at the mouth of Canyon Creek on the Colorado River in the SW¼SE¼ sec. 32 was being done by a prospector. Local reports indicate that only a small amount of gold was recovered.

The northwest to north-northwest quartz veins and associated (rare) gold mineralization of the southwestern part of the area seemingly are related to the Gore fault zone and, specifically, to dilation and filling of subparallel fractures within and just to the east of this zone. Fracture filling not only included quartz but also granophyre. The granophyre and probably the quartz veins that contain gold are approximately Pikes Peak in age. The Pikes Peak batholith of the Colorado Front Range and its satellite plutons were emplaced 1.04-1.01 billion years ago according to Hutchinson and Hedge (1967).

The placer gold on the Colorado River at the mouth of Canyon Creek is probably derived from northwest to north-northwest mineralized fractures and quartz veins up the Canyon Creek drainage and the northwest to north-northwest mineralized fractures and quartz veins up the Canyon Creek drainage and the northwest to north-northwest shear zone which is exposed to the east along the railroad cut from Canyon Creek almost to the first tunnel.

Uranium

In the NE¼ sec. 26, T. 1 N., R. 81 W., an adit approximately 30 feet long has been driven into the sandstones and conglomerates at the contact of Morrison Formation and Dakota Sandstone, and a small stope was developed in a clay bed in the conglomerate at the back. Henry Yust of Kremmling, Colo., worked the prospect and reported that he mined rock that contained uranium oxide. The host for the mineralization is a zone of thin (2-4 in.) discontinuous seams of coal in a lenticular clay bed (3 ft thick in the adit area) in the basal chert-pebble conglomerate of the Dakota Sandstone.

R. U. King and R. R. Guilinger of the U.S. Geological Survey looked at this prospect for the Atomic Energy Commission during May 1954. They reported (unpub. report, 1954) that "uranium is chiefly confined to veinlets of black hydrocarbon and secondary mineralization as fracture coatings in the gray mudstone," and "The hydrocarbon veinlets contain 0.5-1 percent uranium and make up possibly 5 percent of the mudstone lens. The mudstone itself contains 0.05 percent uranium."

This prospect was not worked during the field investigation for this report.

Pegmatites

Concordant and crosscutting pegmatite bodies of Precambrian age are widespread in the Precambrian biotite gneiss unit. Commonly, these bodies are 3-5 feet thick, but one which crops out just south of the San Toy Mountain fault and west of the beacon access road is estimated to be about 30 feet thick. Pegmatites were not mapped or sampled by the author, but the pegmatites should be considered as possible sources of feldspar and perhaps rare earths and metals.

Sand and Gravel Deposits

Quaternary terrace deposits associated with the major drainages of the area are local sources of sand and gravel. Most deposits are between 5 and 15 feet thick, but one deposit whose thickest and most extensive remnants lie across secs. 29, 30, and 19, T. 1 N., R. 80 W., and sec. 24, T. 1 N., R. 81 W., and under the Kremmling townsite is locally more than 50 feet thick. This level is currently being quarried at the south edge of Kremmling.

Oil and Gas Deposits

Although no deposits of oil and gas have been found in the area, most of that part of the area east of the Benton and Niobrara contact is underlain by a sedimentary section of more than 1,000 feet of predominantly marine Mesozoic rocks and should be considered potentially interesting for oil and gas prospecting. The nearest exploration by drilling was a 1,205-foot dry hole into the Precambrian basement in the SE¼ sec. 26, T. 2 N., R. 81 W., on the Martin Ranch.

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Table 1.--Mineral modes (volume percent) of representative samples of the biotite gneiss unit. Tr = trace.

