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Geology of the Minturn 15-Minute Quadrangle, Eagle and Summit Counties, Colorado

By OGDEN TWETO *and* THOMAS S. LOVERING

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Geology of the region surrounding a
major zinc mining district and the
Vail recreational area, with emphasis on
the Minturn Formation of Pennsylvanian age

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GEOLOGY OF THE MINTURN 15-MINUTE QUADRANGLE, EAGLE AND SUMMIT COUNTIES, COLORADO

By OGDEN TWETO and THOMAS S. LOVERING

ABSTRACT

The Minturn quadrangle is an area of about 230 square miles (600 square kilometres) in the mountains of central Colorado, 75 miles (120 kilometres) west of Denver. In its northeastern part it includes a segment of the high and extremely rugged Gore Range, and in its southwestern part it includes the northeastern flank of the Sawatch Range. These two ranges consist mainly of Precambrian rocks. A lower but mountainous area between them, which occupies a large part of the quadrangle, consists of sedimentary rocks, mainly of Pennsylvanian and Permian age.

Mining operations at Gilman, in the southern part of the quadrangle, were long the chief industry in the quadrangle. The Gilman district is credited with a production through 1972 of about $328 million in zinc, silver, copper, lead, and gold. The ore deposits of this district are discussed in a separate report.[1] Since the early 1960's a skiing and recreational industry has burgeoned at Vail, in the middle part of the quadrangle, and has surpassed mining as an economic activity in the area.

The rocks exposed in the Minturn quadrangle are of six major categories: (1) Precambrian crystalline rocks, (2) a thin but economically significant sequence of pre-Pennsylvanian Paleozoic sedimentary rocks, (3) a thick sequence of Pennsylvanian and Permian sedimentary rocks, (4) a thin sequence of Mesozoic sedimentary rocks preserved in an area of only about a square mile (2.6 square kilometres) in the northwest corner of the quadrangle, (5) scattered Upper Cretaceous and Tertiary intrusive igneous and volcanic rocks, and (6) unconsolidated Quaternary surficial deposits, mainly of glacial origin.

The Precambrian X rocks exposed in the Gore and Sawatch Ranges consist mainly of migmatite and granitic rocks, but they also include biotite gneiss, diorite, and dike rocks, such as pegmatite and aplite. Biotite gneiss, the oldest rock, was widely converted to migmatite during early phases of granitic intrusion. Biotite-quartz diorite and minor hornblende diorite form many small bodies that were emplaced during and following migmatization and in advance of the main bodies of granitic rocks. The granitic rocks are formally defined here as the Cross Creek Granite. Extensive bodies of this granite in the Sawatch and Gore Ranges are inferred to be parts of a single large batholith. The Cross Creek Granite varies in composition from granodiorite to granite, but most of it is quartz monzonite that is near granodiorite in composition. The granite bodies are typically concordant with the enclosing gneisses and have gradational contacts with the gneisses. The Cross Creek is dated isotopically as about 1,700 million years in age.

The sequence of pre-Pennsylvanian Paleozoic rocks consists, from the base upward, of the Sawatch Quartzite, Peerless Formation, Harding Sandstone, Chaffee Group, and Leadville Limestone (or Dolomite). These rocks are exposed only in small areas, principally along the canyon of the Eagle River and on the lower slopes of the Sawatch Range; some are exposed also in small fault slices along the Gore fault, a major fault along the southwestern side of the Gore Range. The Gore fault marks the western border of an ancient highland that was elevated repeatedly during Paleozoic time, especially late Paleozoic. Consequently, all the Paleozoic formations thin or pinch out toward the Gore Range.

The Sawatch Quartzite, of Late Cambrian age, rests with profound unconformity upon a planar surface cut over Precambrian rocks. The Sawatch consists almost entirely of medium-bedded medium-grained white or lightly tinted quartzite, but it contains local lenses of fine conglomerate at the base and scattered small lenses of brown-weathering dolomitic sandstones in its middle part. It is about 200 ft (feet) (60 m (metres)) thick near the Eagle River and about 100 ft (30 m) thick where preserved along the Gore fault.

The Peerless Formation, of Late Cambrian age, conformably overlies the Sawatch Quartzite and locally is in gradational contact with the Sawatch. The Peerless consists of dolomitic sandstone, sandy dolomite, dolomite, shaly dolomite, and dolomitic edgewise conglomerates. The rocks are locally glauconitic and ferruginous, and they are variously colored brown, maroon, green, and buff. The Peerless is 65–70 ft (20 m) thick near the Eagle River, and a maximum of 20 ft (6 m) of it is preserved near the Gore fault.

The Harding Sandstone, of Middle Ordovician age, lies with erosional unconformity upon the Peerless Formation. The unit consists of white quartzite, green sandstone and conglomerate, and gray and green shale. As exposed along the Eagle River, it ranges in thickness from 14 to 50 ft (4–15 m) and it may be as much as 80 ft (24 m) thick in some of the mine workings at Gilman. It is absent near the Gore fault.

As defined in this report, the Chaffee Group, of Late Devonian and Early Mississippian(?) age, consists from the base upward of the Parting Formation, Dyer Dolomite, and Gilman Sandstone. Near Gilman, the Parting Formation lies with erosional and slight angular unconformity upon the Harding Sandstone; in other areas it overlaps older sedimentary formations, and in places along the Gore fault it lies upon Precambrian rocks. The Parting consists mainly of coarse-grained tan to white quartzite and conglomerate; locally, green shale is also a prominent component. The Parting is typically about 45 ft (14 m) thick near the Eagle River, though it locally reaches 65 ft (20 m). A maximum of about 20 ft (6 m) is preserved near the Gore fault. The Dyer Dolomite lies conformably and with locally gradational contact upon the Parting Formation. The Dyer consists of thin-bedded gray and buff dolomite. It is 75–80 ft (23–24 m) thick near the Eagle River and is absent near the Gore fault. The Gilman

[1] The report on the ore deposits of the Gilman district, Eagle County, has been designated as Geological Survey Professional Paper 1017.

Sandstone, formerly classed as a member of the Leadville Limestone, lies with erosional unconformity upon the Dyer Dolomite and is overlain with erosional unconformity by the Leadville as here redefined. The Gilman consists of sandstone, dolomite, chert, and breccia in various proportions. It is typically about 20 ft (6 m) thick but ranges from 10 to 50 ft (3–15 m) in thickness. In the mineralized area near Gilman, the Gilman Sandstone has been considerably modified in composition and structure by solution and collapse.

The Leadville Limestone (or Dolomite) as here redefined consists of carbonate rocks of Mississippian age overlying the Gilman Sandstone and underlying either the regolithic Lower Pennsylvanian Molas Formation or the Middle Pennsylvanian Belden Formation. In most of Colorado, the Leadville is a limestone, but across the width of the Colorado mineral belt — a distance of as much as 40 mi (65 km) — it is entirely a dolomite. In the Minturn quadrangle, the boundary between the limestone and the dolomite facies is in the valley of Cross Creek, midway between Gilman and Minturn. Northwest of Cross Creek, the Leadville consists of light-gray-weathering foraminiferal limestone, and it is referred to as the Leadville Limestone. Southwest of Cross Creek, the Leadville consists of fine-grained dark-gray dolomite and various recrystallized dolomite facies, referred to as Leadville Dolomite. The fine-grained dark dolomite is concluded to have replaced original limestone during an early stage of Laramide orogeny in Late Cretaceous time, and various recrystallizations of this material occurred later. The top of the Leadville is a karst erosion surface marked by local pockets of regolithic silt referred to the Molas Formation. Because of the uneven karst surface, the thickness of the Leadville varies widely over the region. Along the Eagle River in the Minturn quadrangle, the Leadville is 110–140 ft (33–42 m) thick; it is absent at the Gore fault. The Leadville is the principal host rock of ore deposits in the Gilman district.

Regolithic silt of the Molas Formation is present only locally at the top of the Leadville and is generally only a few inches to a few feet thick. Where present, it was mapped with the Belden Formation. As seen in mine workings, material of the Molas fills solution channels and caves in the Leadville beneath the karst surface, though no layer of Molas may be evident at this surface.

The Leadville, or locally the Molas, is overlain by as much as 10,500 ft (3,220 m) of predominantly clastic rocks of Pennsylvanian and Permian age. These rocks are divided into three formations, the Belden Formation, about 200 ft (60 m) in maximum thickness, the overlying Minturn Formation, as much as 6,300 ft (1,920 m) thick, and the Maroon Formation, as much as 4,200 ft (1,280 m) thick.

The Belden Formation consists of interbedded black shale, limestone, and fine-grained sandstone. Fossils from the type section, near Gilman, indicate an early Middle Pennsylvanian (Atokan) age. An emended type section is presented. The Belden is about 200 ft (60 m) thick near the Eagle River, and it pinches out northeastward toward the Gore fault, probably by nondeposition.

The Minturn Formation, a type section of which is presented in this report, consists predominantly of grit, conglomerate, and sandstone in lenticular beds. These rocks are highly arkosic, micaceous, coarse grained, and poorly sorted. They are mainly gray or of various light pastel colors, but a zone 400–700 ft (120–210 m) above the base is dull red, and a zone several hundred feet thick at the top is bright red. The clastic rocks are inferred to be marine-margin piedmont deposits derived from a highland east of the Gore fault. Several beds of marine limestone are intercalated in the coarse clastic rocks, particularly in the upper half of the formation. The lower half contains a few thinner beds of dolomite and, at several horizons, scattered dolomite reefs. Seven of the most distinctive and persistent limestones or dolomites were designated as members of the Minturn in the Pando area, immediately south of the quadrangle (Tweto, 1949): the Wearyman, Hornsilver, Resolution, Robinson, Elk Ridge, White Quail, and Jacque Mountain Members. All are present in the Minturn quadrangle, but only the last four are widespread. Fossils from the limestones indicate that the Minturn is Middle Pennsylvanian (Atokan and Des Moinesian) in age. The Minturn overlaps the eroded edges of all older formations and extends onto Precambrian rocks near the Gore fault. It is about 6,300 ft (1,920 m) thick near the Eagle River, but it thins abruptly by onlap against the old highland near the Gore fault; there, the Robinson Limestone Member, 4,200 ft (1,280 m) above the Belden in the area farther west, is almost in contact with the granite. Westward, the Minturn rocks become finer grained, and they intertongue with gypsum of the Eagle Valley Evaporite near the western boundary of the quadrangle. The Jacque Mountain Limestone Member marks the top of the Minturn Formation.

The Maroon Formation resembles the Minturn in lithology, but it is entirely red, and, in general, it is less coarse grained. It is about 4,200 ft (1,280 m) thick in the northwestern part of the quadrangle and thins eastward toward the Gore fault. The Maroon is unfossiliferous in the Minturn quadrangle, but, from stratigraphic relations and scant fossils found elsewhere, it is concluded to be Middle and Late Pennsylvanian and Early Permian in age.

In a small area on Red and White Mountain, in the northwestern part of the quadrangle, the Maroon is overlain by Mesozoic rocks comprising the Chinle Formation, Entrada Sandstone, Morrison Formation, and Dakota Sandstone. These units have a total thickness of about 535 ft (160 m).

The Upper Cretaceous and Tertiary igneous rocks of the quadrangle are (1) Pando Porphyry, of Late Cretaceous age, in a sill that intrudes the Belden Formation in the Gilman-Red Cliff area; (2) patches of basalt and tuff of Miocene age in the Piney River area; and (3) scattered dacitic dikes of probable middle Tertiary age in the Gore Range. The unconsolidated deposits consist of (1) a thick colluvium of Pliocene and Pleistocene(?) age in the Red and White Mountain–Piney River area, (2) glacial tills of pre-Bull Lake, Bull Lake, and Pinedale ages, (3) landslide deposits, and (4) stream alluvium and gravels of Pleistocene and Holocene age.

The Minturn quadrangle is divided structurally into three main units, corresponding to the parts in the Gore Range, the Sawatch Range, and the intervening area. The Gore Range is a large fault block of Precambrian rocks, only a part of which is included in the quadrangle. The Gore fault, the bounding fault on the southwestern side of this block, is a complex fault that has several strands. It originated in Precambrian time and underwent movements at many times from then to the late Tertiary. It is, in general, a vertical or steep normal fault. The Sawatch Range, only a small part of which lies within the quadrangle, is a huge anticline. The range consists largely of Precambrian rocks in the core of the anticline; a thin cover of Paleozoic sedimentary rocks, broken by a few small faults, forms dip slopes on the northeastern flank of the anticline, southwest of the Eagle River.

The area between the Gore and Sawatch Ranges is broadly synclinal and only moderately deformed. The principal folds are three north- to northwest-trending synclines arranged echelon in a northwest-trending line. The southeastern — or Black Gore — syncline has a broad, gently dipping southwestern limb that is a part of the flank of the Sawatch anticline and a narrow northeastern limb that turns up steeply against the Gore fault. The middle — or Vail — syncline is a bowed, doubly plunging syncline that is prominently exposed on the sides of the valley of Gore Creek at Vail. The northwestern — or Red and White — syncline occupies most of the area between the mouth of Gore Creek and the Piney River. The southeastern nose of the syncline is blunt and forms an abrupt northwest-dipping monocline along the north side of Gore Creek from the Eagle River to Red Sandstone Creek. This monocline separates a southern area that is structurally a part of the flank of the Sawatch Range anticline from a northern area that is part of a large structural basin that lies northwest of the quadrangle. All three of the synclines are accentuated in the subsurface because of the thinning of the Paleozoic formations toward the Gore Range.

The sedimentary rocks are broken by steep faults in places, but most of the faults have displacements of less than 100 ft (30 m). In the mine workings and canyon walls at Gilman, bedding faults are numerous, and steep faults are rare. The bedding faults, though inconspicuous, played an important role in ground preparation prior to mineralization at Gilman. Faults in the Precambrian rocks in this area are reactivated fractures associated with the Homestake shear zone, a broad northeast-trending Precambrian shear zone that lies mainly to the south of the quadrangle. Most of the faults terminate upward at the base of the Sawatch Quartzite.

INTRODUCTION

GEOGRAPHY

The Minturn quadrangle is an area of about 230 mi^2 (600 km^2) in the mountains of central Colorado, 75 mi (120 km) west of Denver (fig. 1). In its northeastern part it includes a segment of the high and extremely rugged Gore Range, and in its southwestern part it includes the northeastern flank of the Sawatch Range. The Eagle River, which drains all but the northernmost part of the quadrangle, flows along the base of the Sawatch Range. A broad northwest-trending belt between the Eagle River and the high crestal ridge of the Gore Range is mountainous but generally lower than the high crests to the northeast and southwest.

Easy access to the area is provided by U.S. Highway 6 and I–70 which follow Gore Creek westward across the middle of the quadrangle. Access from the south is provided by U.S. Highway 24 and the Denver and Rio Grande Western Railroad, which follow the Eagle River northwestward. Until recent years, population of the quadrangle was centered in the three small towns of Red Cliff, Gilman, and Minturn, along the Eagle River. In the early 1960's, a fourth settlement, Vail, was established as a ski resort on Gore Creek near the mouth of Mill Creek (pl. 1).

Mining conducted in the Red Cliff–Gilman area was long the principal industry within the quadrangle. Red Cliff, the oldest settlement in the quadrangle, was established as a mining town in 1879. The center of mining operations later shifted to Gilman, which since 1918 has been a "company town" of the New Jersey Zinc Co. The mines at Gilman are a principal source of employment for the residents of Minturn also, but Minturn is, in addition, a railroad town that was established as a base for the extra locomotive equipment necessary to move trains over the Continental Divide at Tennessee Pass, 12 mi (19 km) south of Red Cliff.

About 85 percent of the quadrangle is in the White River and Arapahoe National Forests. The forest land supports a summertime sheep-grazing industry and a small lumbering industry. It also supports a skiing and recreational industry which, though only recently established, has surpassed mining as a principal economic activity in the quadrangle. Superb mountain scenery, the virtual absence of habitations outside the valleys of the Eagle River and Gore Creek, and snow and slope conditions ideal for skiing make the area attractive for such activities.

The Gore Range, the predominating topographic feature, rises 5,000 ft (1,525 m) above the valley of Gore Creek at Vail to a crest-line more than 13,000 ft (4,000 m) in elevation. Below the steep and craggy rock slopes of this intensely glaciated range is a broad area of forested, rounded ridges that extends southwestward to the foot of the Sawatch Range. Many grassy slopes and ridges dot the forested area, which is characterized by dense growths of spruce and alpine fir on the north-facing slopes and by lodgepole pine, aspen, and scattered Douglas-fir on the south-facing slopes.

HISTORY OF INVESTIGATION

The earliest geologic investigations in the Minturn quadrangle were made by Peale (1874, 1876), who described the general stratigraphic sequence and structure along the Eagle River and mapped the area in rapid reconnaissance for the Colorado Atlas (Hayden, 1877). Peale's work provided the geologic framework for various reports on the mines of the Red Cliff–Gilman area (for example, Olcott, 1887; Guiterman, 1890; Means, 1915), although it was gradually supplemented by extrapolation of geologic information from the Leadville district, 20 mi (32 km) to the south, with which the Red Cliff–Gilman area has many parallels (Emmons, 1886; Emmons and others, 1927).

The first detailed geologic map of any part of the quadrangle was prepared by Crawford and Gibson (1925), who mapped the area along the canyon of the Eagle River from 1 mi north of Gilman to about 5 mi (8 km) south of Red Cliff and described the ore deposits. Results of private studies of the ore deposits and vicinity, begun as early as 1912 by the New Jersey Zinc Co., are summarized in reports by Borcherdt (1931) and by Radabaugh, Merchant, and Brown (1968).

Geologic mapping of the Minturn quadrangle and study of the Gilman ore deposits in light of the regional geology was begun by us in 1940 for the U.S. Geological Survey in cooperation with the Colorado Metal Mining Fund, a predecessor of the present (1975) Colorado Mining Industrial Development Board. Study of the mineralized area occupied most of the first short field season, and mapping of the quadrangle on a close reconnaissance basis at a scale of 1:48,000 was largely accomplished in the field season of 1941, except for the

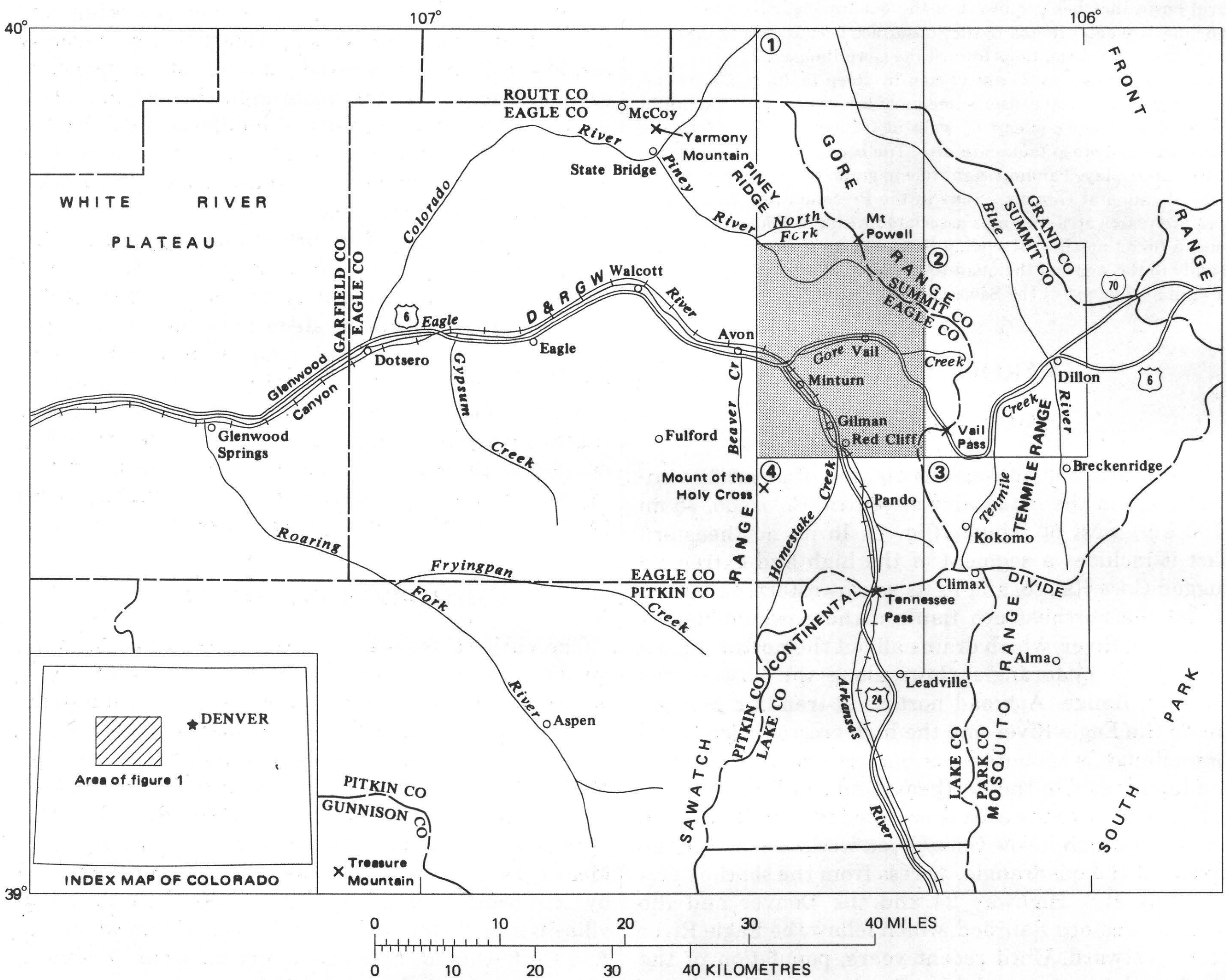


FIGURE 1.—Index map of west-central Colorado showing geographic setting of the Minturn quadrangle (patterned). Adjoining quadrangles are (1) Mount Powell, (2) Dillon, (3) Mount Lincoln, and (4) Holy Cross.

area of Precambrian rocks in the Gore Range. Most of the area in the Gore Range area was mapped during 3 weeks in 1942, and the project was then recessed, owing to wartime pressures for other work. A summary of results to that date (Lovering and Tweto, 1944) was accompanied by the geologic map of the quadrangle, which at that time contained many imperfections and was still blank in the extreme northeast corner. Following work in a few critical areas and in several mines by Tweto in 1946, a summary of the ore deposits was published in 1947 (Tweto and Lovering, 1947). Owing to other demands, the project remained dormant for several years after that date. The last essential stratigraphic and structural fieldwork was completed by Lovering during brief field seasons in 1960–63, and the glacial geology was studied intermittently through the early 1960's by Tweto. Last improvements in the map of the area in the Gore Range were made in 1969 (Tweto and others, 1970).