A. Biotite gneiss and related rocks

Mineral	Sample: V-374d-63	V-20c-63	V-34a-63	V-22a-63	V-410-63	V-21d-63	V-21g-63	V-21a-63	V-45a-63	V-414-63	V-415-63	V-21b-63	V-20a-63a	V-20a-63b
Quartz----------	1	21	37	42	29	4	30	46	55	26	40	19	23	26
Plagioclase-----	18	Tr	28	35	52	42	11	20	17	1	43	<1	9	12
Microcline------	Tr	--	--	--	--	<1	--	--	<1	--	--	--	--	--
Intergrowths[1/] --	--	--	--	--	<1	--	--	--	--	--	--	--	--	--
Biotite---------	73	25	27	14	9	48	27	22	11	56	13	9	3	18
Garnet----------	--	--	--	--	--	2	11	<1	<1	--	--	--	--	--
Sillimanite-----	--	--	--	--	--	--	4	<1	2	4	--	--	--	--
Hornblende------	--	--	--	--	--	--	--	--	--	--	--	42	39	--
Muscovite-------	1	2/12	2	--	2	<1	6	5	3	--	<1	<1	Tr	--
Sericite[3/] ------	Tr	--	4	5	6	1	9	5	10	12	3	18	13	41
Epidote[4/] -------	6	16	<1	1	Tr	<1	--	--	--	--	--	4	10	1
Chlorite--------	--	22	--	Tr	Tr	<1	<1	Tr	--	--	--	3	<1	<1
Calcite---------	--	2	--	--	--	Tr	--	--	--	--	--	--	<1	Tr
Prehnite?-------	--	--	--	--	--	--	--	--	--	--	--	3	--	--
Iron ore--------	<1	1	<1	1	<1	1	1	<1	Tr	<1	<1	<1	1	Tr
Sphene----------	--	--	--	--	--	--	--	--	--	--	--	Tr	<1	--
Apatite---------	Tr	<1	<1	<1	Tr	<1	Tr	Tr	<1	--	--	Tr	Tr	<1
Zircon----------	Tr	<1	<1	<1	Tr	<1	<1	<1	<1	<1	--	Tr	Tr	--

V-374d-63: Schistose layer adjacent to coarse quartz feldspar of compositionally banded biotite-quartz-plagioclase gneiss.
V-20c-63: Biotite schist, northwest part of sec. 5, T. 1 S., R. 81 W.
V-34a-63: Biotite gneiss, NE. cor. sec. 4, T. 1 S., R. 81 W.
V-22a-63: Biotite gneiss, NW¼ sec. 34, T. 1 N., R. 81 W.
V-410-63: Biotite plagioclase-rich gneiss, C N½ sec. 32, T. 1 N., R. 81 W.
V-21d-63: Garnetiferous biotite gneiss, near SE cor. sec. 32, T. 1 N., R. 81 W.
V-21g-63: Sillimanitic garnet biotite gneiss, near SE cor. sec. 32, T. 1 N., R. 81 W.
V-21a-63: Garnetiferous and sillimanitic biotite gneiss, near SE cor. sec. 32, T. 1 N., R. 81 W.
V-45a-63: Garnetiferous sillimanitic biotite gneiss, near SE cor. sec. 32, T. 1 N., R. 81 W.
V-414-63: Sillimanitic biotite schist, just north of C N½ sec. 32, T. 1 N., R. 81 W.
V-415-63: Biotite gneiss associated with sillimanite schist of V-414-63.
V-21b-63: Biotitic hornblende gneiss, near SE cor. sec. 32, T. 1 N., R. 81 W.
V-20a-63a: Biotitic hornblende gneiss, northwest part of sec. 5, T. 1 S., R. 81 W.
V-20a-63b: Coarse-grained biotite plagioclase gneiss layer in hornblende gneiss of V-20a-63a.

A.--continued

Mineral	Sample: V-24e-63a	V-24e-63b	V-24d-63	V-24c-63	V-24a-63	V-24b-63	V-24f-63	V-21c-63	V-20b-63	V-423-63	V-29c-63
Quartz----------	38	18	36	34	40	47	36	40	9	29	30
Plagioclase-----	48	31	43	56	46	21	15	34	52	18	31
Microcline------	Tr?	--	--	Tr?	Tr	7	22	--	Tr	28	12
Intergrowths[1/] --	--	--	Tr	1	2	5	17	--	--	--	2
Biotite---------	6	44	11	5	1	3	<1	18	9	19	<1
Muscovite-------	--	--	<1	Tr	3	10	2/5	1	2	<1	6
Sericite[3/] ------	5/5	3	3	1	4	2	--	5	6/26	5	11
Epidote[4/] -------	2	3	3	1	3	3	4	--	--	--	2
Chlorite--------	--	--	--	--	--	--	--	1	<1	--	5
Calcite---------	--	--	--	--	--	--	--	<1	<1	--	--
Iron ore--------	7/<1	<1	7/2	7/<1	<1	7/<1	Tr	<1	<1	<1	<1
Sphene----------	Tr	<1	<1	Tr	--	<1	--	--	--	<1	--
Apatite---------	Tr	<1	<1	<1	<1	<1	--	Tr	8/<1	Tr	<1
Zircon----------	<1	Tr	<1	--	Tr	--	<1	<1	<1	<1	Tr

V-24e-63a: Quartz-feldspar-rich band in biotite gneiss, NW¼ sec. 3, T. 1 S., R. 81 W.
V-24e-63b: Biotite-rich band in biotite gneiss, NW¼ sec. 3, T. 1 S., R. 81 W.
V-24d-63: Biotite gneiss, NW¼ sec. 3, T. 1 S., R. 81 W.
V-24c-63: Biotite-plagioclase-rich gneiss, NW¼ sec. 3, T. 1 S., R. 81 W.
V-24a-63: Quartz-plagioclase-rich gneiss, NW¼ sec. 3, T. 1 S., R. 81 W.
V-24b-63: Quartz-feldspar-rich gneiss, NW¼ sec. 3, T. 1 S., R. 81 W.
V-24f-63: Biotite microcline gneiss, NW¼ sec. 3, T. 1 S., R. 81 W.
V-21c-63: Porphyroblastic biotite gneiss, near SE cor. sec. 32, T. 1 N., R. 81 W.
V-20b-63: Porphyroblastic biotite gneiss, northwest part of sec. 5, T. 1 S., R. 81 W.
V-423-63: Porphyroblastic migmatite gneiss, near C S½ sec. 29, T. 1 N., R. 81 W.
V-29c-63: Migmatite gneiss, near C N½ sec. 21, T. 1 N., R. 81 W.

B. Amphibolites

Mineral	Sample: V-398-63	V-34b-63	V-22b-63	V-22d-63	V-22f-63	V-22g-63
Quartz----------	4	2	5	6	3	4
Plagioclase-----	43	41	14	28	10	18
Hornblende------	28	48	67	48	56	58
Cummingtonite---	11	--	--	--	--	--
Biotite---------	10	3	4	13	--	Tr
Muscovite-------	--	Tr	--	--	--	--
Sericite[3/] ------	3	5	2	2	15	9
Epidote[4/] -------	Tr	<1	--	Tr	--	<1
Chlorite--------	Tr	<1	<1	1	11	7
Calcite---------	--	--	--	--	<1	Tr
Prehnite?-------	Tr	<1	--	--	--	--
Iron ore--------	<1	<1	6	Tr	3	3
Sphene----------	--	Tr?	Tr	<1	<1	Tr
Apatite---------	Tr	Tr	1	<1	<1	<1
Zircon----------	--	<1	Tr	Tr	--	Tr

V-398-63: Cumuloblastic amphibolite, near C sec. 32, T. 1 N., R. 81 W.
V-34b-63: Cumuloblastic amphibolite, NE cor. sec. 4, T. 1 S., R. 81 W.
V-22b-63: Quartz-rich biotitic amphibolite, southern part of SE¼ sec. 32, T. 1 N., R. 81 W.
V-22d-63: Quartz-rich biotitic amphibolite, southern part of SE¼ sec. 32, T. 1 N., R. 81 W.
V-22f-63: Amphibolite, NW¼ sec. 34, T. 1 N., R. 81 W.
V-22g-63: Amphibolite, southern part of SE¼ sec. 32, T. 1 N., R. 81 W.