With apologies for this long history of delay, we here report on the general geology of the Minturn quadrangle. A separate report (Lovering and others, 1977), deals with the ore deposits of the Gilman district and with the alteration history of the Leadville Limestone. In the many years since the work on the Minturn quadrangle started, studies of various aspects of the geology and of the ore deposits were made by others, and the science of geology made marked advances in concepts, capabilities, and techniques. In the sections that follow we present the results of our interrupted studies as integrated with the later studies of others, without attempting either to achieve balance in the scope of treatment of the various topics or to pursue many topics to the extent that the state of the science nowadays permits. We acknowledge with thanks petrographic data supplied by Tom G. Lovering on our scattered samples of sedimentary and dike rocks from outside the mineralized area.

The geologic map accompanying this report will be found to be geometrically inaccurate in many places, owing to inaccuracies in the topographic base used in the original geologic mapping. Some of the more glaring inaccuracies in the base were latter corrected photogrammetrically, but much of the map remains as plotted on the original base, which was a preliminary version, at a scale of 1 : 48,000, of the 1934 edition of the Minturn 15-minute quadrangle topographic map.

ENGLISH AND METRIC UNITS

Thickness listed in the stratigraphic sections in this report are in feet, as are the contours on the topographic base and the elevations, derived from the contours, in the geologic cross sections. Scales for converting thickness measurements and elevations to metric units are shown in figure 2. Both English and metric values are indicated for other measurements except petrographic dimensions which, in accord with convention, are entirely metric. Conversion units are as follows:

English to metric:

Inches (in.) multiplied by 2.54 = centimetres (cm);
Feet (ft) multiplied by 0.3048= metres (m);
Miles (mi) multiplied by 1.609= kilometres (km);
Square miles (mi^2) multipled by 2.6= square kilometres(km^2).

Metric to English:

Millimetres (mm) multipled by 0.039= inches;
Centimetres (cm) multipled by 0.394= inches;
Metres (m) multipled by 3.281= feet;
Kilometres (km) multipled by 0.621= miles.

ROCK FORMATIONS

The rocks of the Minturn quadrangle are divided into many formations or map units (table 1), but on the basis of their occurrence and geologic connotations they fall into six main groups: (1) Precambrian crystalline rocks, (2) a thin sequence of pre-Pennsylvanian Paleozoic sedimentary rocks, (3) a thick sequence of Pennsylvanian and Permian sedimentary rocks, (4) a thin sequence of Mesozoic sedimentary rocks in a small area on Red and White Mountain, (5) scattered Upper Cretaceous and Tertiary intrusive and volcanic rocks, and (6) unconsolidated surficial deposits.

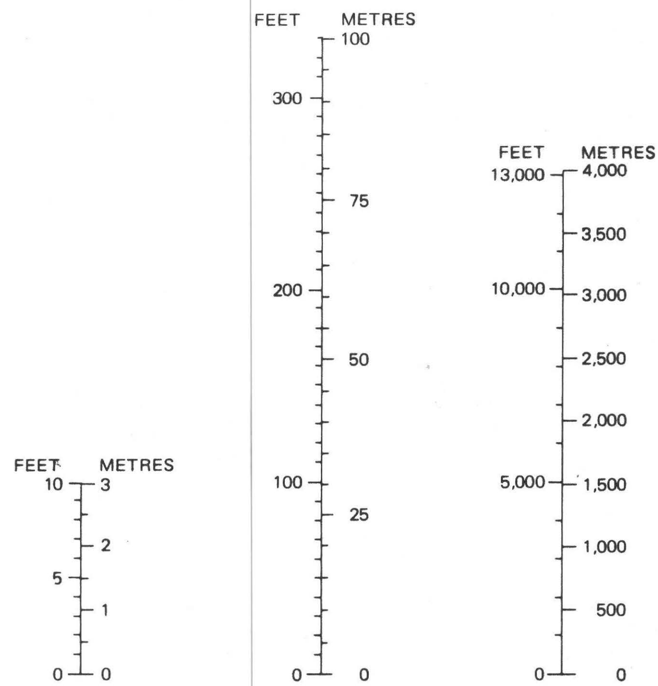


FIGURE 2.—English-metric conversion scales.

The Precambrian rocks, which are principally granite and migmatite, form the high part of the Gore Range in the northeastern part of the quadrangle, and except for a thin cover of sedimentary rocks, they also form the bulk of the flank of the Sawatch Range in the southwestern part of the quadrangle. They are completely covered by sedimentary rocks in the area between the two ranges.

The pre-Pennsylvanian Paleozoic rocks, mainly quartzites and dolomites, are exposed principally in the canyon of the Eagle River (fig. 3) and adjoining lower slopes of the Sawatch Range, although some of them are exposed also in thin fault slices along the Gore fault in the Gore Range. On the flank of the Sawatch Range these rocks form extensive smooth gentle slopes (fig. 22). These slopes are approximate dip slopes, but because they are slightly gentler than the dip, the various formations are in shingled arrangement, with younger units appearing successively downslope and northward. Although thin, aggregating only about 550 ft (168 m), the pre-Pennsylvanian rocks are of special interest as the principal host rocks of the ore deposits of the quadrangle.

The Pennsylvanian and Permian rocks, in contrast, are more than 10,000 ft (3,050 m) thick and are essentially devoid of known mineral deposits in this quadrangle. They occupy the entire area between the Eagle River and the Precambrian rocks of the Gore Range. In this area they form a northwest-trending en echelon

TABLE 1. — *General stratigraphic section in the Minturn quadrangle*

Age	Name		Thickness, feet (meters)	Character
Holocene and late Pleistocene	Alluvium and landslide deposits		0–200? (0–90?)	Alluvium, terrace gravels, pond sediments, and landslide debris.
Pleistocene	Glacial deposits		0–300? (0–90?)	Tills of Pinedale, Bull Lake, and pre-Bull Lake ages.
Pleistocene(?) and Pliocene	Colluvium		0–75 (0–23)	Sandstone blocks and supergene chert in dirt matrix.
Miocene	Volcanic rocks		0–200 (0–61)	Tuff and basalt.
Miocene, Oligocene(?), and Late Cretaceous	Intrusive igneous rocks			Quartz latite, dacite, and quartz basalt porphyries, in sills and dikes.
Early Cretaceous	Dakota Sandstone		150–160 (46–49)	Medium-bedded to massive light-gray sandstone; is dark gray, thin bedded, and shaly at top; locally conglomeratic at base.
Late Jurassic	Morrison Formation		250 (76)	Interbedded light-gray sandstone, green, gray, and purple shale, and gray limestone.
	Entrada Sandstone		60 (18)	Massive, cross-bedded buff to orange sandstone.
Late Triassic	Chinle Formation		70 (21)	Red and purple siltstone, mudstone, and fine-grained sandstone; Gartra Member, at base, is 10–25 ft (3–7.5 m) of coarse white sandstone and conglomerate.
Early Permian, Late and Middle Pennsylvanian	Maroon Formation		1,700–4,200 (518–1,281)	Red sandstone, siltstone, grit, and conglomerate.
Middle Pennsylvanian	Minturn Formation		2,100–6,300 (640–1,921)	Grit, conglomerate, sandstone, and shale in lenticular bodies, and some intercalated limestone and dolomite in persistent beds; predominantly gray but red in upper part and in an irregular zone near base. Some of the limestones are named members; see figure 13 for subdivisions.
	Belden Formation		0–200 (0–61)	Dark-gray to black shale, limestone, and minor sandstone, in thin beds.
Early Pennsylvanian	Molas Formation		0–10 (0–3)	Gray, yellow, and brown regolithic silt and clay containing abundant chert fragments.
Early Mississippian	Leadville Limestone (or Dolomite)		0–140 (0–43)	Dark-gray limestone or dolomite; massive in upper part; medium bedded and cherty in lower part. Dolomite is extensively recrystallized.
Early Mississippian(?) and Late Devonian	Chaffee Group	Gilman Sandstone	0–50 (0–15)	Interbedded yellow-gray sandstone, sandy and cherty dolomite, and breccia.
Late Devonian	Chaffee Group	Dyer Dolomite	0–80 (0–24)	Thin-bedded gray dolomite.
	Chaffee Group	Parting Formation	0–65 (0–20)	Coarse-grained white to tan quartzite and conglomerate; subordinate interbedded green shale.
Middle Ordovician	Harding Sandstone		0–80? (0–24?)	White, gray, and green sandstone and quartzite, and green shale.
Late Cambrian	Peerless Formation		0–70 (0–21)	Brown, red, green, and buff sandy dolomite, dolomitic sandstone, dolomite, and dolomitic shale; irregularly glauconitic and ferruginous.
	Sawatch Quartzite		0–220 (0–67)	Medium- to thick-bedded, medium-grained white quartzite.
Precambrian X	Cross Creek Granite			Coarse-grained, generally porphyritic gneissic to massive quartz monzonite or granodiorite.
	Diorite			Mainly biotite-quartz diorite; gneissic to massive.
	Gneisses			Mainly migmatite; some biotite gneiss.

FIGURE 3.—Canyon of the Eagle River at Belden (in canyon bottom) and Gilman (at top of cliffs). Cliffs of stratified rock in middle part of canyon wall are Sawatch Quartzite, which lies on Precambrian rocks. Discontinuous cliffs higher on canyon wall are Chaffee Group and Leadville Dolomite. Vertical distance between Belden and Gilman is about 600 ft (200 m).

line of synclines. The sedimentary rocks terminate abruptly to the northeast at the Gore fault. This fault flanks the Gore Range and separates the sedimentary and crystalline rocks in the northeastern part of the quadrangle.

The Mesozoic sedimentary rocks are preserved only as a cap about 535 ft (163 m) thick on Red and White Mountain, near the northwest corner of the quadrangle.

The Upper Cretaceous and Tertiary igneous rocks occur only in scattered small bodies, the largest of which is a quartz latite porphyry sill intercalated in the basal Pennsylvanian rocks along the canyon of the Eagle River. The sill is of Late Cretaceous age. Tuff and basalt in small areas in the northwestern corner of the quadrangle are of Miocene age, and small dikes in the Gore Range are of probable middle Tertiary age.

The unconsolidated materials are principally glacial drift, which is widespread throughout most of the quadrangle. The high part of the Gore Range, however, was swept clean by the glaciers, and glacial drift is rare there.

PRECAMBRIAN ROCKS

The Precambrian rocks were mapped only in reconnaissance and were not studied in great detail. Hence, they are divided into only four units on the map (pl. 1), although many other units might be distinguished in more detailed studies. The oldest and least abundant of these units is biotite-quartz-plagioclase gneiss, referred to as biotite gneiss. This gneiss is similar to, and correlated with, the old gneiss of the Front Range and other areas of Precambrian rocks in Colorado, where it has been assigned names such as Idaho Springs Formation (Ball, 1906) or Black Canyon Schist (Hunter, 1925). Presumably, this old gneiss was once far more abundant in the Gore and Sawatch Ranges than it is now, but most of it was converted to migmatite or destroyed during the plutonic-metamorphic episode in which a granite here called the Cross Creek Granite was emplaced. Hence, far more migmatite than biotite gneiss is depicted on the map (pl. 1).

The migmatite and granite are accompanied in many places by a gneissic biotite diorite that seems to grade into both rocks. The diorite is abundant in most areas where both granite and migmatite are present, but much of it is in small bodies that were not distinguished in mapping. Only the larger bodies of dioritic rocks are shown on the map, and in most of them the diorite is mixed with granite, migmatite, and pegmatite.

BIOTITE GNEISS

The predominating rock of the unit here called biotite gneiss is a dark- to medium-gray strongly foliated gneiss consisting of alternating layers that are rich, respectively, in biotite or in quartz and plagioclase. The grain size is variable, and in the facies in which the biotite is coarse and abundant, the rock is a schist. Some of the gneiss contains sillimanite either as scattered needles or as waxy white clots, and some contains small dull-red almandite garnets. In places the gneiss contains lenses or layers of calc-silicate rock or of quartzite a few inches to a few feet thick, and locally it contains a little hornblende gneiss or amphibolite. In general these other rock varieties are much less abundant in the biotite gneiss of the Minturn quadrangle than they are elsewhere in the Precambrian of Colorado.

The biotite gneiss consists of 20–40 percent quartz, 30–60 percent plagioclase (oligoclase/andesine, An_{30-35}), and 15–30 percent biotite. Sillimanite, garnet, cordierite, microcline, or hornblende may constitute as much as 10 percent of some varieties, and magnetite, apatite, and zircon are ubiquitous minor components. Microcline generally constitutes no more than a few percent of the rock, if present at all, except in varieties grading into migmatite, in which it may be a major component. In composition and general character the biotite gneiss is closely similar to that of the Front Range, described in detail by Sims and Gable (1964, p. C14–C19) and by Moench (1964, p. A11–A16).

Although only scattered bodies of biotite gneiss are shown on the geologic map (pl. 1), the gneiss is more abundant than indicated, as it occurs also in many small bodies within the migmatite and the granite. It is, however, much less abundant than in many other areas of comparable size in the Precambrian terranes of Colorado. Viewed regionally, this sparsity is a fairly local feature associated with the Cross Creek Granite and accompanying migmatite. The gneiss is much more abundant a few miles south of the quadrangle in the Sawatch Range, a few miles north of the quadrangle in the Gore Range, and a few miles east of the quadrangle in the Tenmile Range.

The biotite gneiss is the oldest rock recognized in the Minturn quadrangle, just as similar gneiss (together with associated gneisses not present in the quadrangle) are the oldest rocks recognized in the Front Range and elsewhere in Colorado. Isotopic dating by the whole-rock rubidium-strontium method indicates that similar and presumably correlative gneisses of the Front Range and the Black Canyon of the Gunnison were formed by metamorphism 1.7 to 1.8 b.y. (billion years) ago (Hedge and others, 1967; Peterman and others, 1968; Hansen and Peterman, 1968). Age of the sedimentary rocks that were parent to the gneiss remains undetermined but, as suggested by isotopic data, probably does not exceed 2 b.y. (Z. E. Peterman, oral commun., 1970).

CROSS CREEK GRANITE AND RELATED MIGMATITE AND DIORITE

The Precambrian rocks of the Gore and Sawatch Ranges in the Minturn quadrangle are predominantly Cross Creek Granite, which is accompanied in most places by closely related diorite and migmatite. These three kinds of rocks are intimately mixed, grade into one another, and seem to be joint products of a major episode of granitic intrusion and attendant plutonic metamorphism. Because of the intermixing and intergrading, mapping of these rocks is a highly subjective process, and maps made by different workers, or even by the same worker at different times, are likely to differ appreciably.

CROSS CREEK GRANITE

The rock unit here designated the Cross Creek Granite[2] is an inhomogeneous batholithic unit ranging in composition from granodiorite to granite. The unit forms the northern end of the Sawatch Range, where it occupies an area of about 50 mi^2 (130 km^2), and it takes its name from Cross Creek in its type area, where it is well exposed in clean and fresh glaciated outcrops. The unit also forms the bulk of the Gore Range, not only within the Minturn quadrangle but also in adjoining parts of the range in the Dillon quadrangle to the east and in the Mount Powell quadrangle to the north (Tweto and others, 1970). The granite bodies in the two ranges are so similar that they are inferred to be parts of a single large batholith. This inference is supported by magnetic data (Tweto and others, 1970, p. C33, pl. 1) which suggest that the granite is continuous in the subsurface between the Gore and Sawatch Ranges near the latitude of Gore Creek.

So far as is known, the Cross Creek Granite is restricted to the northwest side of a major Precambrian fracture zone called the Homestake shear zone (Tweto and Sims, 1963). This broad northeast-trending zone is

[2]The term Cross Creek Granite was used in the 1944 preliminary report (Lovering and Tweto, 1944) but has not been formally introduced and published. In the interim "granite of Cross Creek" has been used (Pearson and others, 1966; Bergendahl, 1969; Tweto, 1974).

centered only a few miles south of the Minturn quadrangle in the Sawatch Range (Tweto, 1974) and some of its border fractures extend into the southwestern part of the Minturn quadrangle (fig 24). In the Gore Range the shear zone is exposed only to the east of the Minturn quadrangle, south of the latitude of Gore and Black Gore Creeks. As the Homestake shear zone had a left-lateral horizontal displacement of at least several miles (Tweto and Sims, 1963, p. 1003–1004), the Cross Creek batholith is possibly displaced with respect to some unknown continuation to the south or southeast. More likely, however, the shear zone coincides with the edge of the batholith because border facies characterize the batholith along the shear zone. Thus, there may be no offset extension of the batholith southeast of the shear zone.

FIELD RELATIONS

The Cross Creek batholith is characterized by very abundant inclusions of partly granitized gneiss, or migmatite, and by complex relations with bordering wallrocks. The inclusions of gneiss range in size from small fragments only inches across to many square miles. In some areas, as on the west slope of the Gore Range just south of the northern boundary of the Minturn quadrangle, the rock of the batholith is essentially a breccia of gneiss fragments a few inches to several feet in diameter in a matrix of granite. More typically, however, the inclusions are remnants of layers of biotite gneiss or migmatite that have been distended or engulfed and have been partly assimilated by the granite. The gneiss bodies are generally but not everywhere elongate parallel to the foliation in the gneiss, and the primary foliation in the granite, though younger, is parallel to this same direction. Reaction between granite and gneiss was extensive, and hence the contacts between the two rocks are commonly vague or completely gradational. In border areas of the batholith, long tongues of gneiss showing these features project into the granite, and, conversely, irregular but basically concordant bodies of the granite project into the gneiss.

Along or near many contacts between granite and gneiss are lenticular bodies of diorite ranging from a few feet to a few thousand feet in length. The diorite grades both into granite and into biotite gneiss or migmatite, but some of it is at least slightly older than the granite, as it is cut by the granite. Moreover, gneissic diorite occurs as inclusions in the granite, and in some of these the foliation is discordant with that in the granite, although dimensionally the inclusions parallel the foliation in the granite. In many places, granite, diorite, and migmatite are so closely intermixed and are so gradational that only the predominating type could be mapped at the scale used.

Most areas of contact between Cross Creek Granite and migmatite or diorite are characterized by abundant pegmatite and aplite. The pegmatite is of several different ages, as some predates the diorite, some postdates the diorite but predates the granite, some is a facies of the granite, some seems to have replaced granite, and some is in sharply defined dikes cutting the granite. In contrast, most aplite is in dikes that cut the granite, although some is in irregular bodies that grade into the granite and seems to be a textural facies of the same age as the granite.

CHARACTER

In its most typical facies, the Cross Creek Granite is a medium- to coarse-grained irregularly porphyritic gray to pinkish-gray slightly to markedly foliated quartz monzonite. Departures from this norm are common, however. Appearance of the rock, and also the composition, varies with amount, color, and size of potassium feldspar (microcline) crystals, which are erratically distributed. In some of the rock the potassium feldspar is bright rose or salmon pink, and, if abundant, it gives the rock a pink cast, but in other parts of the rock the potassium feldspar is light gray to white and inconspicuous. Some parts of the rock contain only very little potassium feldpsar, in inconspicuous small grains (fig. 4*A*), whereas other parts are characterized by abundant coarse grains or crystals of the feldspar (fig. 4*B*). In some places these crystals attain lengths of 2 in. (5 cm) and constitute as much as 50 percent of the rock. In places, the large potassium feldspar crystals are oriented so as to give a pronounced fluxion structure or grain to the rock, but in other places they have random orientation. If oriented, the feldspar crystals may or may not correspond in orientation to foliation and lineation defined by other minerals in the rock.

Degree of foliation and lineation likewise ranges widely. Most of the rock is gneissic in some degree, but some is essentially structureless. A complete sequence exists from structureless to strongly foliated, banded varieties that resemble, or grade into, coarse-grained biotite gneiss. Coarse banding or streakiness generally characterizes the foliated varieties. The banding may be compositional or textural or both. In some places it reflects only slight differences in biotite or feldspar content between layers or streaks, but in others it is due to streaks of diorite, or to lenses or layers of partly assimilated, or granitized, migmatite or biotite gneiss. In general, the granite is most strongly foliated in the vicinity of gneiss bodies and is only weakly foliated where uncontaminated by gneiss.

In lithology and mode of occurrence, the Cross Creek Granite closely resembles the Boulder Creek Granite of the Front Range (Lovering and Tweto, 1953, p. 8–16; Sims and Gable, 1967, p. E29–E35).

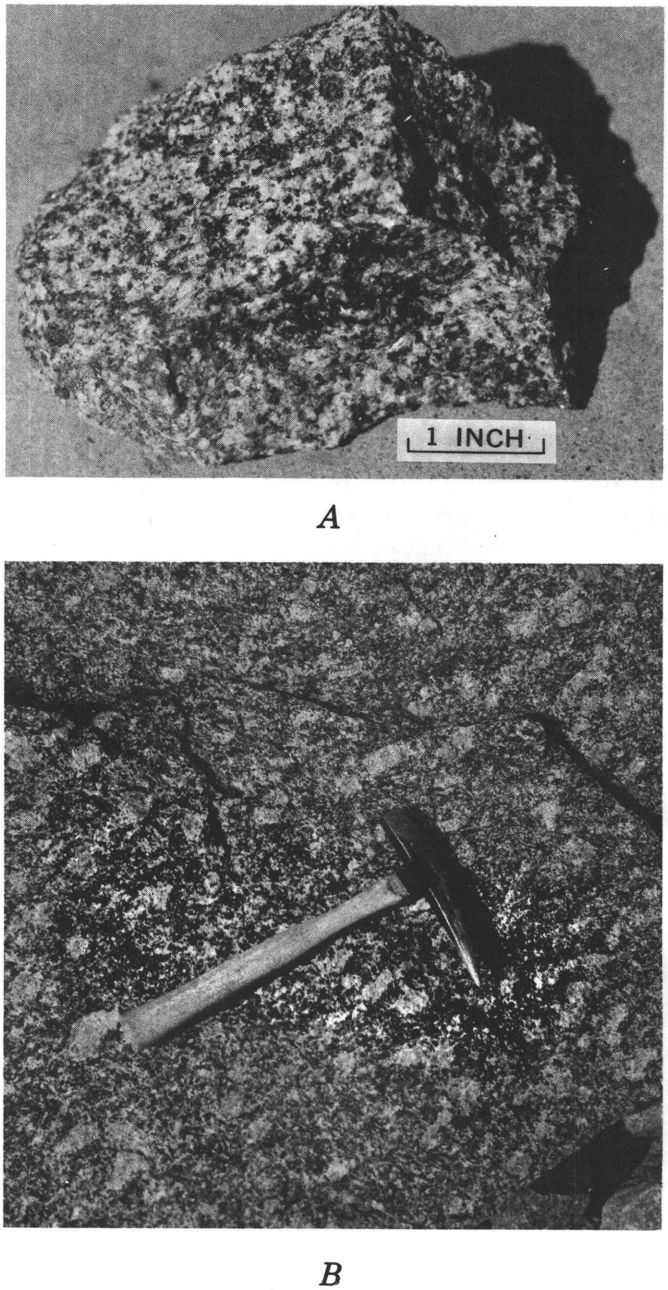


FIGURE 4.—Cross Creek Granite. *A*, Nonporphyritic granodiorite facies; *B*, porphyritic granodiorite facies.

PETROGRAPHY AND COMPOSITION

The predominant quartz monzonite facies of the Cross Creek Granite is composed of 35–50 percent oligoclase, 15–30 percent potassium feldspar, 20–30 percent quartz, 8–15 percent biotite, and minor amounts of accessory minerals. The oligoclase, quartz, and biotite are in fairly constant ratio to each other in the various facies of the rock, but the proportion of potassium feldspar to these other minerals ranges widely. With decrease in the potassium feldspar, the rock grades toward granodiorite, and with increase it grades toward true granite.

Detailed study of the many different facies of the Cross Creek Granite has not been attempted. In table 2, results of chemical and modal analyses of a sample judged to be representative of the most common variety of the quartz monzonite are presented along with similar data for quartz monzonite typical of the Boulder Creek Granite (or Granodiorite). Approximate modes as determined from polished slabs stained to identify the potassium feldspar are given in table 3, illustrating the variability of the rock even in single samples.

The Cross Creek Granite typically has a hypautomorphic-granular and seriate porphyritic texture. In general, the potassium feldspar crystals are the largest in the rock, although locally aggregates of quartz are larger. Exclusive of the potassium feldspar crystals, the grains have a maximum diameter of about 8 mm, and an average of about 2 mm. Most thin sections exhibit a rude gneissic structure due to weak preferred orientation of biotite and to some segregation of biotite in bands. In the more gneissic varieties, quartz and plagioclase grains are also elongated and crudely oriented.

The potassium feldspar grains generally are in the form of prisms partly or wholly bounded by crystal faces. The crystals vary widely in size, and as brought out by staining, they may range in a given slab of rock from 2 mm to 5 cm in maximum dimension. Almost all the potassium feldspar shows the grid twinning of microcline, and many of the larger crystals can be seen in hand specimen to be Carlsbad twins. The microcline is slightly to markedly perthitic, having a content of albite lamellae that ranges from only a percent or two to as much as 25 percent.

In many localities the potassium feldspar crystals show clear evidence of being younger than the other constituents of the rock. In outcrop, this is shown by the gradation of granite with abundant pink feldspar crystals into small pegmatite dikes and, in places by the orientation of the feldspar crystals athwart the gneissic structure in the rock. In thin section, the microcline shows evidence of having replaced other minerals, particularly plagioclase and biotite, and it commonly contains inclusions of these and other minerals, including quartz, apatite, sphene, magnetite-ilmenite, and minor untwinned potassium feldspar. In some samples the plagioclase and biotite inclusions are altered, although the microcline is fresh. In some samples also, the inclusions show cataclastic effects, such as bent and fractured twinning lamellae in plagioclase or crumpled biotite leaves, even though the enclosing microcline is not deformed. Thus, the microcline crystals are more in

TABLE 2. — *Chemical analyses, norms, and modes of Cross Creek Granite as compared with Boulder Creek Granite*

[Chemical analyses of Cross Creek Granite by M. Seerveld, U.S. Geological Survey. Data for Boulder Creek Granite from Sims and Gable (1967, p. E34) Leaders (. . .) indicate not detected]

	Cross Creek Granite[1]	Boulder Creek Granite[2]
Chemical analyses (in weight percent)		
SiO_2	69.46	64.37
Al_2O_3	15.14	15.86
Fe_2O_3	1.22	1.78
FeO	1.62	3.04
MgO	.88	1.69
CaO	2.02	2.37
Na_2O	3.24	3.09
K_2O	4.60	5.00
MnO	.04	.05
H_2O^+	.55	.52
H_2O^-	.04	.08
TiO_2	.39	.72
P_2O_5	.25	.32
CO_2	.03	.23
Cl	.02	.03
F	.07	.12
S	.00	.14
BaO	.15	.23
SrO	.08	. . .
Subtotal	99.80	99.64
Less O	.03	.13
Total	99.77	99.51
Bulk density	2.65	2.66
Powder density	2.69	2.73
Norms		
Quartz	29.10	19.44
Orthoclase	24.46	29.47
Albite	27.25	26.20
Anorthite	9.73	10.29
Hypersthene	2.92	6.34
Magnetite	1.86	2.55
Ilmenite	.76	1.37
Corundum	1.12	1.63
Apatite	.34	.66
Pyrite	. . .	.48
Fluorite	.07	.16
Calcite	. . .	.50
Modes (in volume percent)		
Quartz	27.1	18.3
Potassium feldspar	25.6	34.4
Plagioclase	36.6	32.9
Biotite	9.2	11.9
Muscovite	Trace	1.0
Magnetite-ilmenite	.4	.6
Apatite	.2	.4
Zircon	.1	.2
Calcite	. . .	.3
Composition of plagioclase	An_{26}	An_{27}

[1] Porphyritic quartz monzonite, top of cliffs at knob outlined by 10,800-ft contour on north shoulder of Mount of the Holy Cross, Holy Cross 15-minute quadrangle 1 mi (1.6 km) south of Minturn quadrangle line (See Tweto, 1974).

[2] Quartz monzonite, Mount Pisgah, Central City quadrangle in Front Range, from Sims and Gable (1967, p. E34).

the nature of porphyroblasts than of phenocrysts, as they seem to have grown in the rock after the other constituents had crystallized, and after the stress environment that produced foliation among the other constituents had changed or had disappeared. It is not known at this time, however, whether all the microcline in all the Cross Creek Granite is paragenetically late like this or whether this is a feature only of the batholithic border areas, which happen to be the ones most studied.

The normal plagioclase of the Cross Creek Granite is oligoclase, which ranges in composition from An_{22} to An_{28} in different specimens. In some samples that contain late microcline, the oligoclase grains have narrow, sharply defined outer rims that are more sodic and generally less altered than the main grains. The plagioclase of the rims is mostly oligoclase with a composition of An_{14} to An_{18}, but locally it is albite with a composition of An_6 to An_{10}. Locally, grain contacts between microcline and oligoclase are marked by patches of antiperthitic intergrowths of microcline in oligoclase.

Most quartz in the granite exhibits strong strain shadows and is somewhat fractured. Some quartz was evidently introduced with the microcline, however, as some grains of the strained and fractured quartz are surrounded by aggregates of finer grained, less deformed quartz. The fine-grained quartz also occurs in microscopic veinlets cutting early quartz and other minerals, including the late microcline.

Biotite of the granite is green brown where fresh, but in most localities it is altered and is green, or faded. It is accompanied by exsolved iron and titanium oxides.

Accessory minerals of the granite are magnetite, ilmenite, pyrite, apatite, sphene, and zircon. The pyrite is present only locally, and the apatite and sphene are irregularly distributed, being relatively abundant in some thin sections and absent in others. Muscovite is present in small amounts in most thin sections, occurring both as an alteration product of biotite and in association with late quartz veinlets.

All samples of the Cross Creek Granite studied show cataclastic effects in some degree, and some samples show at least two generations of cataclasis, one that preceded introduction of the large microcline crystals and one or more that followed. Evidence of the early cataclasis is shown by deformed inclusions of plagioclase, biotite, and apatite in undeformed microcline and by replacement relations of microcline against granulated aggregates of other minerals. Younger cataclasis is shown by mortar structure along the edges of the microcline crystals and, where deformation was severe, by jagged fracture zones zigzagging back and forth along cleavages in the microcline. Most of the alteration observed in inclusions in microcline seems to be associated with such fractures; hence it is interpreted to be younger than the microcline rather than older.

MIGMATITE

The migmatite map unit includes several varieties of rocks intermediate between granite or diorite and biotite gneiss. One common variety is of the classical type, consisting of alternating thin layers of dark biotite-rich gneiss and light-colored granitic or pegmatitic material (fig. 5). The layers in this rock are generally less than 1 in. (2.5 cm.) thick, but the granite or pegmatitic layers swell in places into knots or lenses several inches to a few feet thick. The gneiss layers are similar compositionally to biotite gneiss, consisting essentially of biotite, quartz, and plagioclase but locally containing microcline, sillimanite, or garnet. In some places, as in the outcrops near the mouth of Homestake Creek at the south edge of the quadrangle, milky blue cordierite is a prominent constituent of the gneissic layers. The granitic layers consist essentially of quartz, microcline, and plagioclase but generally contain prominent muscovite, also. They are typically richer in quartz and iron oxides than most granite. Banded migmatite occurs principally in the area west of the Eagle River between the mouth of Homestake Creek and Fall Creek and in the higher parts of the Gore Range.

Another variety of migmatite consists of biotite gneiss which has been partly granitized by introduction of feldspars in grains or crystals 0.2–0.8 in. (0.5–2 cm) long, forming a prominently speckled rock that superficially resembles a coarse granite but which consists in large part of biotite gneiss. The introduced, or newly crystallized, feldspars in such rock are generally complex perthitic and myrmekitic intergrowths of different feldspars and quartz. Migmatite of this type occurs in many small bodies in both the Sawatch and Gore Ranges, either bordering granitic rock or isolated from it.

FIGURE 5.—Migmatite in the Gore Range, showing typical mixture of biotite gneiss (dark) and granitic materials (light), and streaking and crenulation resulting from rock flowage.

Another variety of migmatite is intimately associated with, and grades into diorite. It consists of layers, laminae, and wisps of biotite gneiss separated by thin layers of diorite or embedded in larger bodies of diorite. Relations observed at the outcrop in many places suggest that the diorite in such occurrences formed in part by reaction with biotite gneiss (fig. 6) and that the migmatite of this occurrence is a mixture of modified gneiss with the diorite. Migmatite of this kind and associated diorite characterize the border of the Cross Creek batholith along Cross Creek at the quadrangle boundary and immediately southward, and it is also widespread along the border zones of banded migmatite bodies in the Gore Range.

TABLE 3. — *Approximate modes of Cross Creek Granite as measured on stained polished slabs 6–10 square inches in size*

[Determined by R. C. Pearson, U.S. Geological Survey]

Sample	1			2				3		
Slab	A	B	C	A	B	C	D	A	B	C
Quartz	30.2	26.3	29.4	29.7	25.6	25.8	30.0	29.6	23.9	26.1
Potassium feldspar	19.4	26.8	24.4	14.3	24.6	15.5	15.9	27.9	25.9	27.8
Plagioclase	39.1	37.7	36.4	41.0	37.3	42.6	40.6	34.0	38.2	36.6
Biotite	9.8	8.8	8.8	14.3	11.8	15.1	12.5	7.4	11.3	9.2
Accessory minerals	1.5	.4	1.0	.7	.7	1.0	1.0	1.1	.7	.3
Totals	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

SAMPLE DESCRIPTIONS AND LOCALITIES

1. Porphyritic quartz monzonite, cliffs on east side of canyon of the Eagle River at Gilman.
2. Porphyritic quartz monzonite, between 8,450- and 8,500-ft. contours in bottom of valley of Cross Creek, on southeast side of creek.
3. Porphyritic quartz monzonite, railroad cut on east side of canyon of the Eagle River, 2,100 ft (700 m) north of mouth of Rock Creek.

Still another variety of material mapped as migmatite is coarsely interlayered igneous rock, such as granite, quartz monzonite, granodiorite, or diorite, and biotite gneiss or banded migmatite. In such material, comparatively pure and presumably intrusive igneous rock in generally concordant layers a few inches to many feet thick alternates with biotite gneiss or banded migmatite in layers of similar thickness. Material of this kind is widespread in the Gore Range. Where the gneiss fraction predominates, it was mapped as migmatite, and where the igneous fraction predominates, it was mapped as granite or diorite. Thus, much of the rock mapped as Cross Creek Granite in this range differs only in degree from the migmatite unit.

Finally, breccias of gneiss fragments in a granite matrix in the Gore Range were mapped as migmatite where the fragments predomiminate, and as granite where the matrix predominates.

DIORITE

Several varieties of diorite occur in close association with the Cross Creek Granite, but they have not been studied in detail. Most of the varieties are older than the Cross Creek, as they are cut by the granite or by pegmatites related to it, or occur as inclusions in the granite, or have been partly granitized by the granite. Some varieties seem to have crystallized at the same time as the granite, however, and at least one variety is younger than the granite. As a group, the diorites are thought to be closely related to the Cross Creek batholith in age and origin. The diorites occur in countless small bodies as well as in the scattered larger ones indicated on the map (pl. 1). Most of these bodies are concordant, paralleling the foliation in bordering gneiss or granite, but crosscutting bodies of diorite are also found. Many diorite bodies are laced by dikes of diorite pegmatite consisting of andesine, quartz, and biotite.

The most abundant variety of diorite is dark gray, medium-grained, slightly gneissic, biotite-quartz diorite. Locally, this rock contains minor hornblende. Biotite-quartz diorite is closely associated with migmatite, especially near granite contacts, and as noted above, part of it formed by recrystallization of biotite gneiss (fig. 6). The bulk of the diorite, however, is believed to be magmatic and intrusive in origin. The diorite typically consists of 30–45 percent plagioclase, which is andesine, An_{32-44}, 20–33 percent biotite, 15–30 percent quartz, and 2–5 percent magnetite-ilmenite and other accessory minerals. Where partly granitized, the diorite contains a few percent of potassium feldspar, and more quartz, less biotite, and a slightly more sodic plagioclase than the normal rock. Where the adjoining rocks include amphibolite, the diorite generally contains hornblende, and where they include

FIGURE 6.—Gneissic diorite showing structure inherited from original migmatite. It occurs in upper Piney River area, Gore Range.

calc-silicate rock, it contains as much as several percent of epidote. Where cut by granite pegmatites, the diorite is commonly recrystallized to a form rich in coarse biotite.

Various gneissic diorites and diorite gneisses are similar in composition and occurrence to the diorite just described. They are believed to be fundamentally the same rock but were subjected to a magmatic or tectonic movement environment that induced a gneissic structure.

Hornblende and hornblende-biotite diorites occur principally in dikes or small pluglike bodies, although some are of the same occurrence as the biotite-quartz diorites just described. Most of the hornblendic diorites thus appear to be younger than the biotite-quartz diorites, but only rarely are they seen to cut Cross Creek Granite. Most of the hornblendic diorites lack foliation, though a few are markedly gneissic. The plagioclase of the hornblendic diorites is as calcic as labradorite (An_{55}), and quartz is only a minor constituent or is absent.

On the whole, the suite of diorites accompanying the Cross Creek Granite is similar to—although more abundant than — the suite accompanying the Boulder Creek Granite of the Front Range (Lovering and Tweto, 1953; Harrison and Wells, 1959; Sims and Gable, 1967).

INFERRED HISTORY

From field relations and petrography, development of the Cross Creek Granite batholith is inferred to have begun with the intrusion of small bodies of diorite and the migmatization of preexisting biotite gneiss in advance of the rising batholith of granitic rocks. The early diorite reacted extensively with the biotite gneiss, transforming some of the gneiss into diorite and diorite migmatite. Concurrently, other biotite gneiss was migmatized and was riddled by early pegmatites in advance of the main batholith. The batholith was emplaced as magma of a composition ranging from granodiorite to calcic quartz monzonite. Emplacement occurred under conditions that promoted extensive reaction between magma and wallrocks, causing extensive assimilation and granitization of gneiss as well as the formation of granite-gneiss mixtures, here classed as migmatite, along with the earlier or banded migmatite. The biotite gneiss and migmatite wallrocks were plastic in this environment, and they were deformed by and along with the granite of the invading and moving batholith, resulting in parallel foliations and generally concordant contacts. Minor diorite and abundant pegmatite developed within the batholith and its border zones, both during and following batholith emplacement.

Movement of the batholith, or parts of it, continued as crystallization proceeded, resulting in local deformation of early minerals. Finally, potassium essential to the formation of microcline, and accompanying sodium and silicon were introduced into the essentially consolidated rocks from deeper levels in the batholith. Microcline crystals of porphyroblastic habit, sodic rims of oligoclase, and late quartz veinlets and rims formed as a result, transforming much of the primary granodiorite and calcic quartz monzonite to a more alkalic quartz monzonite or, locally, to true granite.

Petrographic relations would allow an interpretation that the microcline is a product of some geologic event later than the emplacement and crystallization of the Cross Creek batholith and that the rocks of the batholith were deformed and even altered in the interim. Field relations and isotopic dating indicate, however, that the microcline is related to the crystallization history of the batholith and that the present microcline-bearing rock is a product of a single continuous process rather than of two processes separated by a geologically appreciable time interval. The microcline is restricted to the granitic rocks of the batholith or to metasedimentary rocks immediately bordering granite, and hence it is most likely related to the batholith in origin. If it were related to some other geologic event, such as the intrusion of a younger granite at depth, then it would not be likely to be so exactly coincident in occurence with the batholith but would extend either less or more widely. Similarly, if the microcline were significantly younger than the rest of the rock, then microcline-bearing facies should yield younger isotopic ages than other facies, but as discussed in the following section, the greatest ages obtained thus far are on the porphyritic, microcline-bearing facies.

AGE AND CORRELATION

As indicated previously, the Cross Creek Granite resembles the Boulder Creek Granite (or Granodiorite) of the Front Range both in composition and occurrence. Both granite units range in composition from granodiorite to true granite, are characteristically gneissic, are generally concordant and syntectonic, have gradational contacts resulting from reaction with their gneissic wallrocks, and are accompanied by diorites that range in age from pregranite to postgranite. These characteristics are those of the oldest (Precambrain X) of three general age groups of granites recognized in Colorado (Tweto, 1964; Hutchinson and Hedge, 1967). The Cross Creek Granite is accordingly classed on geologic grounds as a member of the old group and as an approximate—if not exact—correlative of the Boulder Creek Granite.

Isotopic dating corroborates the geologic correlation. Age of the Boulder Creek Granite is established as 1.70 b.y. (Peterman and others, 1968) or 1.71 b.y. (Hutchinson and Hedge, 1967). Age of the Cross Creek Granite, on the basis of a recently determined six-point rubidium-strontium isochron, is firmly established as 1.71 b.y. (C. E. Hedge, written commun., 1974). The samples used to establish this isochron came from the Cross Creek and Grouse Creek drainages just west of the Minturn quadrangle. Some samples from Cross Creek valley within the Minturn quadrangle and from the Gore Range in the Dillon quadrangle, analyzed earlier by Hedge (written commun., 1968) also yielded ages of about 1.7 b.y. Other samples, however, gave younger ages, as did samples dated by the potassium-argon method (Pearson and others, 1966, p. 1115). The younger ages probably reflect heating and consequent migration of elements in local areas during the second episode of granitic intrusion in Colorado, 1.35–1.45 b.y. ago. Granites of this age, which include the Silver

Plume Granite of the Front Range, the St. Kevin Granite of the Sawatch Range, and many others, have not been observed in the Minturn quadrangle but occur as podiform dikes in Cross Creek Granite just east of the quadrangle, south of Gore Creek.