C. Amphibolitic dikes and aplite

Mineral	Sample: V-399-63	V-306-63	V-21e-63	V-21f-63
Quartz----------	1	2	50	49
Plagioclase-----	2	34	11	6
Microcline------	--	--	1	12
Biotite---------	1	11	--	9/<1
Garnet----------	--	--	--	8
Hornblende------	48	51	--	--
Muscovite-------	8	--	30	18
Sericite[3/] ------	Tr	Tr	8	7
Epidote[4/] -------	36	1	--	--
Chlorite--------	Tr	Tr	--	(9)
Prehnite?-------	Tr	--	--	--
Calcite---------	--	--	--	--
Iron ore--------	3	<1	Tr	Tr
Sphene----------	<1	<1	--	--
Leucoxene?------	<1	--	--	--
Apatite---------	Tr?	<1	Tr	--
Zircon----------	--	Tr	Tr	Tr
Axinite?--------	--	--	Tr	--

V-399-63: Amphibolitic dike rock, S½N½ sec. 32, T. 1 N., R. 81 W.
V-306-63: Amphibolitic dike rock, NW¼ sec. 16, T. 1 N., R. 81 W.
V-21e-63: Sample from aplite dike of Fig. 17; SW cor. sec. 33, T. 1 N., R. 81 W.
V-21f-63: Contaminated edge of aplite dike of V-21e-63, sec. 32, T. 1 N., R. 81 W.

1/ Constituents too finely or complexly intergrown to identify and count separately; principally myrmekite but also some perthite, antiperthite, and graphic intergrowths of quartz in microcline.
2/ Includes some sericite.
3/ Includes some clay alteration in some samples, particularly in those containing K-feldspar.
4/ Includes some zoisite-clinozoisite and rare allanite.
5/ Includes rare hydromuscovite?
6/ Includes some very finely divided calcite.
7/ Includes euhedral skeletal crystals of pyrite.
8/ Occurs as scattered grains and with calcite in veinlets cutting plagioclase.
9/ Biotite and chlorite counted together.

Table 2.--Some paired and grouped linear elements in biotite gneiss. The members of each numbered pair or group of lineations were observed in close association on a single outcrop.

Location in T. 1 N., R. 81 W. 6th P.M.	Description of linear element	Orientation	Special field relations between members of some lineation pairs	Description of linear element	Orientation
(1) N½ sec. 32----------	Sillimanite prisms, B_2 lineations	40° S. 45° W. 45° S. 30° W. 40° S. 20° W.	-----------------------	Quartz-feldspar boudins, A_2 lineations	40° N. 25° W. 37° N. 18° W. 24° N. 5° W.
N½ sec. 32----------	Biotite streaks, B_2 lineations	40° S. 16° W. 38° S. 40° W.	-----------------------	----do-----------------	65° N. 7° W. 60° N. 35° W.
(2) SW¼ sec. 33---------	Axis of small fold, B_2 lineations	35° N. 43° E.	Warps-----------------	Axis of small open fold-	60° S. 25° W.
(3) South of river, S½S½ sec. 28	Axis of small fold	40° N. 80° W.	----do----------------	Biotite streak, B_1 lineation	50° N. 50° W.
(4) North of river, N½S½ sec. 28	----do---------------	30° S. 85° E.	-----------------------	Crenulations, B_1 lineation	45° S. 40° E.
(5) Inspiration Point, SE¼ sec. 32	Welt----------------- Crenulation---------- Biotite, streak------ Welt----------------- Axis of small fold--- Each of the above is a B_2 lineation	68° N. 55° E. 47° S. 40° W. 30° S. 45° W. 61° S. 45° W. 45° S. 35° W.	-----------------------	Crenulation------------	43° S. 17° W.
(6) North side river, NW¼SW¼ sec. 23	Biotite streak------	45° N. 5° E.	-----------------------	Crenulation, B_1 lineation	70° N. 30° W.
(7) North side river, NW¼NE¼ sec. 27	Axis of small- to medium-scale fold, B_2 lineation	30° N. 50° E.	Warps-----------------	Biotite streak, A_2 lineation	45° S. 15° E.
(8) N½ sec. 21---------	Axis of small open fold, B_2 lineation	15° S. 60° W.	-----------------------	Crenulation------------	20° N. 85° W.
	Crenulation----------	41° S. 81° W.	-----------------------	Axis of small open fold-	27° N. 85° W.
(9) SE¼NE¼ sec. 28------	Crenulation----------	22° S. 85° W.	Warps-----------------	Muscovite streak, B_1 lineation	62° N. 35° W.
(10) S½S½ sec. 33--------	Axis of small fold, B_2 lineation	35° S. 30° W.	-----------------------	Axis of small fold, B_1 lineation	42° S. 50° E. (average)
(11) South of river, NW¼NE¼ sec. 33	Axis of small fold, B_2 lineation	60° S. 50° W.	Warps-----------------	Crenulation------------	65° N. 25° E. (average)
(12) South of river, NW¼NE¼ sec. 33	Axis of small fold, B_2 lineation	20° S. 55° W.	-----------------------	Axis of small fold, A_2 lineation	40° N. 25° E.
South of river, NW¼NE¼ sec. 33	Crenulation and biotite streak, B_2 lineation	48° S. 50° W.	-----------------------	Axis of small fold, A_2 lineation	40° N. 25° E.
(13) South of river, NW¼NE¼ sec. 33	Small fold-----------	10° S. 31° W.	Warps-----------------	Axis of small fold------	10° N. 70° E.
(14) South of river, NE¼NE¼ sec. 33	Axis of medium fold, B_2 lineation	12° S. 60° W.	Warps-----------------	Axis of small fold------	45° W. 50° N. 85° W. 11° S. 25° W.