CAMBRIAN SYSTEM

Rocks of Cambrian age in the Minturn quadrangle and surrounding region are assigned to two formations, the Sawatch Quartzite and the Peerless Formation, both of Late Cambrian age. The Sawatch Quartzite rests with profound unconformity upon a virtually planar surface cut over Precambrian rocks of various kinds. The contact between the quartzite and the predominantly dolomitic rocks of the Peerless Formation is gradational in most places but locally is sharply defined. Both units were included in the Sawatch Quartzite as originally defined by Eldridge (1894) in the Crested Butte area, on the western side of the Sawatch Range. In the Leadville area, where these strata were earlier known as "Lower Quartzite" or "Cambrian quartzite," the part nowadays comprising the Peerless was commonly distinguished as "transition shale" or "Red-cast beds" (Emmons, 1886, p. 58–60). These informal terms were supplanted in 1932 when Behre (1932) assigned the reddish dolomitic strata to the Peerless Shale Member of the Sawatch Quartzite. Because the term "shale" is a misnomer as applied to the Peerless in most places and because the unit is readily mappable over a wide area, it has been classed as the Peerless Formation since 1947 (Singewald, 1947).

SAWATCH QUARTZITE

The Sawatch Quartzite consists of about 200 ft (60 m) of nearly uniform medium- to thick-bedded light-colored quartzite. The quartzite is perhaps the most resistant rock in the quadrangle, and it generally forms cliffs or ledges wherever exposed. On the dip slopes, however, it breaks down to sharply angular fragments or blocks and is poorly exposed. The quartzite is well displayed in the walls of Eagle Canyon where it forms nearly vertical cliffs rising abruptly above somewhat gentler cliffy slopes of Precambrian rocks (fig. 3). It is exposed also in the walls of canyons southwest of the Eagle River, though it is partly buried by talus along most of these canyons. It is not seen northeast of the canyon of the Eagle River, except in a few narrow fault slices along the Gore fault, the largest of which is on the southern spur of Bald Mountain, west of Booth Creek (fig. 25).

The surface of Precambrian rocks on which the quartzite rests seems to be planar wherever exposed in the Minturn quadrangle (fig. 7), but only a mile or two south of the quadrangle, in the area of the Homestake shear zone, the surface has a relief of as much as 50 ft (15 m) (Tweto, 1949, p. 160; Tweto and Sims, 1963, p. 1008). In most places the Precambrian rocks beneath the quartzite are weathered and are soft and crumbly to depths of a few inches to a few feet, but in some places they are fresh. Where bedding-plane movement has occurred at the base of the quartzite, the soft, altered Precambrian rock is deformed into ridges or mounds as much as 5 ft (1.5 m) high, giving a deceptive appearance of relief in the depositional surface.

Basal beds of the Sawatch Quartzite are generally somewhat coarser grained than the remainder of the quartzite, and locally they contain lenses of quartz granule conglomerate a few inches thick. The granules in such conglomerate are typically 1/8–1/4 in. (3–6 mm) in diameter and are well rounded; they consist of quartz of various colors, white predominating. In most places the basal 10–30 ft (3–9 m) of the quartzite is gray, pink, or light tan, but in some places this part is white like the remainder of the formation.

The main body of the Sawatch is predominantly vitreous white quartzite made up of well-sorted rounded and subrounded medium-sand quartz grains. Along the canyon of the Eagle River, the zone between 75 and 160 feet (23 and 48 m) above the base of the quartzite contains scattered lenses of brown-weathering dolomitic sandstone or sandy dolomite. This feature was not noted elsewhere in the quadrangle or adjoining areas,

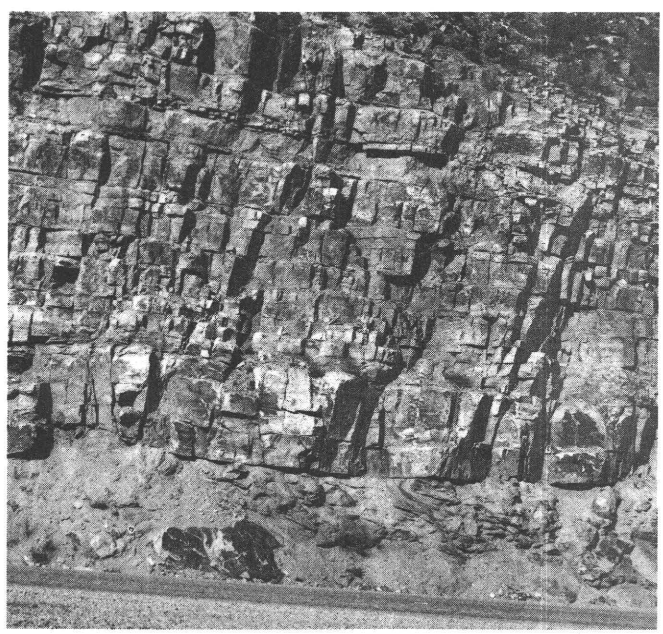


FIGURE 7.—Sawatch Quartzite (bedded rock) resting upon nearly planar surface cut over Precambrian rocks (at base of photograph). Roadcut on U.S. Highway 24, 600 ft (180 m) northwest of high bridge near Red Cliff.

though it exists also in Glenwood Canyon, 40 mi (65 km) to the west (Bass and Northrop, 1963, p. J4–J7). A few green shaly partings occur on bedding planes in the quartzite sequence, and, near Gilman, a shaly sandstone bed 4–6 ft (1.2–2.0 m) thick about 70 ft (21 m) above the base of the quartzite serves as a useful stratigraphic marker. The upper 30–40 ft (9–12 m) of the quartzite is very vitreous and brittle and has a crackled appearance in outcrop. This quartzite is white in the Eagle Canyon area, but more commonly in the region it is pink, particularly in the uppermost part. In the Gilman area, the upper vitreous quartzite contains brecciated and mineralized beds that are known locally as the Rocky Point zone. One or more of these beds, each 1– 4 ft (0.3–1.2 m) thick may be present in any part of the upper vitreous quartzite, but in most places they are in the upper middle part, 10–20 ft (3–6 m) below the top of the Sawatch Quartzite. The quartzite of the Rocky Point zone is stained yellow by the oxidation products of pyrite and forms a conspicuous color band near the top of the quartzite cliffs.

As seen in thin sections, quartzite of the Sawatch is somewhat variable; the sand grains in most beds are well sorted and rounded, but in some beds they are poorly sorted and are subrounded to subangular. The grains range from 0.2 to 1.3 mm in diameter, though in most of the rock they are 0.25–0.5 mm. In some samples, the sand grains are in a matrix of very small (0.05 mm) angular quartz fragments that resemble a microbreccia. Many of the larger quartz grains contain inclusions of tourmaline, sillimanite, or rutile, and they commonly show strain shadows and lines of fluid inclusions. Accessory detrital minerals are not abundant but include muscovite, biotite, chert, potassium feldspar, sphene, green tourmaline, and zircon. The tourmaline is especially consistent and is seen in all sections of the quartzites. Feldspar is present only in the uppermost quartzite beds, and it is abundant in sandstone of the overlying Peerless Formation. The feldspar grains generally are fresh and most of them are microcline, though some untwinned potassium feldspar is present also.

The Sawatch Quartzite is 190–220 ft (58–67 m) thick in the canyon area of the Eagle River, and it has a similar thickness of about 200 ft (60 m) at the northern end of the Sawatch Range to the west, at the 12,000-ft contour west of the head of West Grouse Creek. The quartzite thins to the northeast and to the south of the canyon area. In the fault slice on Bald Mountain, it consists of about 100 ft (30 m) of white quartzite and relatively coarse quartzite conglomerate lying on Precambrian rocks and overlain by red hematitic mudstone of the Peerless Formation. Near Pando, 5 mi (8 km) south of Red Cliff, the quartzite thins to about 120 ft (37 m) upon crossing the Homestake shear zone and then thins gradually southward to about 100 ft (30 m) in the Leadville area (Tweto and Sims, 1963, p. 1008).

The character of the Sawatch Quartzite is shown in the following stratigraphic section which was measured as a standard of reference for studies in the mine workings.

Section of the Sawatch Quartzite

[Measured along railroad at north end of canyon of the Eagle River, beginning 2,550 ft (778 m) south of highway overpass. See fig. 8]

	Thickness (feet)	*Distance above base (feet)*
Sawatch Quartzite:		
Top of formation		220.3
33. Quartzite, white, vitreous, medium-bedded	11.7	208.6
32. Sandy quartzite, white to gray, medium- to thin-bedded, fine-grained, locally slightly glauconitic; weathers conspicuous ocherous brown. Rocky Point zone of Gilman mines	3.0	205.6
31. Quartzite, white, fine-grained, vitreous, medium-bedded	10.5	195.1
30. Dolomite, tan, medium-grained to coarsely crystalline, rough weathering	1.0	194.1
29. Quartzite, white with some pink bands, medium- to fine-grained, vitreous, locally slightly dolomitic; becomes dolomitic and red toward base. Wavy contact with unit below	12.0	182.1
28. Dolomitic shale, orange-red with purple blotches, finely sandy and micaceous, thin- to medium-bedded. Wavy contact with unit below	1.0	181.1
27. Quartzite, light-gray, medium-grained, massive; is dolomitic and pink near base and grades on strike into dolomite	4.7	176.4
26. Quartzite, medium-bedded	2.0	174.4
25. Dolomite, tan-pink	.9	173.5
24. Quartzite, white, vitreous, medium- to thick-bedded	4.0	169.5
23. Dolomitic sandstone and quartzite in thin beds; crossbedding weathers in relief. Dolomitic sandstone is buff to pink; quartzite is white	4.0	165.5
22. Shale and dolomite in alternating thin beds, purplish-pink; forms shelf along cliff	2.5	163.0
21. Quartzite and dolomitic sandstone, gray and pink, thin-bedded	2.0	161.0
20. Quartzitic sandstone, white, medium-grained, sugary, massive	7.8	153.2
19. Quartzitic sandstone, white, medium-grained, sugary, and interbedded brown, medium-grained, soft sandy dolomite	12.0	141.2
18. Quartzite sandstone, white, medium-grained, sugary, massive	6.0	135.2

Section of the Sawatch Quartzite — Continued

	Thickness (feet)	Distance above base (feet)
Sawatch Quartzite — Continued		
17. Quartzite, white, vitreous, fine- to medium-grained, massive; contains interbedded brown, coarse, soft, sandy dolomite in short lenses 2 in. to 3 ft thick which become less abundant downward. Quartzite beds are 1–5 ft thick; quartzite is argillaceous near base of unit, and at 18 ft above base, contains 7-in. shaly bed	62.1	73.1
16. Limy and shaly sandstone, thin- and irregular-bedded; weathers dark chocolate brown; contains thin micaceous laminae with numerous dark-brown fossil fragments in some laminae. Micaceous at base. White alum efflorescence on outcrop. Unit is bounded above and below by bedding-plane slips	6.0	67.1
15. Sandstone, light-gray, medium-grained; mottled with dark shell fragments of inarticulate brachiopods; is thin bedded and irregular bedded	1.6	65.5
14. Quartzite, light-tan, vitreous, medium-bedded. Weathered surface is marked by thin horizontal pits 1/8–1/4 in. long	1.5	64.0
13. Quartzitic sandstone, light-tan-gray, knobby-weathered. Contains abundant small brachiopods (*Dicellomus* sp.) and shell fragments on weathered surface	1.8	62.2
12. Quartzite, light-gray to light-tan, vitreous, medium- to fine-grained, thin- to medium-bedded. Beds separated by thin micaceous partings with knobby or lenticular structure. At base of unit is 6-in. bed of coarse-grained, light-gray, quartzitic sandstone with abundant fossil fragments, chiefly brachiopods	6.0	56.2
11. Sandy quartzite, light-gray, fine-grained, massive	3.3	52.9
10. Shaly sandstone, light-bluish-gray, very thin bedded, finely micaceous; slightly pink on weathered surfaces	.6	52.3
9. Quartzite, white, medium- to fine-grained, gritty	1.0	51.3
8. Covered	1.0	50.3
7. Quartzite, white, medium- to coarse-grained, massive- to medium-bedded; clay speckled (arkosic?); weathers mottled tan. Thin lens of fine conglomerate with thin shaly layer above it at 7 in. from top	15.5	34.8
6. Sandstone, gray-white, finely conglomeratic, quartzitic	2.3	32.5
5. Quartzite, white, massive; lower 3 in. strongly sheared; bedding-plane slips above and below unit	2.0	30.5

Section of the Sawatch Quartzive — Continued

	Thickness (feet)	Distance above base (feet)
Sawatch Quartzite — Continued		
4. Quartzite, white, vitreous, massive, medium-grained. 4-in. shaly zone at base of interval; strong shear slip 5 ft above base	6.0	24.5
3. Quartzite, white, gritty, coarse-grained; has thin sandy partings	7.5	17.0
2. Sandy quartzite, white to pink, medium- to coarse-grained, massive; weathers with vertical tubular holes from 1/2 to 2 1/2 in. long	1.0	16.0
1. Conglomeratic and quartzitic sandstone, light-gray, coarse-grained, medium- to thin-bedded. Wavy basal contact	16.0	0
Total measured thickness of Sawatch Quartzite	220.3	
Precambrian granite:		
Top 6 in. to 3 ft is soft, altered, and sheared.		

As indicated in the preceding stratigraphic section, fossil fragments are abundant in certain beds in the lower half of the Sawatch Quartzite, but fossils that are complete enough to identify are rare. The only fossils identified from the Sawatch Quartzite in the Minturn quadrangle are tiny inarticulate brachiopods assigned to the upper Cambrian genus *Dicellomus* by Dr. W. C. Bell of the University of Texas (oral commun., 1941). These fossils are from unit 13 of the preceding stratigraphic section. Better preserved and more abundant brachiopods from about the same level in the Sawatch in the Pando area, a few miles south of Red Cliff, also were identified by Bell as *Dicellomus* sp. (Tweto, 1949, p. 159). Later, as quoted by Berg and Ross (1959, p. 107), Bell reported brachiopods in the Sawatch (presumably in the collections discussed here) to be "*Dicellomus* of the *pectenoides* and *nanus* types, both 'lower' Dresbachian." These determinations by Bell represent almost the only reliable information on fossils from the Sawatch. Trilobites are mentioned in the early literature, but they seem to have come mainly from the strata now assigned to the Peerless Formation (Johnson, 1934, p. 20). Trilobite fragments can be distinguished among the fossil fragments in the quartzite of the Gilman and Pando areas, but most of the fragments are of brachiopods.

The quartz sand that later became the Sawatch Quartzite has been widely recognized to have been formed as the Late Cambrian sea gradually transgressed over a surface of very low relief cut in the Precambrian rocks. The rocks at this surface were weathered, and the quartz residue from them was an abundant source of quartz sand. This sand probably was in part derived by direct wave action on the

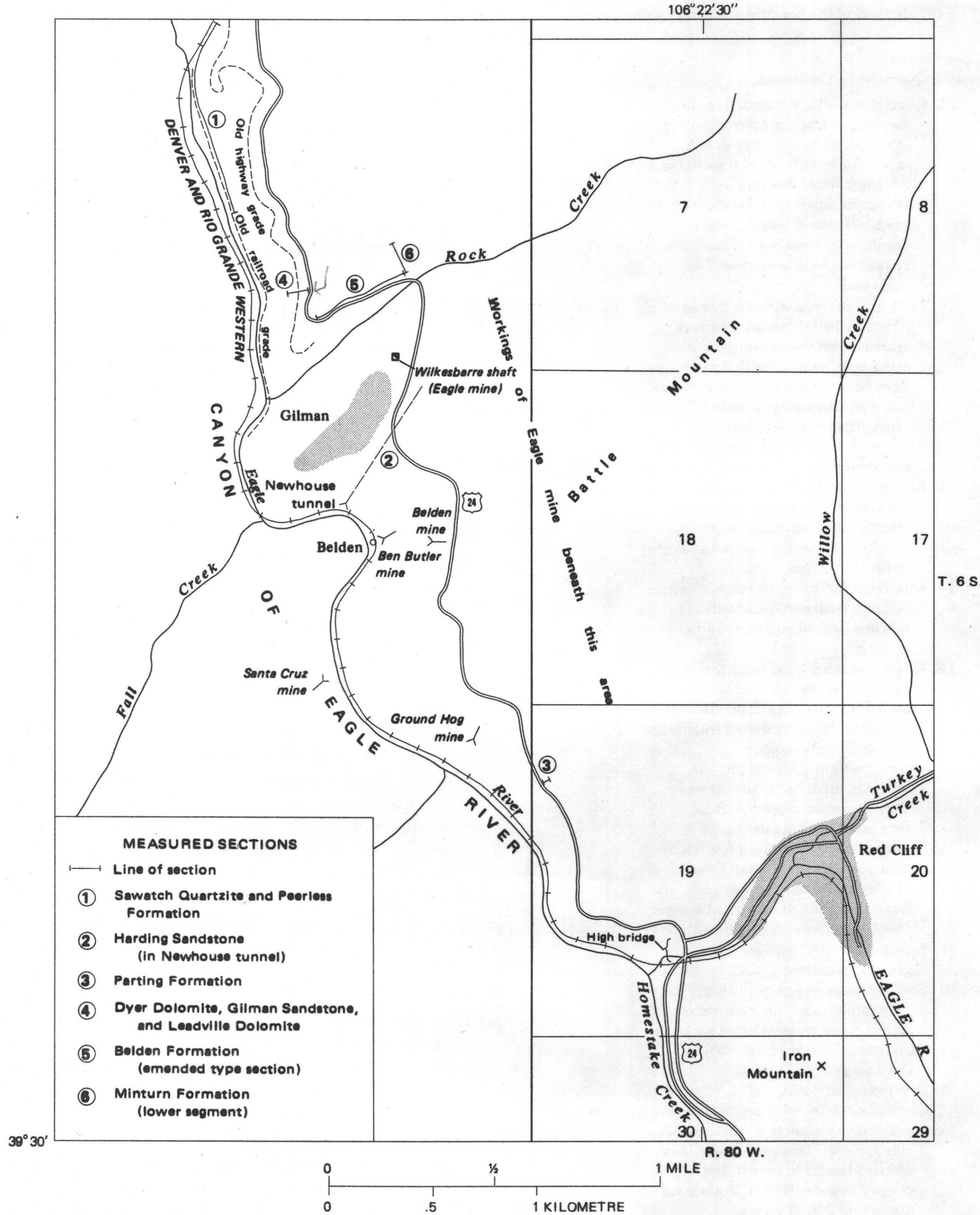


FIGURE 8.—Gilman area and canyon of the Eagle River showing locations of mines referred to and measured sections.

weathered rocks and was in part brought to the sea by streams from land that lay to the east, as regional relations indicate that the transgression was generally eastward (Lochman-Balk, 1956, p. 565–574), and paleocurrent data indicate westward transport of the sand on the sea bottom (Seeland, 1968). The occurrence of fresh detrital microcline and biotite in the uppermost beds of the Sawatch indicates that by that time streams somewhere had removed the weathered mantle and were eroding fresh Precambrian rock. Whether this fresh rock was later covered by Sawatch sediments or remained an island is not known, because the Sawatch has been removed by erosion from so much area since its deposition. However, the rapid thinning of the Sawatch between the Eagle River and Bald Mountain and the relatively coarse conglomerate in the Sawatch at Bald Mountain suggest that land, or an island, may have lain somewhere in the vicinity of the present Gore Range.

PEERLESS FORMATION

The Peerless Formation consists of 65–70 ft (20–21 m) of highly varied but predominantly dolomitic rocks. In most places the lower 20–30 ft (6–9 m) of the Peerless is a sandy dolomite or dolomitic sandstone which commonly is glauconitic and locally is ferruginous or chloritic. This dolomite or sandstone has a slabby appearance in outcrop even though individual beds are as much as 3 ft (1 m) thick, and it weathers dark brown to dark maroon; thus, it contrasts markedly with the underlying white quartzite of the Sawatch. Thin beds of white or pink quartzite in the lower 5–10 ft (1.5–3 m) of the dolomite or sandstone make the contact with the Sawatch a gradational one in many places.

Abundant iron-bearing material characterizes the lower part of the Peerless. The sandstones locally contain red earthy hematite, either in thin beds or as a matrix of the clastic grains. Some of the hematite appears oolitic, but generally the "oolites" are quartz grains heavily coated with hematite. In places the sandstones contain lenses that are as much as 50 percent glauconite, and in other places they contain abundant bright-green iron-rich chlorite, which petrographically appears to be authigenic rather than detrital. Dolomite beds of all the Peerless, but especially of the lower part, commonly contain thin limonitic laminae generally accompanied by sand grains or argillaceous matter, that weather in relief, giving the rock a wavy laminated appearance. Locally, minute limonitic veinlets form a reticulate network in the dolomite. Bright-red hematitic mudstone is also common in the Peerless; near the Gore fault on Bald Mountain, the Peerless is 20 ft (6 m) thick and consists entirely of the red mudstone.

The middle part of the Peerless consists of tan, buff, maroon, and pale-green thin-bedded sandy dolomite, dolomitic shale, dolomite, mudstone, and minor micaceous shale. This unit is soft and nonresistant, and it generally weathers to covered slopes. The upper part of the formation is somewhat thicker bedded than the middle part, and it is also more purely dolomitic, though it, like all the Peerless, differs in lithology from place to place. On the dip slopes west of Gilman and along Cross Creek, the upper 40 ft (12 m) of the Peerless is pure dolomite which is thin bedded, buff, and coarsely crystalline.

The dolomitic rocks of the Peerless are characterized by color mottling and by great variety in sedimentary structures. Bedding planes are wavy, and many are coated with mud or mica or are spotted with mud lumps. Fucoidal markings and worm trails are common on the bedding planes. Ripple marks are conspicuous, and many thin beds have mud cracks filled with material that contrasts in color or composition with the rest of the rock. Many thin beds of the dolomite are flat-pebble or edgewise conglomerate that consists of slightly abraded pebbles of maroon or purple dolomite in a buff crystalline dolomite matrix. Chips of maroon clay, mudstone, or micaceous shale are also scattered through some of the conglomerates. Other beds are mottled buff and purple, but pebbles cannot be distinguished in them. Some such beds also have various unidentified small curly color markings, as well as concentric structures that may be either concretionary or algal, or both. Many of the markings of various kinds are maroon, as are some beds of the dolomite, and hence the term "Red-cast beds" was once applied to these rocks. As a unit, however, the part of the Peerless above the dark lower beds is mainly buff, though it is splotched or is streaked maroon and pale green in places.

As seen in thin section, the sandy dolomites and dolomitic sandstones of the Peerless consist largely of dolomite, quartz, and feldspars in various proportions, though glauconite and chlorite are also abundant constituents of some samples. The feldspar grains include both microcline and sodic plagioclase, which generally are fresh or only slightly altered. Chlorite, in small irregular flakes and sparse larger, rounded flakes, is most abundant in the arkosic varieties of the rocks. Glauconite is in rounded grains that are among the coarsest in the rocks. Common accessory minerals are muscovite, zircon, and tourmaline; hematite or limonite coats many of the clastic grains. The quartz and feldspar grains are subrounded to subangular and well-sorted. They range in maximum size from 0.2 mm in some beds to 0.5 mm in others. In some of the dolomitic sandstones the dolomite is concentrated in discrete microlenses or pockets in an otherwise quartzitic rock, whereas in other sandstones the dolomite is a matrix or cement for the clastic grains. In the sandy dolomite, the clastic grains are less well sorted than in the sandstones, and they are scattered unevenly through the dolomite.

Character of the Peerless in the vicinity of Gilman is shown by the following stratigraphic section. As may be seen by comparison with sections measured 1.6 and 2.0 mi (2.6 and 3.2 km) south of Red Cliff (Tweto, 1949, p. 164–165), the Peerless differs markedly from place to place.

Section of the Peerless Formation

[Measured southward along railroad at north end of canyon of the Eagle River, beginning 1,800 ft (550 m) south of highway overpass. See fig. 8]

	Thickness (feet)	*Distance above base (feet)*
Harding Sandstone:		
Sandy quartzite and arkosic sandstone, white, medium- to fine-grained, massive, slightly crossbedded.		
Peerless Formation:		
Top of formation		66.5
15. Flat-pebble dolomite conglomerate, purplish-pink to buff, medium- and thin-bedded; weathers light chocolate brown; contains partings of purple conglomeratic shale	2.0	64.5
14. Flat-pebble dolomite conglomerate, mottled purplish-pink and light-green, thin-bedded; contains partings of fissile greenish-gray to greenish-buff micaceous dolomitic shale	6.0	58.5
13. Shaly dolomite, mottled green and gray-buff, thin-bedded; weathers with fine siliceous ridges on weathered surface	1.5	57.0
12. Dolomitic shale, greenish-gray to buff-gray, thin-bedded	1.0	56.0
11. Flat-pebble dolomite conglomerate, light-buff, thin-bedded; grades downward into green and purple-pink fissile, sandy shale	1.2	54.8
10. Covered	5.0	49.8
9. Flat-pebble dolomite conglomerate, mottled purple and tan, medium-bedded, buff-weathering	1.5	48.3
8. Shale, fissile, greenish-gray, fine-grained	1.5	46.8
7. Dolomite, mottled light-tan and green, medium- to thin-bedded, green-buff weathering	1.5	45.3
6. Dolomitic shale, light-tan, thin-bedded	1.0	44.3
5. Flat-pebble dolomite conglomerate, light-tan with local purple mottling; contains shale fragments and some laminae of green shale	1.0	43.3

Section of the Peerless Formation — Continued

	Thickness (feet)	*Distance above base (feet)*
Peerless Formation — Continued		
4. Dolomite, greenish- to light-tan, fine-grained, massive, somewhat argillaceous; weathered surfaces are brown and threaded with thin limonitic argillaceous ridges; 4-in. glauconitic shale bed in middle and 2-in. bed at base	3.3	40.0
3. Sandy dolomite, light-gray, coarsely crystalline, medium-bedded; has coarse green glauconitic grains and coarse quartz sand. Weathers tan, with quartz grains and argillaceous ridges in relief, giving rough surface. Contains purple and green shaly fragments in a few thin seams, and near top, a seam of purple, micaceous shale	31.0	9.0
2. Sandy dolomite, pink, massive, brown-weathering, medium-crystalline; has thin coarsely crystalline bands. Weathers rough, with coarse crystals and sand in relief. Grades downward into pink dolomitic crossbedded sandstone	5.0	4.0
1. Sandstone, white, fine-grained, chalky-looking; has thin beds of pink sandy dolomite at top; medium bedded and crossbedded; weathers brown. Conformable contact with underlying quartzite	4.0	0
Total measured thickness of the Peerless Formation	66.5	
Sawatch Quartzite:		
Vitreous white quartzite.		

Fossils found sparingly in the Peerless Formation at various localities in central Colorado establish the formation as middle Late Cambrian (Franconian Stage) in age. We found no fossils within the quadrangle, but Crawford and Gibson (1925, p. 35) reported the Upper Cambrian trilobite *Saukia pepinensis* and Resser (1942, p. 66) reported the trilobites *Ellipsocephaloides butleri* and *Briscoia* in material from "near Gilman" acquired by C. D. Walcott prior to the mid-1920's. The trilobites reported by Resser are indicative of the Franconian Stage, as are others (*Ptychaspis, Idahoia*) reported by Berg and Ross (1959) from the Manitou Park area near Colorado Springs. A trilobite from a bed 44 ft (13 m) above the base of the Peerless in the Holy Cross quadrangle, 1.6 mi (2.6 km) south of Red Cliff was identified by Josiah Bridge of the U.S. Geological Survey (written commun., 1950) as *Pterocephalia* cf. *P. sanctisabae* Roemer? and as "characteristic of the *Elvinia-Camaraspis* zone of the Franconian Stage." Brachiopods from the same locality were identified by W. C. Bell (reported in the Bridge communication) as *Obolus* *maeschae* Lochman, "characteristic of the *Cedaria* and *Crepicephalus* zones of the early Late Cambrian (Dresbachian stage)." Later, however, brachiopods from this same collection were reported by Berg and Ross (1959, p. 107) to have been tentatively identified by Bell as *"Dicellomus?* cf. *mosaica* of the *Conaspis* zone or an unnamed species from the *Cedaria* zone." (The *Conaspis* zone is in the Franconian Stage, above the *Elvinia-Camaraspis* zone and below the Briscoia zone).

These data on the age of the Peerless are significant in the evaluation of the unconformity at the top of the Peerless. In the Gilman area, the Peerless is overlain unconformably by the Middle Ordovician Harding Sandstone, and on Bald Mountain and locally in the Pando area (Tweto, 1949, p. 163) it is overlain by the Upper Devonian Parting Formation. In most of the Sawatch Range region, however, it is overlain by the Lower Ordovician Manitou Dolomite (Johnson, 1944). At Glenwood Canyon, 40 mi (64 km) west of Minturn, additional Cambrian strata intervene between the Peerless and the Manitou. Bass and Northrop (1953; 1963) divided the strata of Cambrian age at Glenwood Canyon into two formations, the Sawatch Quartzite, 517 ft (158 m) thick, and the predominantly dolomitic Dotsero Formation, about 100 ft (30 m) thick. Although a well-defined unit with lithology characteristic of the Peerless is present in the area (observation by Tweto), Bass and Northrop did not distinguish it as Peerless because it is overlain by about 150 ft (45 m) of quartzites typical of the Sawatch. They, therefore, placed these quartzites and the 69 ft (21 m) of underlying Peerless equivalent (unit 10 of Sawatch Quartzite stratigraphic section; Bass and Northrop, 1963, p. 6) in the Sawatch Quartzite, which accounts for the relatively great thickness of 517 ft (158 m) reported for this unit, as contrasted with the 220 ft (67 m) at Gilman. The carbonate rocks containing Upper Cambrian fossils above the quartzite were assigned by Bass and Northrop (1953) to the Dotsero Formation as redefined from the original usage of Bassett (1939).

Since the redefinition of the Dotsero, it has been a common practice to correlate the Dotsero and Peerless (for example, Berg, 1960; Stevens, 1961), but this is in error as indicated not only by the presence of a unit with typical Peerless lithology and thickness within the Sawatch as applied by Bass and Northrop, but also paleontologically. The Dotsero is characterized by fossils of late Late Cambrian age (Trempealeauan Stage) as determined by A. R. Palmer (Bass and Northrop, 1953, p. 896), whereas the Peerless is older, of the Franconian—and possibly even Dresbachian—Stage, as discussed above. This difference in age and the presence of 250 ft (75 m) of Cambrian strata between the Peerless equivalent and the Manitou in Glenwood Canyon strongly suggest that in areas where the Manitou lies on the Peerless some Cambrian strata were removed by erosion before deposition of the Manitou. Such an erosional break between the Upper Cambrian and Lower Ordovician was noted by Berg and Ross (1959) in the Colorado Springs area and as a general feature in Colorado by Tweto (1968a, p. 561).

It is thus likely that in the Minturn quadrangle some part of the Peerless as well as formerly overlying Cambrian strata were removed by erosion prior to Early Ordovician time and that an additional part of the Peerless may have been removed by erosion in pre-Middle Ordovician time, when the Manitou Dolomite was eroded from the area, as discussed below. Some of the eroded Cambrian rocks presumably were carbonate rocks similar to those of the Dotsero Formation.

The central Colorado Upper Cambrian sequence of the Sawatch Quartzite, Peerless Formation, and Dotsero Formation or equivalent is remarkably similar to the Middle Cambrian sequence of the Grand Canyon, described in detail by McKee (1945). Like the Bright Angel Shale of the Grand Canyon, the Peerless displays a very extensive combination of lithic types that indicate shallow-water deposition, rapidly changing environments of deposition, disturbed and noncontinuous deposition, and repeated regressive-transgressive shifts within the broadly transgressive sequence. The abundant flat-pebble conglomerates of the Peerless indicate repeatedly agitated waters and breaks in sedimentation, especially as they include fragile chips of clay or coarse mica shale that can only have been torn by wind or waves from other Peerless sediments nearby. These chips, and also mudcracks, suggest repeated exposure to the air, as on mudflats. In combination, features, such as the shale chips, glauconite, ripple marks, fucoid markings, the conglomerates, and irregular bedding planes, suggest deposition in shallow water. The abundance of iron, as expressed by hematite, limonite, glauconite, and authigenic chlorite, suggests slow deposition under conditions of restricted circulation and high salinity, and the variety of iron minerals suggests changing conditions within this framework (James, 1966). Color mottling in the nonconglomeratic dolomites also suggests these conditions (McKee, 1945, p. 75–77).

ORDOVICIAN SYSTEM

In central Colorado the Ordovician System comprises three formations—the Manitou Dolomite, Harding Sandstone, and Fremont Limestone. These formations, of Early, Middle, and Late Ordovician ages, respectively, are separated one from the other and from post-Ordovician rocks by unconformities that represent widespread erosion after deposition of each unit (Lovering and Johnson, 1933; Johnson 1944; Sweet, 1954). As a result, the three formations are preserved only in remnants of their original extent. Of these remnants, the Manitou is by far the most extensive and the Harding and Fremont are areally much more restricted. The distribution of these remnants is of economic concern because the Manitou and Fremont are mineralized in many mining districts in central Colorado. The Manitou was referred to as the "White limestone" or "Yule limestone" in older literature in many of the mining districts (Emmons, 1886; Emmons and others, 1927).

In much of the region surrounding the Minturn quadrangle, such as the Leadville area and adjoining Mosquito Range, the western side of the northern Sawatch Range north of Aspen, Glenwood Canyon, and the White River Plateau, the Manitou is the only Ordovician formation present. In the Minturn quadrangle, however, the Manitou is absent and the Ordovician is represented only by the Harding Sandstone. This occurrence of the Harding constitutes an outlier 25 mi (40 km) north of the general area of Harding occurrence, as shown on a map by Sweet (1954, fig. 1). The closest known approach of the Manitou to the Minturn quadrangle is in the Pando area about 8 mi (13 km) south-southeast of Red Cliff, where the Manitou tapers to an eroded edge unconformably beneath the Harding (Tweto, 1956). The Manitou is also present about 9 mi (14 km) southeast of the Minturn quadrangle at Mayflower Gulch in the Kokomo district (Tweto, 1949, p. 156), where it is 20 ft (6 m) thick, lies on Precambrian rocks, and is overlain by the Parting Formation.

The Fremont Limestone is even less widespread than the Harding; its nearest exposures are more than 30 mi(48 km) south of the Minturn quadrangle.

HARDING SANDSTONE

Strata assigned to the Harding Sandstone of Middle Ordovician age consist of white and green quartzite, sandstone, and shale a few feet to perhaps 80 ft (24 m) thick that lie unconformably on the Peerless Formation and are unconformably overlain by the Parting Formation. No fossils have been found in these rocks, but as the rocks are lithologically similar to the Harding exposed in many places along the sides of the Sawatch Range farther south, and as they clearly overlie the Manitou Dolomite south of the Minturn quadrangle in the area between Pando and Tennessee Pass (Tweto, 1956), they are assigned with confidence to the Harding.

The Harding is continuous, although of variable character and thickness, from the north end of the canyon of the Eagle River southward to the quadrangle boundary. Farther south, it is in discontinuous lenses (Tweto, 1949), and it finally pinches out completely about a mile north of Tennessee Pass (Tweto, 1956). It is continuous westward from the canyon area at least to Beaver Creek, about 2 mi (3 km) west of the quadrangle boundary, but it must pinch out farther west. At Fulford, 7 mi (11 km) west of Beaver Creek, only the Manitou is reported between the Peerless and Parting (Gabelman, 1950). The Harding must also pinch out eastward from the canyon area as it is absent at Bald Mountain and at Mayflower Gulch in the Kokomo district.

The Harding is varied in composition but commonly consists of massive white quartzite in discontinuous lenses at the base; thin-bedded green and maroon sandstone, quartzite, and conglomerate in the middle part; and green shale and sandstone in the upper part. At the north end of Eagle Canyon, the Harding consists of 6 ft (2 m) of massive white quartzite overlain by about 10 ft (3 m) of purple-mottled green clay shale. One-half mile farther south it is represented by a single massive 25-ft (7.5-m) bed of white quartzite. In the Newhouse tunnel of the Eagle mine it is 39 ft (12 m) thick and consists of 22 ft (7 m) of basal white quartzite overlain by 17 ft (5 m) of green-gray quartzites, arkosic quartzites, and sandy green shales. In roadcuts 1.5 mi (2.4 km) south of Gilman, the Harding is only 14 ft (4 m) thick and consists of 2–3 ft (0.6–1 m) of basal white quartzite overlain by 11–12 ft (3.4–3.7 m) of interbedded pink, gray, and green quartzite, conglomerate, sandy shale, and clay shale. On the slopes of the Sawatch Range the Harding consists of at least 35 ft (10.7 m), and possibly as much as 50 ft (15 m), of massive white quartzite. In the lower levels of the Eagle mine the Harding has an apparent thickness of as much as 80 ft (24 m) and consists of 30 ft (9 m) of white and green quartzites overlain by about 50 ft (15 m) of soft variegated clay shale. The shale has been deformed by low-angle faults wherever seen, however, and it may have been thickened by repetition of beds.

Although the Harding normally appears to be merely disconformable with the formations below and above it, small angular discordances exist. In the Pando area, a discordance of as much as 6° between the Peerless and the Harding was measured in cliff exposures, and some of the basal white quartzite occupies steep-sided channels cut in the Peerless (Tweto, 1949, p. 166–169). In the Newhouse tunnel at Gilman (fig. 8), a discordance of 2° was measured between the Harding and the overlying Parting Formation.

Throughout the canyon area and southward into the Pando area, the Harding locally grades at the top into a bed of tough massive green clay from 1 to 2.5 ft (0.3 to 0.75 m) thick that is characteristically marked by dark purple spots and streaks. This clay layer shows no bedding but in places displays a slightly kneaded structure. In places where the Harding is discontinuous, such as south of Red Cliff, this massive clay bevels the Harding and lies directly on the Peerless Formation. The clay bed is interpreted as a residual soil developed on the older rocks prior to the deposition of the overlying Upper Devonian beds. It is a product of unconformity and technically is not a part of either the Harding or the Parting, but its thinness dictates that it be mapped with one or the other. In the Minturn quadrangle it was generally included in the Harding because of its gradational relation with the Harding, but in the Pando area it was included by Tweto (1949, p. 170–173) with the Parting because it lies above the surface of angular discordance between the Harding and Parting.

The Harding Sandstone commonly weathers to a partly or completely covered slope, and the best exposures are found in mine openings. The following section was measured in the Newhouse tunnel, which crosscuts the stratigraphic section from Precambrian rocks at the portal to the Chaffee Group.

Section of the Harding Sandstone

[Measured in Newhouse crosscut tunnel, Gilman. See fig. 8]

	Thickness (feet)	*Distance above base (feet)*
Parting Formation:		
White quartzite, uneven-grained, finely conglomeratic.		
Unconformity, 2° discordance		39.2
Harding Sandstone:		
16. Quartzite, green, uneven-grained, sandy and shaly; contains subangular quartz pebbles as much as 1/4 in.	2.3	36.9
15. Shale, green, nodular, sandy. Nodules are pink quartzite, irregular in shape and 1/4–1 in. long	1.2	35.7
14. Shale, green, sandy	.2	35.5
13. Quartzite, white, massive, glassy, fine-grained	2.6	32.9
12. Quartzite, medium-grained; lower part is arkosic and feldspars are kaolinized	.5	32.4
11. Sandstone, green, shaly	.2	32.2
10. Quartzite, greenish-gray, medium-grained; stained pinkish brown in scattered 1/4-in. angular spots	3.0	29.2
9. Shale, green, sandy	.1	29.1
8. Quartzite, light-green-gray, medium-grained, massive; bottom 3–in. layer is arkosic and contains many white kaolinized grains in slightly chloritic matrix	1.8	27.3
7. Shale, green, sandy	.1	27.2
6. Quartzite, light-gray to greenish-gray, medium-grained, with a few 1/2- to 1-in. pinkish-brown layers	4.8	22.4
5. Quartzite, greenish-gray, fine-grained	.2	22.2
4. Shaly sand parting	.3	21.9
3. Quartzite, white, medium-grained	3.5	18.4

Section of the Harding Sandstone — Continued

	Thickness (feet)	*Distance above base (feet)*
Harding Sandstone — Continued		
2. Quartzite, white and gray banded; alternating coarse- and fine-grained layers	16.7	1.7
1. Quartzite, white, fine-grained; contains a few very small black grains	1.7	0
Total measured thickness of the Harding Sandstone	39.2	
Peerless Formation:		
Dolomite, brown, micaceous, medium-grained sandy.		

Petrographic examination of two samples of sandstone from the Harding, one fine-grained and the other coarse-grained, shows that the sandstone consists of quartz, abundant interstitial sericite, minor calcite in scattered small lenses less than 1 mm in length, and accessory tourmaline, green biotite, chlorite, ilmenite/leucoxene, sphene, and zircon. Unlike the sandstones of the Peerless, feldspars are absent except as inclusions in some of the quartz grains. The feldspar of this occurrence is an untwinned variety of low refractive index. In the fine-grained sandstone the quartz is in well-sorted grains 0.1–0.2 mm in diameter which have recrystallized to produce irregular interlocking grain boundaries; sericite is in elongated shreds and flakes that have a strong preferred orientation parallel to the bedding but are unevenly distributed. In the coarse-grained sandstone the quartz grains are poorly sorted and range from 0.1 to 2 mm in diameter. Some of the larger grains are well rounded but most are irregular, with interlocking boundaries. Hydromica or sericite fills in around quartz grains and also fills fractures cutting them. A sample of green siltstone from the Harding contains flakes of muscovite as much as 0.2 mm long in a matrix of sericite, clay minerals, and amorphous limonite.

DEVONIAN AND MISSISSIPPIAN SYSTEMS

The Devonian and Mississippian rocks of the Minturn quadrangle and surrounding region consist of a basal quartzite, typically about 40 ft (12 m) thick, and overlying carbonate rocks, typically about 250 ft (75 m) thick. Originally, these strata were divided into two units, the Parting Quartzite and the Leadville Limestone or "Blue Limestone" (Emmons, 1882, 1886). Kirk (1931) later restricted the Leadville to "limestones of Mississippian age," and assigned the carbonate rocks in the lower part of the Leadville of previous usage, along with the Parting strata, to the Upper Devonian Chaffee Formation. Kirk designated the basal quartzite the Parting Quartzite Member of the Chaffee Formation, and Behre (1932, p. 60) later designated the carbonate strata the Dyer Dolomite Member.