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Table 3.--Mineral modes (volume percent) of representative samples of the Boulder Creek Granodiorite. Tr = trace.

A. Rocks typical of the Boulder Creek and of amphibolitic phases-found well within the borders of the Boulder Creek Granodiorite

Mineral	V-195-63	V-194-63	V-42-63	V-330-63	V-46-63	V-381-63	V-382-63	V-328-63	V-32a-63
	Sample								
Quartz	17	25	27	29	34	14	3	53	1/ 1
Plagioclase	51	29	32	45	35	42	44	25	1/ Tr
Microcline	--	24	22	11	7	1	<1	18	--
Intergrowths 2/	--	<1	<1	Tr	2	<1	--	1	Tr
Biotite	9	9	14	10	13	22	2	1	--
Hornblende	7	--	--	--	--	3	25	--	82
Muscovite	3/ <1	4/ <1	<1	--	--	--	--	1	--
Sericite 5/	13	9	3	3	7	8	14	Tr	1/ 14
Epidote 6/	1	<1	<1	<1	<1	7/ 7	2	Tr	2
Chlorite	<1	<1	Tr	--	--	<1	2	--	Tr
Calcite	Tr	--	--	--	--	--	--	--	1/ Tr
Prehnite?	<1	<1	Tr	<1	Tr	--	<1	Tr	Tr
Iron ore	<1	1	<1	1	<1	<1	3	<1	<1
Sphene	<1	<1	--	<1	1	1	3	--	Tr
Apatite	<1	<1	Tr	<1	<1	1	1	Tr	--
Zircon	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	--

V-195-63: Hornblende biotite granodiorite, showing some amphibolitic contamination, NW¼ sec. 4, T. 1 N., R. 81 W.
V-194-63: Porphyritic biotite quartz monzonite, NW¼ sec. 4, T. 1 N., R. 81 W. (Sample V-195-63 collected a few tens of feet to the east; sample V-192-63 collected a few hundred feet to the west.)
V-42-63: Biotitic quartz monzonite, near center N½ sec. 8, T. 1 N., R. 81 W.
V-330-63: Porphyritic biotite granodiorite, SW¼ sec. 17, T. 1 N., R. 81 W.
V-46-63: Biotite granodiorite, near north edge NE¼ sec. 17, T. 1 N., R. 81 W.
V-381-63: Biotite granodiorite, near SW. cor. sec. 16, T. 1 N., R. 81 W.
V-382-63: Hornblende granodiorite contaminated by amphibolitic xenolith, near SW. cor. sec. 16, T. 1 N., R. 81 W.
V-382-63: Coarse-grained leucocratic quartz monzonite, SW¼SW¼ sec. 16, T. 1 N., R. 81 W.
V-32a-63: Amphibolite from large xenolithic mass mapped near middle of S½ sec. 17, T. 1 N., R. 81 W.