In restricting the Leadville and defining the Chaffee, Kirk selected as the lower boundary of the Leadville an unconformity at the base of a thin sandstone and breccia unit then known to occur in the Leadville area (Emmons and others, 1927, p. 34), in the Mosquito Range (Behre, 1929, p. 38), and in the Gilman area (Crawford and Gibson, 1925, p. 36). This sandstone and breccia unit was later found to be far more widespread and was designated the Gilman Sandstone Member of the Leadville Limestone (Tweto and Lovering, 1947; Tweto, 1949).

Thus, in the usage of the U.S. Geological Survey since 1931, the Devonian and Mississippian rocks of central Colorado have been divided into two formational units: (1) the Chaffee Formation, consisting of the Parting Quartzite Member and the Dyer Dolomite Member, and classified as Upper Devonian; and (2) the Leadville Limestone (or Dolomite), consisting of the Gilman Sandstone Member and an unnamed carbonate rock member, and classified as Lower Mississippian.

Geologic mapping and stratigraphic studies by many workers since 1931 have established that the Parting, Dyer, and Gilman are each a widespread mappable unit in central and northwestern Colorado. Further, the presence of an unconformity between the Gilman and the overlying carbonate rocks of the Leadville was established (Tweto, 1949, p. 179; Banks, 1967, p. 41), and a close relationship in lithology and origin between the Gilman and the Dyer was recognized. In the White River Plateau area, where the Dyer consists of a lower limestone unit and an upper dolomite unit (Bass and Northrop, 1963, p. 21), Campbell (1970) distinguished these units as members and raised the Dyer and Parting in rank to formation and the Chaffee in rank to group.

The classification of Campbell is here adopted with modification. The Parting is designated "Formation" rather than "Quartzite" because it has a mixed lithology or is largely shale in many places. The Dyer is designated the Dyer Dolomite. The Gilman is removed from the Leadville and is designated the Gilman Sandstone, thereby restricting the Leadville to carbonate rocks above the Gilman and below the Pennsylvanian strata. The Chaffee Formation of former usage, plus the Gilman, is designated the Chaffee Group. The Gilman is placed in the Chaffee Group because of its close relation to the Dyer in character, origin, and probably in age. Thus, the Chaffee Group consists, from the base upward, of the Parting Formation, Dyer Dolomite, and Gilman Sandstone.

As discussed in the following sections, the Parting Formation and the lower half or more of the Dyer Dolomite are established to be Upper Devonian. The upper part of the Dyer Dolomite and the Gilman Sandstone might be either Late Devonian or Early Mississippian in age. Accordingly, the Dyer Dolomite and Chaffee Group are referred to the Upper Devonian and Lower Mississippian(?). The Gilman Sandstone is referred to the Upper Devonian or Lower Mississippian.

CHAFFEE GROUP

The Chaffee Group is exposed in the Minturn quadrangle only in the area near the Eagle River and—in part—in small fault slices along the Gore fault in the Gore Range. Near the Eagle River the group is 140–165 ft (43–50 m) thick—a normal thickness for the region. However, the Chaffee Group thins northeastward toward the Gore Range. In this direction, it overlaps the eroded edges of older formations, and its eroded edge is in turn overlapped by the Pennsylvanian Minturn Formation. In fault slices near the Gore fault, the Parting Formation is the only part of the group preserved beneath the Pennsylvanian rocks. These relations, among others, led Lovering and Johnson (1933) to the concept of a persistent highland in the area of the Gore and Front Ranges in early as well as late Paleozoic time.

Rocks of the Chaffee Group are resistant, and they commonly crop out in cliffs. In the canyon of the Eagle River, they form the lower part of the upper cliffs (fig. 3), which rise above a slope that represents the Harding Sandstone and Peerless Formation.

Though thin, the rocks of the Chaffee Group are of special economic interest because they—along with the overlying Leadville Dolomite—are the host rocks of the principal ore deposits at Gilman, Leadville, and several other mining districts. In such areas, and at Leadville especially, the thin sandy units comprising the Parting and the Gilman provide the principal stratigraphic control in a sequence of mineralized and altered dolomites. In areas where the Dyer and Leadville Dolomites have been replaced by jasperoid, the sandstone in the Gilman—though extensively replaced also—is particularly significant as a stratigraphic marker. Areas of jasperoid northwest of Gilman and west of Minturn are indicated on plate 1 and are discussed in the report on the ore deposits by T. S. Lovering, Tweto, and T. G. Lovering (1977).

PARTING FORMATION

In the southwestern part of the Minturn quadrangle, the Parting Formation consists of 40–65 ft (12–20 m) of predominantly quartzitic rocks. It lies unconformably on the Harding Sandstone in this area, though a few miles to the south it locally lies on the Peerless Formation (Tweto, 1949). As exposed in fault blocks along the Gore fault in the Gore Range, the Parting is 10–30 ft (3–9 m) thick and rests, in different places, on Precambrian rocks, on Sawatch Quartzite, or on a thin remnant of the Peerless Formation (fig. 25).

In the Minturn quadrangle and nearby areas, the Parting Formation consists chiefly of quartzite and quartzite conglomerate, but locally it contains abundant turquoise-green shale which in places is streaked and is mottled maroon. The quartzite is typically light tan to white, poorly sorted, coarse grained, thick bedded to massive, prominently crossbedded, and vitreous. Quartzite conglomerate, characterized by well-rounded to angular white and pink quartz pebbles 1/4–2 in. (0.6–5 cm) in diameter, generally is present at the base and occurs also in scattered lenses throughout the unit. Quartzite of the Parting can generally be distinguished from that of the Sawatch—or from the white quartzite present locally in the Harding—in isolated exposures by the coarse and uneven grain, the presence of clear quartz as contrasted to cloudy white quartz of the Sawatch and Harding, and, commonly, by tan color of the rock.

The quartzite of the Parting is composed almost entirely of quartz grains but contains sparse interstitial sericite and a few detrital grains of zircon and leucoxene. Some of the quartz grains contain small inclusions of muscovite, green tourmaline, and slender needles of sillimanite, together with lines of minute fluid inclusions. Many of the grains show marked strain shadows. The quartz grains in the nonconglomeratic beds range in size from 0.1 to more than 1 mm; most of them were originally rounded but recrystallization and secondary quartz overgrowths have produced an irregular interlocking texture.

The green shale in the Parting occurs in local thin beds between the heavy quartzite beds and also in thick lenses that locally constitute as much as half the thickness of the formation, as at the north end of the canyon of the Eagle River, south of Cross Creek. Much of the shale is sandy, and some of it contains thin beds of vitreous white quartzite. Thin sections show that the green shale is composed of alternate layers of fine arkosic sand and green chloritic material. The arkosic layers are composed chiefly of quartz, microcline, and a pale-green micaceous mineral tentatively identified as a chlorite. Small flakes of detrital muscovite are common in the arkosic material, and the accessory detrital minerals are tourmaline, sphene, and zircon.

Character of the Parting Formation is illustrated by the following section, measured in the canyon between Red Cliff and Gilman. As measured in sections a few miles farther south (Tweto, 1949, p. 171–173), the uppermost sandstone and quartzite beds of the Parting are dolomitic, and the contact with the overlying Dyer Dolomite is gradational.

Section of the Parting Formation

[Measured in cut along U.S. Highway 24, 0.6 mi (1 km) northwest of high bridge over the Eagle River one-half mile (0.8 km) west of Red Cliff. See fig. 8]

	Thickness (feet)	*Distance above base (feet)*
Dyer Dolomite:		
Covered, 10 ft.		
Parting Formation:		
Approximate top		47.0
15. Quartzite, white, vitreous, coarse-grained, uneven-grained	1.0	46.0
14. Sandy quartzite, light-yellowish-gray, thick-bedded; contains white vitreous quartzite fragments and bands of intraformational conglomerate of these fragments in sandy quartzite	4.0	42.0
13. Quartzite, white, massive, vitreous, coarse, uneven-grained, slightly conglomeratic; contains buff-gray specks of altered feldspar	4.0	38.0
12. Quartzite, light-gray, vitreous, even-grained, medium- to fine-grained; abundant buff flecks. Weathers with hackly surface	5.0	33.0
11. Quartzite, white, coarse-grained, slightly sandy, many clear quartz grains as much as 1/4 in. in diameter	7.0	26.0
10. Sandy quartzite, banded white and greenish-gray, coarse-grained; contains clear quartz granules	2.5	23.5
9. Quartzite, white, vitreous, fine-grained; contains very few buff specks	7.0	16.5
8. Quartzite, light tan, very coarse and poorly sorted; locally conglomeratic; glassy quartz pebbles	1.5	15.0
7. Sandstone, shaly, greenish-gray, brown-weathering, fine-grained. Grades down into green-gray shaly and arkosic friable sandstone	1.5	13.5
6. Sandstone, quartzitic, conglomeratic, contains some hematite; grades down into shaly sandstone	.5	13.0
5. Quartzite, conglomeratic, white, micaceous, vitreous. Contains pebbles of clear and pink quartz and 1/2-in. angular fragments of gray shaly sandstone that may be from Harding Sandstone	1.5	11.5
4. Sandy shale and shaly sandstone, light-greenish gray, fine-grained, nonmicaceous	4.0	7.5
3. Quartzite, light-pink, medium-grained, vitreous, finely banded. Grades downward into white, vitreous, poorly sorted quartzite; is finely conglomeratic at base. Fragments of clear quartz	5.0	2.5
2. Quartzite, banded pink and gray, coarse-grained, conglomeratic; has abundant fragments of pink quartz as much as 3/8 in. in diameter. Many grains of kaolinized feldspars as much as 1/8 in. in diameter	1.5	1.0

Section of the Parting Formation — Continued

Parting Formation — Continued	*Thickness (feet)*	*Distance above base (feet)*
1. Clay-shale, tough, green with purple bands and spots; is micaceous; has kneaded appearance. Probably a regolith	1.0	0
Total measured thickness of the Parting Formation	47.0	

Harding Sandstone:
Quartzite, white, vitreous, fine- and even-grained.

In many places the quartzite beds of the Parting contain rusty cavities that can be seen to be molds of brachiopods, pelecypods, or crinoid stems, but generally these are too vaguely imprinted in the coarse quartzite matrix to be more closely identified. On the dip slope traversed by the Tigiwon Road 1.2 mi(1.9 km) northwest of Gilman, somewhat better preserved casts and molds were found in abundance in the Parting. These fossils were identified by Edwin Kirk of the U.S. Geological Survey (written commun., Feb. 5, 1953) as:

Schizophoria striatulata var. *australis* Kindle
Spirifer (Cyrtospirifer) whitneyi (Hall)
Productella sp.
Paurorhynca endlichi (Meek)
Aviculopecten? sp. (fragmentary)

Kirk stated "Although poorly preserved, the above listed fossils can be recognized. It is a typical Ouray (Upper Devonian) fauna." A generally similar group of fossils has been reported from the Parting in the southern Sawatch Range (Dings and Robinson, 1957, p. 15). More recently, C. A. Sandberg of the U.S. Geological Survey (written commun., 1971) has reported a conodont fauna containing *?Clydgnathus ormistoni* from the Parting in Glenwood Canyon.

Except for these three invertebrate collections, the chief fossils found in the Parting in central Colorado are fish remains (Bryant and Johnson, 1936; Denison, 1951; Bass and Northrop, 1963, p. J20–J21). On the basis of the fish fossils, particularly the genus *Bothriolepis,* the Parting has been classed as early Late Devonian in age (Denison, 1951; Poole and others, 1967). On the other hand, the brachiopod *Paurorhynca endlichi* and the conodont *?Clydgnathus ormistoni* reported above indicate a late Late Devonian age. This difference in age probably is an expression of different levels of fossil occurrence in the Parting, though it does establish that some of the Parting is younger than was previously known. The Parting is a transgressive unit that progressively thins and becomes younger northeastward. Most of the fish localities are on the southwest side of the Sawatch Range, 60 mi (97 km) southwest of the Minturn quadrangle, in thin-bedded limy, shaly, and sandy strata nearly 100 ft (30 m) below the Dyer. The brachiopod locality in the Minturn quadrangle, in contrast, is in quartzite no more than 20 ft (6 m) below the Dyer, and the conodont locality is only 21 ft (6.4 m) below the Dyer. One fish locality is in the Mosquito Range north of Salida, in a red shale unit that underlies the typical quartzite of the Parting. This shale unit extends discontinuously northward to the Leadville area, but it is absent in the Minturn quadrangle. Beds thought by Behre and Johnson (1933) to represent this shale at Gilman are of different character and are herein assigned to the Harding Formation.

From regional studies of the Upper Devonian rocks, and from the fact that most of fish remains in the Parting and correlative units are of fresh or brackish water forms, Denison (1951) concluded that the Parting represents nearshore, shallow-water marine deposits, possibly including freshwater stream-channel and flood-plain deposits. Character of the Parting in the Minturn quadrangle supports such a conclusion. The widely occurring molds of brachiopods and crinoids indicate marine deposition, but the lenticular conglomerates suggest channel deposition, particularly as they show crossbedding of the stream gravel-bar type. General increase in coarseness of the Parting northeastward suggests a source area and depositional margin not far northeast of the Minturn quadrangle, if not at the site of the Gore Range. From studies of crossbedding and grain size in the Parting from Minturn westward to Rifle, Campbell (1967) concluded that the lower part of the Parting was derived from sources to the east and the upper part was derived from sources to the north. Local areas of nondeposition of the Parting were recognized by Singewald (1931) in the Alma distrct, 16 mi (25 km) southeast of the Minturn quadrangle.

Throughout the region, the Parting Formation is separated from underlying rocks by a major unconformity. The youngest formation known beneath this unconformity is the Fremont Limestone of Late Ordovician age, and regionally the Parting bevels formations of all ages from Fremont down to Precambrian. Though the unconformity was long thought to represent erosion in Silurian time, the discovery of Silurian and Upper Ordovician limestones in diatremes in the Front Range (Chronic and others, 1969) along with other, indirect evidence suggests that both the Fremont and a Silurian limestone may once have been widespread over the state. If so, these rocks were eroded in Early and Middle Devonian time, when most of the Rocky Mountain region was a land area (Poole and others, 1967; Sandberg and Mapel, 1967). The paleontological data just discussed indicate that in the area of the Minturn quadrangle erosion probably continued through the early part of the Late Devonian also.

DYER DOLOMITE

The Dyer Dolomite lies conformably, locally with gradational contact, upon the Parting Formation and is unconformably overlain by the Gilman Sandstone. The Dyer is uniformly 75– 80 ft (23– 24 m) thick in most of the area near Gilman and southward to Leadville. In a few places, however, the overlying Gilman Sandstone fills broad channels cut to depths of as much as 25 ft (7.5 m) into the Dyer, reducing the thickness of the Dyer to as little as 50 ft (15 m).

The Dyer consists almost entirely of dolomite, which characteristically is fine grained and thin bedded and breaks into small, sharp, hackly fragments (fig. 9). The dolomite is gray to black; much of it is finely laminated in shades of gray. The laminations are wavy, and Campbell (1970) has interpreted them as stromatolitic in origin. In outcrop, the lower half to two-thirds of the member weathers light buff or yellowish gray, and the upper part weathers dark brown to bluish gray. Argillaceous matter coats many of the bedding planes and occurs also in scattered beds of shaly breccia in the lower, yellow-weathering unit. Such beds are bounded by wavy bedding surfaces that are evident minor disconformities or diastems; they commonly have a bleached-looking, light-gray or yellow color and lie upon dolomite that is similarly bleached to depths of a few inches. Such argillaceous breccia zones are interpreted as weathered zones formed during periods of interrupted deposition and temporary exposure. Other beds in both the lower and upper parts of the member have a fine breccia structure but are without argillaceous matter or bleaching. These are interpreted as wave breccias.

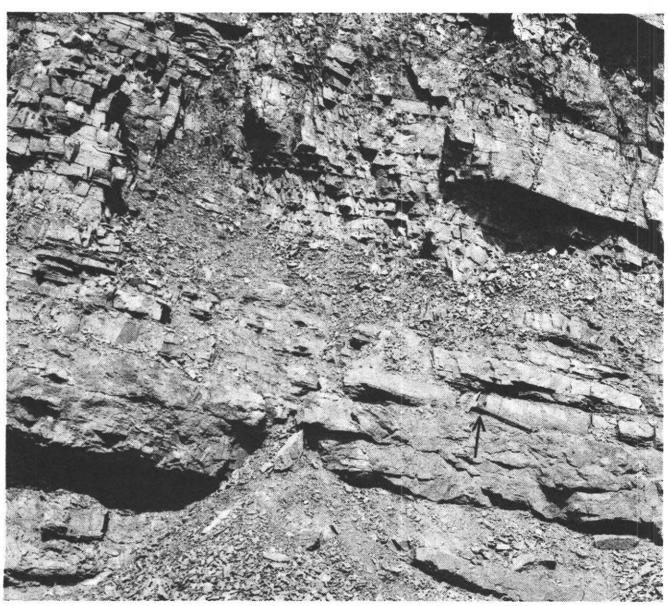


FIGURE 9.—Thin-bedded dolomite characteristic of Dyer Dolomite in roadcut of abandoned highway 0.3 mi (0.5 km) northwest of Gilman. Hammer (arrow) shows scale.

Within the canyon of the Eagle River and in adjoining mines, the Dyer contains several distinctive and persistent beds that are useful as stratigraphic markers. A 7-ft (2.1-m) bed that contains abundant black chert in small nodules and lenticular stringers is present 15 ft (4.5 m) above the base. Thin but persistent shale partings occur at 22 and 32 ft (6.7 and 9.8 m) above the base. At 45 ft (14 m) above the base is a bed of dense black dolomite 3–8 ft (1–2.4 m) thick that shows in cliff exposures as a black band at or near the boundary between the yellow- and the blue-gray-weathering parts of the member. At the base of this black bed is a thin sandy stratum known locally as the "sand grain marker."

The "sand grain marker" is typically 1– 2 in. (2.5– 5 cm) thick, but locally it is as thin as 1/4 in. (6 mm) or as thick as 5 in. (13 cm). It consists of dark dolomite sprinkled with rounded, frosted quartz sand grains generally 0.5– 1 mm in diameter. In some places the sand grains are so abundant as to constitute a sandstone. In others, they are so sparse as to require very close scrutiny for identification; nevertheless, this thin stratum has proved to be remarkably persistent and widespread (Lovering and Tweto, 1944, p. 23; Tweto, 1949, p. 175; Banks, 1967). Other sandy zones of similar character occur locally in the upper part of the Dyer, and Campbell (1970) has noted the presence of disseminated quartz sand grains and local thin stringers of sandy dolomite throughout the uppermost part of the Dyer in the White River Plateau area. The frosted, well-rounded grains of the "sand grain marker" and other, local, sandy layers are interpreted to be of eolian origin, blown from coastal dunes into the shallow waters and tidal flats in which the carbonate muds of the Dyer accumulated.

Character of the Dyer is illustrated by the following stratigraphic section, measured in the canyon of the Eagle River.

Section of the Dyer Dolomite

[Measured along first gully north of Rock Creek, beginning at abandoned highway grade below U.S. Highway 24. See fig. 8]

	Thickness (feet)	*Distance above base (feet)*
Gilman Sandstone:		
Quartzite and dolomite breccia.		
Unconformity.		77.8
Dyer Dolomite:		
16. Dolomite, gray, brown- to gray-weathering, finely crystalline, brittle, thin-bedded	9.0	68.8
15. Dolomite, dark-bluish-gray, finely crystalline, brittle, hackly, thin-bedded, and finely banded	3.5	65.3
14. Dolomite, tan-gray, finely crystalline, brittle, thick-bedded	2.0	63.3

Section of the Dyer Dolomite — Continued

Dyer Dolomite — Continued	*Thickness (feet)*	*Distance above base (feet)*
13. Dolomite, grayish-black, finely crystalline, thin-bedded; contains 1/8–1/4 in. mud lumps at top	4.0	59.3
12. Dolomite, black, dark-brownish-gray-weathering, medium-crystalline to finely crystalline, medium-thin-bedded	5.0	54.3
11. Dolomite, shaly, gray, thin-bedded	.8	53.5
10. Dolomite, blue-black, finely crystalline, massive. Weathers dark blue gray to black. "Black marker bed." 2- to 5-in. bed of sandy dolomite at base is "sand grain marker"	8.0	45.5
9. Dolomite, dark-gray; weathers light buff to greenish gray; is thinly banded; forms massive bed	10.0	35.5
8. Dolomitic shale, dark-gray, thin-bedded; grades upward into overlying bed. "Shale marker"	3.0	32.5
7. Dolomite, argillaceous, dark-bluish-gray grading to gray downward, green-buff-weathering, fine-grained, irregularly bedded	9.0	23.5
6. Shale, dolomitic, green, thin-bedded	1.0	22.5
5. Dolomite, cherty, light-gray, buff-weathering, fine-grained, thin-bedded. Chert is black, in scattered lenses as much as 18 in. long and 3 in. thick. "Cherty marker"	7.5	15.0
4. Shale, calcareous, gray-green, fissile	0.5	14.5
3. Dolomite, light-gray, gray-weathering, very fine grained, thin-bedded	4.0	10.5
2. Shaly dolomite, light-gray, thin bedded	0.5	10.0
1. Dolomite, light-gray, finely crystalline, medium-bedded; weathers buff and to smoothly rounded ledge. Contains a few shale partings. Basal 3 ft is very thinly banded, irregularly bedded, and knobby weathering. Conformable contact with quartzite below	10.0	0
Total measured thickness of Dyer Dolomite	77.8	

Parting Formation:
Sandy quartzite, white and pinkish-white, rust-spotted, coarse- and uneven-grained; is slightly dolomitic in irregular areas.

Under the microscope, typical Dyer Dolomite is seen to consist of dolomite grains averaging about 0.05 mm in diameter, most of which contain minor amounts of opaque dark carbonaceous matter as "dust." This dusty organic matter probably accounts for the dark color of the rock. A few tiny irregular masses, of quartz and of a clay interpreted as halloysite, are also present; no other minerals were observed.

Fossils are rare in the Dyer Dolomite in the northern Sawatch and Mosquito Ranges, but they have been found in several localities farther west and south. We found none in the Minturn quadrangle, though the Upper Devonian brachiopod *Spirifer whitneyi* var. *animasensis* Girty was reported by Crawford and Gibson (1925, p. 37–38). At Glenwood Canyon, 40 mi (64 km) west of Minturn, the Dyer contains a basal unit of limestone that has yielded an abundant fauna of Upper Devonian brachiopods (Bass and Northrop, 1963, p. J21–26). Similar fossil assemblages have been reported from several localities in the lower part of the Dyer on the western side of the Sawatch Range (Johnson, 1944, p. 329–330) and from the southern end of the range (Dings and Robinson, 1957, p. 15). The fossils from the lower part of the Dyer are the basis for the assignment of the Dyer to the Upper Devonian, though close affinities with Lower Mississippian faunas have been recognized (for example, P. E. Cloud, in Bass and Northrop, 1963, p. J26).

Though the upper part of the Dyer has been classed as Devonian by many authors, it is poorly fossiliferous and its age is not well established. Helen Duncan of the U.S. Geological Survey (in Morris and Lovering, 1961, p. 87) reported that a sparse coral fauna "suggests * * * Early Mississippian age." Both Hallgarth (1959) and Rothrock (1960) concluded from subsurface studies in western Colorado that the upper part of the Dyer passes westward into limestones classed as Lower Mississippian on the basis of lithology and sparse fossils. In southwestern Colorado and adjoining Utah, Baars (1966, p. 2089) reported Early Mississippian endothyrid foraminifera in the upper part of the Ouray Limestone, with which the Dyer is generally correlative. Therefore, we class the Dyer as Late Devonian and Early Mississippian(?) in age.

GILMAN SANDSTONE

The Gilman Sandstone is a thin but widely persistent unit of sandstone, breccia, and dolomite that lies with erosional unconformity upon the Dyer Dolomite and is overlain with erosional unconformity by the Leadville Limestone (or Dolomite). The unit is typically about 20 ft (6 m) thick in the Minturn quadrangle and surrounding region, but it thins locally to about 10 ft (3 m), and in a few places it thickens to as much as 50 ft (15 m). Where thick, the sandstone fills broad channels cut into the underlying Dyer Dolomite. One such channel was observed in the Eagle mine, and others occur south of the quadrangle.

The Gilman is varied in lithology, but in most places a major part is sandstone or sandy dolomite. A basal bed of sandstone 1–2 ft (0.3–0.6 m) thick is commonly present. This bed is generally overlain by a few feet of interbedded sandstone and dolomite in beds that pinch and swell, and this is overlain by lenticular bodies of breccia, dolomite, and sandstone or sandy dolomite. Chert is abundant in some of the breccia and dolomite.

The top of the Gilman is marked in many places by a bed of structureless brown-gray lithographic dolomite called the "waxy bed" by the mine geologists at Gilman and also referred to by that name by Engel, Clayton, and Epstein (1958) and by Banks (1967, p. 41). This bed is irregular in thickness, ranging from a few inches to several feet, and is generally separated from underlying strata by a wavy contact. A more pronounced wavy contact separates it from overlying bedded carbonate rock of the Leadville. Though cut out by unconformity in places, the "waxy bed" has been traced throughout the region from the White River Plateau to the Sangre de Cristo Range (Engel and others, 1958, p. 376; Banks, 1967, p. 36–42).

In cliff exposures of the Chaffee Group and Leadville Limestone (or Dolomite), the Gilman generally shows up as a yellowish-gray massive unit separating thin-bedded gray dolomite of the Dyer below from thick-bedded gray carbonate rocks of the Leadville above. In such exposures, the "waxy bed" commonly forms a shallow indentation in the cliff.

In mineralized areas, the Gilman displays compositional and structural features that are interpreted as products of solution processes. These features are discussed in the report on the ore deposits (Lovering and others, 1977). In most unmineralized areas solution features are absent and the sandstone and sedimentary breccia of the Gilman are essentially unmodified. Previous descriptions of the Gilman by us (Lovering and Tweto, 1944; Tweto, 1949) were based on studies in the Gilman and Leadville mineralized areas, and they consequently emphasized solution features that are now known to be of restricted occurrence in the Gilman.

Where not modified by solvent action, the unconformity at the base of the Gilman is a smooth but wavy surface that commonly shows relief of several inches in only a few feet along strike, and a relief of several feet over longer distances. Where modified by solvent action, this surface is irregular and is marked by abrupt pits and pinnacles that have relief of as much as several feet. Strata above the modified surface show local sag structures and internal faults and are cut by dikelets of black clay, breccia, quartz sand, or dolomite sand.

Sandstone of the Gilman is yellow to light gray and consists of well-sorted, rounded quartz grains about 0.5 mm in diameter cemented by dolomite, calcite, or silica. Some of the sandstone is speckled with minute particles of white clay. As judged from several thin sections, the sandstone is devoid of detrital heavy minerals. The sandstone closely resembles that of the "sand grain marker" and other thin sand lenses in the Dyer Dolomite, and, like them, it is probably of eolian origin, though obviously reworked in water.

Except in the "waxy bed", the dolomite in the Gilman is in part identical to the gray, fine-grained, finely laminated dolomite in the underlying Dyer and in part a breccia or edgewise conglomerate of dolomite fragments cemented by dolomite. Both varieties locally contain sparse to abundant quartz grains similar to those of the sandstone, and both varieties occur in cherty or chert-free forms. The "waxy bed," in contrast, is devoid of quartz grains and chert and shows no lamination or bedding.

The chert in the Gilman is predominantly black, but a light-gray to white variety is also present. The chert occurs principally in sharp to somewhat abraded fragments. The fragments are most abundant in the dolomite breccias, but they are scattered through the laminated dolomite also. The chert has been studied in detail by Banks (1970) who distinguished an early variety that was deposited from hypersaline waters penecontemporaneously with the enclosing dolomite, though the chert was broken and redistributed by wave action as dolomite deposition proceeded, and a late chert that transects primary sedimentary structures in the dolomite. Banks attributed the late chert to groundwater action during karst erosion after deposition of the Leadville Limestone.

A section of the Gilman Sandstone in the Gilman area follows. In this locality, the Gilman shows effects of solution and collapse, and also of hydrothermal alteration in some of the dolomite. Sections in other areas show less breccia and little or no hydrothermal alteration (Tweto, 1949, p. 179–180).

Section of the Gilman Sandstone

[Measured in gully in cliffs 0.4 mile northwest of Gilman, at abandoned highway grade below U.S. Highway 24. See fig. 8]

	Thickness (feet)	*Distance above base (feet)*
Leadville Dolomite:		
Light-gray finely crystalline dolomite.		
Unconformity, wavy surface.		30.0
Gilman Sandstone:		
8. Dolomite "waxy bed"; is dark gray, brown-gray weathering, dense, uniform; hackly fracture; 3-in. layer of black chert at base	9.0	21.0
7. Dolomite, hydrothermally altered; is brownish-gray, porous, vuggy; has zebra-rock structure in patches	1.6	19.4
6. Dolomite, gray, fine-grained; contains sparse black chert	4.6	14.8
5. Sandy dolomite and sandstone, gray, thin-bedded	1.0	13.8
4. Dolomite-chert breccia. Dolomite fragments are irregular in size and shape; chert fragments are small. Contains scattered chunks of dolomitic sandstone, and a few subangular fragments of limestone as much as 1 ft in diameter. Contact with underlying sandstone very irregular	5.1	8.7

Section of the Gilman Sandstone — Continued

	Thickness (feet)	*Distance above base (feet)*
Gilman Sandstone — Continued		
3. Sandstone, dolomitic, buff-gray, medium-grained	1.2	7.5
2. Dolomite-chert breccia; has some chunks of sandstone	5.5	2.0
1. Sandstone, dolomitic, tan to gray, medium-grained; single thick bed	2.0	0
Total measured thickness of the Gilman Sandstone	30.0	

Unconformity.
Dyer Dolomite:
Dolomite, gray, thin-bedded, and brittle.

Except for differences in proportions of sandstone and dolomite, the Gilman closely resembles the underlying Dyer in lithology, and like the Dyer, it shows abundant evidence of shallow-water deposition. After detailed study of the upper Dyer and Gilman throughout the region, Banks (1967, 1970) concluded that the dolomite in these units was deposited from shallow hypersaline waters in a mudflat environment subject to agitation by waves and frequent subaerial exposure and that the sand was introduced by wind. Similarly, Campbell (1970) concluded a tidal flat origin for his Coffee Pot Member of the Dyer (equivalent of all the Dyer in the Minturn quadrangle).

The Gilman Sandstone is unfossiliferous, and, like the upper part of the Dyer, it might be either late Devonian or Early Mississippian in age. Kirk (1931) assigned it to the Mississippian Leadville Limestone rather than to his underlying Upper Devonian Chaffee Formation because of the unconformity he recognized at its base. However, the unconformity at its top, not recognized by Kirk, seems to mark a far more significant break in sedimentation. The strata of the Gilman and Dyer below this unconformity are reworked eolian sands and primary dolomites deposited in shallow hypersaline waters. The strata above, in the Leadville, are normal marine limestone, some of which was later hydrothermally dolomitized (Lovering and others, 1977). As seen in local outcrops, the unconformity at the top of the Gilman is a wavy surface with relief of as much as 18 in. (45 cm), but over longer distances the relief is several feet, as indicated by erosional truncation of upper units of the Gilman Sandstone. Some depressions in the surface of unconformity are filled with pebbles of quartzite and chert (Tweto, 1949, p. 179). The quartzite indicates that in some nearby area erosion extended to a stratigraphic level below the Gilman, probably in the Sawatch Quartzite. Banks (1967, p. 41) interpreted the unconformity as a karst erosion surface.

LEADVILLE LIMESTONE (OR DOLOMITE)

In most parts of central Colorado, the carbonate rocks of the Leadville Limestone are predominantly or entirely limestone. Through most of the Minturn quadrangle, however, and southeastward through the Leadville district and the Mosquito Range to the vicinity of Buffalo Peaks, a distance of 42 mi (68 km), the carbonate rocks of the Leadville are dolomite. Through this area the Leadville is accordingly called the Leadville Dolomite. The boundary between the limestone and dolomite facies lies approximately along Cross Creek in the Minturn quadrangle; hence, the Leadville is referred to either as limestone or as dolomite in this report, depending on the area involved.

The Leadville is of prime economic interest because it is the principal host rock of ore deposits at Gilman, Leadville, and Aspen as well as in several lesser mining districts in the Sawatch and Mosquito Ranges. The ore deposits are predominantly in the dolomite facies. East of the Sawatch Range, the belt of dolomite coincides with the width of the Colorado mineral belt (fig. 24).

The Leadville lies unconformably on the Gilman Sandstone and is overlain unconformably either by very thin patches of the Molas Formation or by the Belden Formation of Pennsylvanian age. The unconformity at the top of the Leadville is a karst erosion surface that irregularly truncates the carbonate rocks. In the canyon area between Minturn and Red Cliff and in the Eagle mine, the Leadville ranges from 110 to 140 ft (34 to 43 m) in thickness, except as affected locally by cavities and channels in the karst surface. The Leadville thins to zero at some place beneath the Pennsylvanian rocks east and northeast of the canyon area, for it is absent beneath Pennsylvanian rocks in fault slices along the Gore fault. It also thins southeastward. Two miles (3 km) south of Red Cliff it is 67 ft (20 m) thick, and in the Kokomo district, it is 25 ft (7.6 m) thick (Tweto, 1949, p. 185–186). At Leadville the thickness averages about 80 ft (24 m), although it ranges from 0 to 190 ft (0 to 58 m) (Tweto, 1968b).

The dolomite of the Leadville, from Cross Creek southeastward through Red Cliff to Leadville and beyond, consists of several varieties or facies. Most abundant and oldest is a finely crystalline dark-gray dense dolomite in which bedding is well preserved. Superposed on this are various coarser grained and lighter colored facies resulting from recrystallization under hydrothermal conditions. Bedding is partly obliterated in the recrystallized rocks, making them appear more massive than the medium- to thick-bedded dark dense dolomite. The origin of the dark dense dolomite—whether syngenetic or hydrothermal—has been considerably debated. (See Radabaugh and others, 1968; Tweto, 1968a.) It was concluded to be hydrothermal by Engel, Clayton, and Epstein (1958), and it is interpreted by us to be hydrothermal.

The character and origin of the various dolomite facies in the Leadville are discussed in the report on ore deposits (Lovering and others, 1977), but as the dolomite facies have a stratigraphic expression in the Gilman area, they are described briefly here. The lower 80–100 ft (24–30 m) of the Leadville in the Gilman area consists of predominant dark-gray to black finely crystalline dolomite and subordinate interbedded medium-gray and medium-crystalline dolomite. The lower 50–65 ft (15–20 m) of the dolomite contains conspicuous black chert. An especially cherty bed about 10 ft (3 m) thick lies about 50 ft (15 m) above the Gilman Sandstone. A persistent streak of fragmental chert—the "chert breccia marker" of the Gilman mines—is at the base of this bed, and above it is dolomite that contains abundant chert in long lenses or thin beds. Banks (1970, p. 3033) concluded that the chert was "precipitated from ground waters as amorphous silica after initial lithification [of the limestone] but prior to or during karst erosion of the formation in Late Mississippian(?) and Early Pennsylvanian time."

The lower unit of dolomite just described is separated from an upper unit by a brecciated and slightly sandy and shaly dolomite zone 1–4 ft (30–120 cm) thick that is known as the pink breccia. This zone has been markedly affected by bedding fault movement and hydrothermal alteration. It may mark an unconformity within the Leadville, but it has not been identified outside of the mine area.

Above the pink breccia in the Gilman area is an upper unit of the Leadville that consists largely of recrystallized dolomite and is known at Gilman as the "discontinuous banded." This unit is characterized by abundant patches of zebra rock consisting of alternating bands of black or dark-gray fine-grained dolomite and white coarse-grained vuggy dolomite. The bands are 1/16– 1/2 in. (1.5–13 mm) thick and generally are approximately parallel to the bedding, although markedly discordant locally. The zebra rock in turn has recrystallized irregularly into a corase-grained, vuggy, light-brown-gray dolomite known locally for its luster as pearly or brown pearly dolomite. Neither zebra rock nor pearly dolomite are confined to the upper unit of dolomite. At Gilman they occur sporadically in the lower unit, and in places elsewhere in the region, as at Leadville, they locally constitute the full thickness of the Leadville. Conversely, dark-gray dense dolomite is abundant at the level of the "discontinuous banded" in many places outside the Gilman area.

Characteristic lithology of the Leadville Dolomite in the Gilman area is shown in the following section:

Section of the Leadville Dolomite

[Measured in gully in cliffs, 0.4 mile northwest of Gilman, starting just below level of U.S. Highway 24. See fig. 8]

	Thickness (feet)	*Distance above base (feet)*
Belden Formation:		
Black shale, ocherous at base.		
Unconformity, with karst topography.		126.6
Leadville Dolomite:		
12. Dolomite, light-gray with pinkish-gray streaks, medium- to coarsely crystalline, massive; weathers with light brown, granular, pitted surface; has vuggy zebra-rock structure	13.0	113.6
11. Dolomite, dark-gray, gray-weathering, fine- to medium-crystalline, massive	1.5	112.1
10. Shale, gray, thin-bedded	1.0	111.1
9. Dolomite, light-gray to tan- and blue-gray, medium-coarse-grained, vuggy, massive, slightly calcareous. Weathers brownish and rough	30.5	80.6
8. Dolomite, nearly black, gray-weathering, finely crystalline, dense, massive. Has blocky fracture distinct from that of unit 9. Upper contact is marked by 2-ft shaly breccia zone	7.5	73.1
7. Dolomite; same as in unit 8 but with sharp, hackly, weathered surface, and denser and slightly calcareous. Black shale parting at base	11.0	62.1
6. Dolomite, medium blue-gray, finely crystalline, massive. Weathers blue- to brown-gray and to rounded surfaces. Forms bench at shale parting at top	11.0	51.1
5. Cherty dolomite, bluish-gray, blue-gray-weathering, medium-grained, massive. Black chert in lenses 1/2–2 in. thick and 3–12 in. long, and in bedding layers 1 in. thick and several feet long; layers 3–6 in. apart. Some zebra-rock structure	5.0	46.1
4. Cherty dolomite, blue-black, dense, finely crystalline, hackly, thin-bedded; contains argillaceous laminae that weather in relief; contains black chert in beds 1/2 –2 in. thick; interval weathers streaky gray and brown. Base of interval is irregular and wavy; marked by chert	11.3	34.8
3. Dolomite, light-gray, medium-fine-grained, massive, dark-brownish-gray weathering, with some vuggy zebra banding. Cherty in upper 3 ft, but chert less abundant and lighter than in interval above. Chert in bedding layers. Some sandy banding with chert	15.3	19.5

Section of the Leadville Dolomite — Continued

	Thickness (feet)	Distance above base (feet)
Leadville Dolomite — Continued		
2. Cherty dolomite, gray-black, dense, fine-grained, thin-bedded, hackly. Black chert in 1-in. layers, weathers light gray and brown specked	10.5	9.0
1. Dolomite, light-gray, buff- and knobby-weathering, finely crystalline; contains thin lenses of chert and chert breccia, and several 1-in. bands of brown-weathering siliceous dolomite	9.0	0
Total measured thickness of Leadville Dolomite	126.6	

Gilman Sandstone:
Dolomite of waxy bed, dark-gray, brown-gray-weathering, dense, somewhat hackly.

The boundary between the dolomite and limestone facies of the Leadville is buried beneath the moraines at the mouth of Cross Creek. The northernmost exposure of the dark dense dolomite facies is on the north side of the bedrock knob west of Bolts Lake (pl. 1). In exposures a mile farther north, near the Minturn Ranger Station, the Leadville above the Gilman is entirely limestone except for irregular patches of coarse-grained vuggy hydrothermal dolomite. This limestone is dark gray, finely crystalline to lithographic, thick bedded to massive, and cherty, and it weathers light bluish gray. Thin sections show abundant recrystallized foraminifera in the limestone.

The limestone facies is poorly exposed in the Minturn area. To the northwest, where it is well exposed, Engel, Clayton, and Epstein (1958) reported that the limestone is divisible into two main units. The lower one, resting on the syngenetic dolomite of the "waxy bed" at the top of the Gilman, consists of medium- to very fine grained, dark- to medium-gray cherty limestone and is commonly about 40 ft (12 m) thick, although it ranges from 30 to 70 ft (9 –21 m). The chert is not abundant and is concentrated near the top and bottom of the unit. Exclusive of the chert, the limestone contains from 1.3 to 3.15 percent silica and less than 0.5 percent Al, Fe, Mg, and other minor constituents. The upper unit is a remarkably pure limestone containing 99 percent or more calcite. It is 60–150 ft (18–46 m) thick and is gray, fine grained, and thick bedded. It consists in large part of foraminiferal material but also contains abundant small fragments of other fossils and is locally oolitic.

Despite its composition and the abundance of foraminiferal and other fossil remains in parts of it, the Leadville Limestone of central Colorado is rather poor in diagnostic fossils. We found no fossils other than recrystallized fragments in it, though the Lower Mississippian brachiopod *Spirifer centronatus* Winchell was reported by Crawford and Gibson (1925, p. 37) from a location a few feet above the Gilman.

The Leadville is classed as Early Mississippian, or late Kinderhookian and Osagean, in age (Weller and others, 1948). A Meramecian or Late Mississippian age for some of the upper strata was reported by Hallgarth and Skipp (1962). However, Skipp later amended her earlier identification of *Endothyra* aff. *E. scitula* Toomey on which the Meramecian age assignment was based (oral commun., Feb. 1969) and, as reported by Conley (1965), she found no foraminifera younger than late Osagean in extensive collections of well preserved microfossils made by Conley in the White River Plateau.

The Leadville is generally recognized as an approximate, if not exact, equivalent of the Madison Limestone of extreme northwestern Colorado and west-central Wyoming. Sando (1967) established that a thin basal dolomitic unit of the Madison in west-central Wyoming is Kinderhookian, that limestone making up the main body of the formation is Osagean, and that a thin upper member is Meramecian.

So far as the Leadville of the Minturn quadrangle is concerned, it is most likely only Lower Mississippian (Kinderhookian and Osagean), because it was here eroded more deeply before deposition of the Pennsylvanian rocks than in areas to the west and northwest.