B. Rocks typical of the Boulder Creek Granodiorite near and within the zone of biotite gneiss intercalated with Boulder Creek Granodiorite

Mineral	V-385-63	V-384-63	V-383-63	V-324-63	V-327-63	V-379-63	V-380-63	V-424-63	V-375-63	V-390-63	V-391-63	V-373-63
	Sample											
Quartz	23	21	31	25	35	35	42	24	27	32	13	18
Plagioclase	45	54	51	35	47	37	29	52	51	36	56	45
Microcline	<1	?	1	24	<1	<1	2	<1	Tr	Tr	Tr	<1
Intergrowths 2/	<1	--	<1	<1	Tr	--	--	--	--	<1	--	--
Biotite	21	13	10	3	13	15	16	18	9	16	16	13
Hornblende	--	2	--	--	--	--	--	--	<1	--	1	3
Muscovite	2	--	1	3	2	3/ 4	<1	1	--	<1	3/ <1	4
Sericite 5/	4	6	8/ 3	8	2	6	8	3	8	11	9	9
Epidote 6/	1	9/ 3	2	<1	<1	<1	<1	1	1	2	7/ 2	3
Chlorite	--	<1	<1	Tr	--	--	--	--	Tr	<1	1	<1
Calcite	--	--	--	--	--	--	--	--	--	Tr	--	--
Prehnite?	Tr	Tr	Tr	Tr	Tr	<1	<1	Tr	<1	<1	<1	2
Iron ore	2	1	<1	<1	<1	<1	2	<1	3	2	1	1
Sphene	<1	<1	<1	Tr	--	<1	<1	--	Tr	Tr	--	1
Apatite	<1	<1	<1	1	<1	<1	Tr?	<1	<1	<1	<1	<1
Zircon	Tr	<1	<1	Tr	<1	Tr	<1	Tr	Tr	Tr	<1	Tr

V-385-63: Xenolithic layer of biotite gneiss in granodiorite of zone of biotite gneiss intercalated with Boulder Creek Granodiorite, NW¼ sec. 21, T. 1 N., R. 81 W.
V-384-63: Amphibolitically contaminated granodiorite from zone of biotite gneiss intercalated with Boulder Creek Granodiorite, NW¼ sec. 21, T. 1 N., R. 81 W.
V-383-63: Fine-grained biotite granodiorite from zone of biotite gneiss intercalated with Boulder Creek Granodiorite, NW¼ sec. 21, T. 1 N., R. 81 W.
V-324-63: Locally porphyritic quartz monzonite at contact, near middle of edge of NW¼ sec. 21, T. 1 N., R. 81 W.
V-327-63: Biotite granodiorite near contact, S½SW¼ sec. 16, T. 1 N., R. 81 W.
V-379-63: Slightly porphyritic (plagioclase) biotite granodiorite, sec. 21, 500 feet west of V-324-63.
V-380-63: Migmatitic biotite gneiss from partially assimilated biotite gneiss xenolith in granodiorite, S½SW¼ sec. 16, T. 1 N., R. 81 W.
V-424-63: Biotite granodiorite from zone of biotite gneiss intercalated with Boulder Creek Granodiorite, near C S½ sec. 29, T. 1 N., R. 81 W.
V-375-63: Biotitic granodiorite from south edge of Boulder Creek Granodiorite, near C N½ sec. 29, T. 1 N., R. 81 W.
V-390-63: Biotite granodiorite, near C N½ sec. 29, T. 1 N., R. 81 W.
V-391-63: Biotite granodiorite, near C N½ sec. 29, T. 1 N., R. 81 W.
V-373-63: Biotite granodiorite slightly contaminated by amphibolitic xenolith, SW¼ sec. 20, T. 1 N., R. 81 W.

C. Rocks of the Boulder Creek Granodiorite within and adjacent to fault zones.

Mineral	V-48-63	V-49a-63	V-50-63	V-163-63a	V-163-63b	V-164-63	V-165-63a	V-165-63b	V-166-63	V-167-63	V-168-63	V-170-63	V-189-63	V-190-63	V-192-63
	Sample														
Quartz	2	29	31	13	16	10	9	35	<1	11	10	35	32	33	14
Plagioclase	27	34	5	6	27	10/ 54	21	27	3	56	24	14	18	9	35
Microcline 11/	10	29	32	<1	2	< 1	1	--	--	3	4	20	29	29	37
Biotite	--	--	--	--	12/ 4	--	--	--	--	8	--	Tr	--	3	Tr
Hornblende	18	--	?	13	5	12	25	7	42	10	19	--	--	--	1
Muscovite	2	--	Tr	--	--	--	--	--	--	--	--	Tr	2	Tr	--
Sericite and clay	13	--	26	54	35	--	20	21	45	5	34	26	12	24	10
Epidote 6/	13	3	1	4	3	7	8	2	7	2	3	2	4	2	1
Chlorite	6	2	4	6	5	7	10	7	2	1	3	Tr	2	Tr	2
Calcite	--	--	--	<1	--	--	--	--	<1	--	--	--	--	--	--
Prehnite?	--	--	--	<1	<1	Tr	Tr	--	<1	Tr	Tr	--	Tr	Tr	--
Leucoxene	--	--	--	--	--	--	Tr	--	--	--	--	--	--	--	--
Iron ore	Tr	3	<1	1	<1	<1	1	<1	<1	<1	1	3	1	Tr	Tr
Sphene	1	--	--	<1	1	<1	4	<1	<1	1	1	--	--	--	Tr
Apatite	<1	--	--	<1	<1	<1	Tr	--	--	<1	<1	Tr	Tr	Tr	Tr
Zircon	Tr	--	Tr	--	--	--	Tr	--	--	--	--	Tr?	--	Tr	--
Epidote in veinlets	7	--	--	--	--	7	--	Tr	--	<1	--	--	--	--	--

V-48-63: Contaminated, cataclastic; Boulder Creek Granodiorite, near small fault in NW¼ sec. 17, T. 1 N., R. 81 W.
V-49a-63: Cataclastic? and sheared leucocratic quartz monzonite in shear zone in SW¼ sec. 8, T. 1 N., R. 81 W.
V-50-63: Cataclastic? and sheared leucocratic quartz monzonite in shear zone in SW¼ sec. 8, T. 1 N., R. 81 W.

V-163-63a through V-168-63, V-170-63, V-189-63, V-190-63, and V-192-63: Boulder Creek Granodiorite, collected from west to east along upper half of steep slope north of stream in N½ sec. 5, and NW¼ sec. 6, T. 1 N., R. 81 W. All except V-170, V-189, and V-190 contain evidence of contamination by varying amounts of amphibolitic material and exhibit varying degrees of cataclasis and the effects of later superimposed shearing and associated mineral alteration. V-163-63a is the more altered part of the same hand sample from which V-163-63b was taken. V-165-63a is partially assimilated amphibolite and V-165-63b is a felsic cary in the same rock.

1/ Sericite, plagioclase, calcite, and quartz in veinlets not counted.

2/ Constituents too finely or complexly intergrown to identify and count separately; principally myrmekite but also some perthite, antiperthite, and graphic intergrowths of quartz in microcline.

3/ And rare hydromuscovite?

4/ Or hydromuscovite?

5/ Includes some clay alteration, mostly of K-feldspar.

6/ Mostly pistacite, may also include some zoisite-clinozoisite and rare allanite (generally noted when present).

7/ Includes 1 percent allanite.

8/ Estimated.

9/ Includes rare allanite.

10/ Includes as much as 3.5 percent albite in saussuritic plagioclase.

11/ Some sodic-plagioclase in (saussuritic) rare calcic plagioclase may have been misidentified as K-feldspar in plagioclase and included in this mineral category.

12/ Mostly bleached biotite (hydromuscovite?)

TABLE 5.--Lists of fossils from the Niobrara Formation

A. List of fossils from section of Niobrara measured in SE¼ sec. 32, T. 1 N., R. 80 W., east side of Blue River

Sample No.	Location in section[1]	Mollusks (identified by W. A. Cobban)	Foraminifera (identified by J. F. Mello)
V-91-64	Unit 8. Thin fossil hash at top.	Ostrea congesta Conrad	
V-85-64	Unit 4. Shale.	Inoceramus sp.	?Bulimenella carseyse Plummer Rugoglobigerina? sp. Biglobigerinella? sp. Gyroidina cf. nitida Reuse Gyroidina cf. depressa (Alth) Heterohelix globulosa (Ehrenberg) Gaudryina sp. Heterohelix plummerae (Loetterle)
V-83-64	Unit 4. 10-12 in. chalky argillaceous limestone at base.	Inoceramus cf. I. inconstans	Gaudryina sp. ?Bulimenella carseyae Plummer Heterohelix plummerae (Loetterle) Rugoglobigerina? sp. Biglobigerinella? sp. Gyroidina cf. nitida Reuss Gyroidina cf. depressa (Ehrenberg) Bulimina sp.
V-77-64	Unit 3. 64 ft from base	Inoceramus sp	Gaudryina sp., possibly G. bentonensis Heterohelix plummerae (Loetterle) Heterohelix globulosa (Ehrenberg) Heterohelix globifera (Reuss) of Loetterle(?) ?Buliminella carseyae Plummer Anomalina sp. Rugoglobigerina? sp. Globorotalites subconicus (Morrow)
V-76-64	Unit 3. 24 ft from base.	Inoceramus erectus Meek	Heterohelix globifera (Reuss of Loetterle(?)) Heterohelix pulchra (Brotzen) Heterohelix globulosa (Ehrenberg) Heterohelix plummerae (Loetterle) Lenticulina? sp. (juvenile) Astacolus? sp. (juvenile) Eouvigerina cf. acuteata Cushman Eouvigerina genae Morrow Planulina sp. Gyroidina cf. nitida (Reuss) Biglobigerinella sp. Rugoglobigerina? sp. Globotruncana sp. Globotruncana sp., possibly G. marginata (Reuss) Neobulimina? sp.
V-74-64	Unit 2. Lower part.	Ostrea sp.	Globotruncana sp., possibly G. marginata (Reuss) Planulina kansasensis Morrow Neobulimina sp., possibly juvenile specimens of N. irregularis Cushman and Parker Heterohelix plummerae (Loetterle)
V-71-64	Unit 1 Upper 2 ft.	Ostrea sp.	Eouvigerina genae Morrow ?Buliminella carseyae Plummer Biglobigerinella sp. Rugoglobigerina? sp. Heterohelix plummerae (Loetterle) Gyroidina cf. nitida (Reuss) Planulina kansasensis Morrow

[1] Unit 8, 305.5-424- ft from base of Smoky Hill Shale Member.
Unit 4, 150-167 ft from base of Smoky Hill Shale Member.
Unit 3, basal 150 ft of Smoky Hill Shale Member.
Unit 2, 4-16 ft from base of Fort Hays Limestone Member.
Unit 1, basal 4 ft of Fort Hays Limestone Member.

B. List of fossils from section of Niobrara measured in the SW¼NE¼ sec. 32, T. 1 N., R. 80 W., west side of Blue River

Sample No.	Location in section[1]	Mollusks	Foraminifera
V-81-64	Unit 4. In limestone 4 in. from base.	Ostrea sp.	
V-78-64	Unit 3.	Ostrea sp. Inoceramus sp.	Gaudryina sp. Globotruncana sp., possibly G. marginata of Loetterle Rugoglobigerina? sp. Planulina kansasensis Morrow Heterohelix plummerae (Loetterle) Gyroidina cf. nitida (Reuss)

[1] Unit 4, 3-15 ft from base of Fort Hays Limestone Member.
Unit 3, basal 3 ft of Fort Hays Limestone Member.

C. List of fossils from a limestone outcrop of the Fort Hays Limestone Member, NE¼NE¼ sec. 10, south side of Sheep Creek

Sample No.	Location in section	Mollusks	Foraminifera
V-2-64	---------------	Ostrea sp.	Rugoglobigerina? sp. Heterohelix plummerae (Loetterle) ?Buliminella carseyae Plummer Gyroidina cf. nitida (Reuss) Heterohelix cf. planata (Cushman)