PRE-BELDEN UNCONFORMITY AND MOLAS FORMATION

As indicated in the preceding section, the Leadville Limestone was unevenly eroded before deposition of overlying marine Pennsylvanian sediments began. Chemical weathering of the limestone during at least the latter part of this erosion period produced a karst erosion surface characterized by caves, sinkholes, and irregular channels, and it also produced a residuum of clay, silt, and chert, derived from the insoluble materials in the limestone. This residuum or regolith, containing varying amounts of admixed materials from other sources, constitutes the Molas Formation.

The Molas Formation was first recognized in southwestern Colorado (Cross and Howe, 1905), where it forms a thin unit associated with the karst erosion surface at the top of the Mississippian limestone and beneath marine Pennsylvanian rocks. Subsequently, it has been recognized at the base of the Pennsylvanian sequence in scattered localities throughout central Colorado, and Henbest (1958) has described generally equivalent units in Wyoming and New Mexico.

In the Minturn quadrangle the Molas occurs principally as a filling in caves and channelways in the Leadville Limestone (or Dolomite), but locally a few inches to a few feet of it lies between the Leadville and the Belden Formation. A few miles south of the quadrangle the Molas reaches a thickness of as much as 70 ft (21 m) in local areas, and at Leadville it is as much as 40 ft (12 m) thick (Tweto, 1968b, p. 688, 701). Where present in such thicknesses, the Molas consists of reworked regolithic materials and silts and sands from other sources. Thus, thickness of the Molas is not a measure of amount or duration of weathering of the Leadville. Because it is so thin and discontinuous in the Minturn quadrangle, the Molas was not mapped as a separate formation but was included with the Belden Formation.

In most exposures in the Minturn quadrangle the Molas has been altered and bleached by hydrothermal action, and the bright yellow and red colors characteristic of the formation elsewhere are uncommon. The principal occurrence is as a filling in caves, which are exposed widely in the mine workings. The Molas of this occurrence consists of sericitic silt, clayey material, very fine grained sandstone, and variable amounts of fragmental chert. Except for some of the chert, these materials are bleached white and are soft and pasty. They normally have a highly contorted, kneaded structure and evidently have flowed plastically independent of their competent wallrocks under the influence of bedding-fault movements and of gravitative adjustments in the massive bodies of sulfide ores. This material is called "shaly lime" by the mine geologists at Gilman, though it is not calcareous.

Lenses of Molas lying at the top of the Leadville (stratigraphic section of the Belden Formation) are principally very fine grained sandstone, some of which is conglomeratic and contains pebbles of quartzite, limestone, and chert. In places a carbonaceous fossil soil zone is preserved at the top of the Molas, immediately beneath the basal shale of the Belden.

The weathering and erosion that produced the regolithic Molas Formation destroyed some part of the stratigraphic record of the Mississippian; therefore, the date at which the Molas began to accumulate cannot be certainly fixed. Erosion probably began in Mississippian time, as rocks representing most of the Upper Mississippian are absent over a wide region in Colorado and bordering areas. The regolith of the Molas, however, probably represents only the latter part of the long time span involved. In the Minturn quadrangle, the Pennsylvanian marine transgression occurred in early Middle Pennsylvanian time. The Molas probably is not much older.

PENNSYLVANIAN AND PERMIAN SYSTEMS

The Mississippian and older rocks of the Minturn quadrangle and neighboring areas are overlain by as much as 10,500 ft (3,220 m) of clastic rocks that are principally Pennsylvanian in age but Permian in the upper part. No physical boundary between the rocks of these two ages has been recognized, and as the time boundary is indistinguishable within unfossiliferous red beds that constitute the upper half of the clastic sequence, the two systems are discussed together.

The Pennsylvanian and Permian rocks were deposited in a long and rather narrow trough that extended from northwestern Colorado southeastward into New Mexico. In central Colorado, this trough lay between two highlands that were the source of the sediments—the Front Range highland on the northeast and the Uncompahgre–San Luis highland on the southwest. Both of these highlands were elements of the so-called Ancestral Rockies, elevated in Pennsylvanian time. Within the trough, coarse clastic sediments were deposited near the bordering highlands, and evaporites were deposited in basins strung along the center of the trough. The regional distribution of these sediments and the general paleotectonic setting have been described by Lovering (1929), Lovering and Johnson (1933), Brill (1952), Curtis (1958), Mallory (1958), and Hallgarth (1967).

The Minturn quadrangle straddles the boundary between the depositional trough and the flank of the Paleozoic Front Range highland to the east. Thus, coarse-grained Pennsylvanian and Permian clastic rocks that cover much of the quadrangle wedge out rapidly against the flank of the Gore Range, which was part of the early highland. The quadrangle also straddles the boundary between the clastic and the evaporite facies of the Pennsylvanian and Permian rocks, and thus the clastic rocks pass westward into gypsiferous fine-grained sediments in the area where the Eagle River leaves the quadrangle.

Many different nomenclatures have been applied to the Pennsylvanian and Permian rocks as a consequence of their relatively great thickness, their lenticularity, their facies changes, and the paucity of diagnostic fossils in their upper half. History of the nomenclature has been reviewed by Brill (1944; 1952) and Tweto (1949) and will be considered only briefly here. Shaly and limy strata at the base of the sequence were originally called Weber shale by Emmons (1882), and coarse clastic rocks of gray aspect above them were called Weber grit. Eldridge (1894) applied the name Maroon formation to all the strata between the Weber shale (or limestone) and what is now recognized as the Jurassic Entrada Sandstone in the Crested Butte area.

In the Tenmile (Kokomo) area immediately southeast of the Minturn quadrangle, Emmons (1898) restricted the Maroon to the lower part of the red-bed sequence above the gray Weber grit and applied the name "Wyoming formation" to the upper part of the red-bed sequence. The term Wyoming was later abandoned, and the term Maroon was applied to all the red beds above the Weber grit (or "Wever? formation") in west-central Colorado (Johnson, 1934). Brill (1942) proposed the name "Battle Mountain formation" for all of the former Weber shale and Weber grit plus all but the uppermost part of the former Maroon. In doing so, he distinguished the former Weber shale as the Belden Shale Member of the Battle Mountain, and he applied the name State Bridge Formation—obtained from a report by Donner (1936, 1949)—to the uppermost and fine-grained part of the red-bed sequence. In the preliminary Minturn report, Lovering and Tweto (1944) applied the term Maroon Formation to all the strata between the Leadville and the Triassic rocks, distinguishing the Belden as a member. In the same year, Brill (1944) abandoned the term Battle Mountain, replacing it with Maroon Formation, and elevated the Belden to formation rank.

On the basis of work in the adjoining Holy Cross quadrangle as well as the work in the Minturn quadrangle, Tweto (1949) defined the Minturn Formation as including the strata, about 6,000 ft (1,830 m) thick, between the Belden and the top of a well-known limestone unit defined as the Jacque Mountain Limestone Member of the Minturn. Pennsylvanian(?) and Permian red beds above the Jacque Mountain were assigned to a restricted Maroon Formation. In this usage, gypsiferous strata were regarded only as facies of the three recognized formations, Belden, Minturn, and Maroon. In the Glenwood Springs area, however, Bass (1958) and Bass and Northrop (1963) applied the southwestern Colorado name Paradox Formation to the main gypsum unit, and referred all Pennsylvanian rocks beneath it (except the Molas) to the Belden, and the pre-Triassic red beds above it to the Maroon Formation. Subsequently, Lovering and Mallory (1962) assigned the gypsiferous rocks to a new formation, the Eagle Valley Evaporite, noting that with disappearance of the Jacque Mountain Limestone Member in the "gypsum basin" immediately west of the Minturn quadrangle, no lithologic basis exists there for distinguishing the Minturn and Maroon Formations. The Eagle Valley was later further described by Mallory (1971).

In summary, the sequence of Pennsylvanian and Permian rocks in the Minturn quadrangle is divided into three units: (1) a thin basal unit, the Belden Formation, 0–200 ft (0–61 m) thick, (2) the Minturn Formation, as much as 6,300 ft (1,920 m) thick, and (3) the Maroon Formation, as much as 4,200 ft (1,280 m) thick. A fourth unit, the Eagle Valley Evaporite, laterally equivalent to part or all the Minturn and part of the Maroon, is recognizable at the western boundary of the quadrangle but is not distinguished on the map (pl. 1).

BELDEN FORMATION

Interbedded dark-gray to black shale, limestone, and sandstone at the base of the Pennsylvanian sequence in west-central Colorado was first designated the Belden Shale Member by Brill (1942, p. 1385), then the Belden Shale (Brill, 1944, p. 624), and finally the Belden Formation (Brill, 1952, p. 812). The type section as designated by Brill (1942) is in cuts along U.S. Highway 24 on the north side of Rock Creek, opposite Gilman. The name was taken from the station of Belden on the railroad in the canyon bottom below Gilman (fig. 8), and the station name was derived in turn from the Belden mine, in the canyon wall at Gilman.

In the Minturn quadrangle the Belden Formation is exposed only along the canyon of the Eagle River or near the mouths of tributary canyons, as of Turkey Creek and of Rock Creek. In this area the formation is about 200 ft (61 m) thick but it probably wedges out rapidly to the northeast beneath the Minturn Formation, for it is absent along the Gore fault, as is also the lower half of the Minturn Formation. From the Minturn quadrangle the Belden thins southward to as little as 25 ft (7.5 m) (Tweto, 1949; 1953; 1956) and then thickens abruptly to as much as 400 ft (122 m) at Leadville (Tweto, 1968b). Westward from the quadrangle, the Belden thickens to more than 600 ft (183 m) (Brill, 1944, p. 644, 653) and locally to as much as 900 ft (274 m) (Murray, 1958, p. 50). As applied by Bass (1958) and Bass and Northrop (1963), who extended it up to the gypsiferous unit they called the Paradox Formation, it is 600–1,000 ft (183–305 m) thick in the Glenwood Springs quadrangle.

The Belden (fig. 10) consists principally of dark-gray to black shale and interbedded thin-bedded black limestone, but it also contains thin beds of dark-gray fine-grained sandstone and sandy mudstone, and lenses of brown-weathering black dolomite. Locally, it also contains lenses of impure coal a few inches thick and thin beds or lenses of dirty brown anhydrite or gypsum. Proportions of the various constituents range widely, though shale generally predominates. At the type section the Belden contains little sandstone, but elsewhere, particularly to the south, it contains abundant fine-grained sandstone and quartzite.

The base of the Belden is sharply defined and generally is marked by black shale lying unconformably on Leadville Limestone (or Dolomite) or on the regolithic material comprising the Molas Formation. The black shale is the "caprock" of the mineralized area near Gilman; there, the contact with the Leadville is quite irregular, owing not only to the karst topography at the top of the Leadville but also to low-angle faults along the contact and to slump collapse over a second generation of channels and caves formed by hydrothermal action during mineralization. A porphyry sill of Late Cretaceous age lies within the Belden in the Gilman–Red Cliff area (fig. 18). The sill is 5–30 ft (1.7–9 m) above the base of the Belden and is 30– 80 ft (9–24 m) thick.

The top of the Belden is marked in the Gilman area by a channeled surface above which are thick-bedded coarse-grained gray and green micaceous sandstones of the Minturn Formation (fig. 11). In many places, however, the contact with the Minturn is gradational. In such places the contact is placed at the level where sandstone and green-gray micaceous shale begin to predominate over black shale and limestone.

In defining the Belden, Brill (1942, p. 1385–1386) presented a type section that does not clearly indicate the location of the top of the formation, or its thickness.

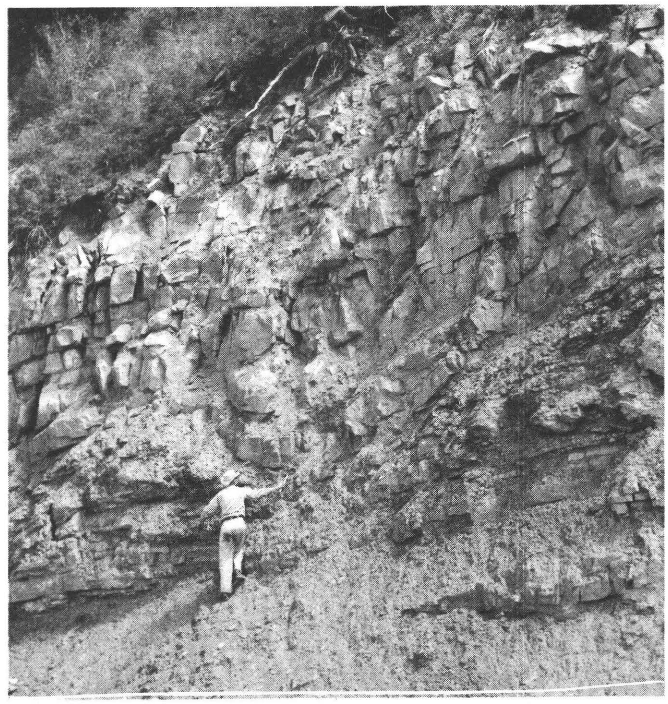


FIGURE 11.—Channeled contact (at man's hand) between thin-bedded rocks of the type section of the Belden Formation (north of Gilman) and overlying thick-bedded sandstone of the Minturn Formation.

FIGURE 10.—Belden Formation in roadcut on U.S. Highway 24, 1.2 mi (1.9 km) north of Gilman. Lower part of Minturn Formation is exposed in cliff at upper left.

The following emended type section corrects these shortcomings and illustrates in greater detail the character of the Belden.

Emended type section of the Belden Formation and section of the Molas Formation

[Section measured along U.S. Highway 24 on the north side of Rock Creek, 0.25 mi (400 m) north of Gilman. Section begins at U-shaped bend in highway at Rock Creek and extends west-southwest along highway to top of Leadville Dolomite at curve where highway turns north. See fig. 8]

	Thickness (feet)	*Distance above base (feet)*
Minturn Formation:		
Arkosic sandstone and conglomeratic grit with sparse quartz pebbles.		
Scour-and-fill contact		198.0
Belden Formation:		
27. Clay shale, dolomitic shale, and dolomite, interbedded. Shale is dark gray to grayish black, except some layers at top are dusky red to dark olive gray; is noncalcareous and slightly micaceous, except highly micaceous at top. Some of shale beds cut across underlying beds in troughs as much as 3 ft deep, making pinch-and-swell structure. Dolomite is dark to light gray and in beds 3–12 in. thick	9.5	188.5
26. Shale, bluish gray to dark gray, thin- and irregular-bedded, noncalcareous	6.0	182.5
25. Shale, dolomite, and mudstone, interbedded. Shale is dark gray to black and fissile. Dolomite is mottled		

Emended type section of the Belden Formation and section of the Molas Formation — Continued

	Thickness (feet)	Distance above base (feet)
Belden Formation — Continued		
25. Shale, dolomite, and mudstone — Continued light pinkish gray and light gray; weathers yellowish brown to light orange brown; is thin bedded, vuggy, and medium grained; occurs in beds 3–10 in. thick. Lower $2^{1}/_{2}$ ft of unit is olive-gray dolomitic shale and mudstone. Productid brachiopod impressions in shale 4 ft above base of unit	8.0	174.5
24. Shale and limestone, interbedded; are medium gray; weather light yellowish brown and yellowish gray. Shale is calcareous, micaceous, and laminated. Some is crystalline, in beds 3–6 in. thick	7.0	167.5
23. Dolomite, recrystallized, calcitic, light-gray to white; contains many small vugs lined with coarse crystals of dolomite	0.5	167.0
22. Limestone, shale, and mudstone, dark-gray.	4.0	163.0
21. Shale and limestone, interbedded. Shale is dark olive gray to grayish black, fissle, and finely micaceous. Limestone is argillaceous, dense to very fine grained, and medium gray; weathers light olive gray; is medium bedded but breaks into 1-in. rhombic blocks	8.0	155.0
20. Sandy limestone, medium-gray; weathers tan; is thin bedded. Quartz sand is fine to very fine grained and most abundant at top	1.0	154.0
19. Shale, somewhat calcareous, and minor interbedded platy dolomitic limestone. Shale is olive gray; weathers light olive gray; is thin and irregular bedded; is fissile and micaceous near top	7.0	147.0
18. Limestone, yellowish-brown to dusky-red, thin-bedded; lower part is micaceous; contains fragments of shale $^{1}/_{4}$–$^{3}/_{4}$ in. in diameter, and small amount of fine sand	1.0	146.0
17. Limestone and shale interbedded. Limestone is dark gray, dense to fine grained, thin to medium bedded; upper 4 in. is banded brown dolomite. Shale is olive gray to dark gray	2.0	144.0
16. Covered zone, mostly dark shale and minor limestone	30.0	114.0
15. Shale and limestone. Shale is medium gray; weathers light gray; is fissile. Limestone is dark to very dark gray, in beds 1–6 in. thick; makes up about 10 percent of unit	4.0	110.0
14. Limestone and shale. Limestone is medium gray; weathers light orange brown; is dense to very fine grained and thin to medium bedded. Shale is medium gray; weathers medium orange brown; is most abundant in lower part of unit	7.0	103.0
13. Limestone, dense, medium-gray to medium-olive-gray; weathers olive gray to yellow brown and blocky, except top 1 ft weathers rounded; 6-in. bed of dark-gray shale in middle of unit	4.0	99.0
12. Limestone and shale. Limestone is dark to medium gray, dense to very fine grained, and thin to medium bedded; composes 70 percent of unit. Shale is very dark gray to black, and very thin bedded to fissile	17.0	82.0
11. Shale and limestone, dark-gray; weather light orange brown; limestone is platy, in 1- to 2-in. beds.	5.0	77.0
10. Mudstone and limestone, clayey, dark-bluish-gray; weather olive brown; are thin bedded	7.0	70.0
9. Shale and limestone, interbedded; are dark to very dark gray. Shale is noncalcareous and fissile. Limestone is dense to fine grained, thin to medium bedded, and has flaggy to platy fracture; 2-ft bed of limestone at top weathers yellowish brown.	20.0	50.0
8. Limestone, dark-bluish-gray; weathers yellowish brown to dark brown, somewhat speckled with black; is dense to very fine grained, and medium bedded; has irregular upper and lower surface.	3.0	47.0
7. Shale, dark-gray to dark-greenish-brown; weathers gray to brown; is laminated to very thin-bedded.	1.5	45.5
6. Mudstone, calcareous, greenish-brown; weathers light buff brown to light brownish gray; has thin, irregular bedding.	4.0	41.5
5. Shale, limestone, and shale-chip conglomerate. Shale is black to brownish black; weathers black to gray; is fissile; in top 1.5 ft of unit, is greenish gray, limy, and contains shale fragments as much as $1^{1}/_{2}$ in. across and $^{1}/_{4}$ in. thick. Limestone is black; weathers light yellow brown to light orange brown; is thin to medium bedded with irregular bedding surfaces; is somewhat vuggy. Unit lies on porphyry sill.	10.5	31.0
Porphyry sill, light-gray to orange-gray or pinkish-gray; weathers buff to yellowish-gray. Approximate thickness of about 60 ft (18 m) is not included in the stratigraphic distances.		
4. Shale, black, contorted; lies beneath porphyry sill.	2.0	29.0

Emended type section of the Belden Formation and section of the Molas Formation — Continued

	Thickness (feet)	Distance above base (feet)
Belden Formation — Continued		
3. Limestone and shale. Limestone is medium to very thin bedded or laminated; is in layers 6–18 in. thick separated by shale partings; contains echinoid spines 3 ft above base.	7.0	22.0
2. Shale and sandstone, interbedded. Shale is grayish black; weathers dark gray; is fissile to very thin and irregular bedded. Sandstone is dark gray, in thin lenticular beds.	18.0	4.0
1. Shale and limestone, dark-gray to black, thin- to medium-bedded. Shale is platy and irregular bedded. Limestone is shaly and slabby.	4.0	0
Total measured thickness of the Belden Formation	198.0	
Erosional unconformity.		
Molas Formation:		
Regolithic mudstone and chert; uppermost layer is fissile carbonaceous shale that suggests old soil	2.0	
Sandstone, conglomeratic, white. Matrix is very fine grained, well-sorted quartz sand. Pebbles are white quartzite, black limestone and dolomite, and subordinate chert, 1/2 –3 in. in diameter	8.0	
Total measured thickness of the Molas Formation	10.0	
Erosional unconformity marked by pinnacles of Leadville Dolomite rising 10–15 ft (3–4.5 m) above general level of formation; Molas in the depressions between pinnacles.		
Leadville Dolomite.		

The Belden Formation is moderately to highly fossiliferous. On the basis of its fossils, it has been assigned ages ranging from late Early Pennsylvanian to middle Middle Pennsylvanian, or from Morrowan through Atokan to Des Moinesian. Brill (1944, p. 626) assigned it a Des Moinesian (Cherokee) age based on collections from unspecified localities in west-central and northwestern Colorado. Henbest (in Thomas and others, 1945; also in Henbest, 1946) and Thompson (1945) assigned at least the lower part of the Belden in the Glenwood Springs area to the Morrowan. Bass and Northrop (1963, p. J35) considered the lower 600 ft (183 m) of the Belden in the Glenwood Springs area to be Morrowan in age and the remainder to be Atokan.

The Belden of the type section near Gilman and of nearby localities in the Minturn and Holy Cross quadrangles is classed as Atokan (early Middle Pennsylvanian) in age by Mackenzie Gordon, Jr., and E. L. Yochelson of the U.S. Geological Survey (written commun., Feb. 16, 1966), based on studies of eight collections of megafossils. The fossils reported by Gordon and Yochelson are listed in table 4. Their statement follows:

The Belden Shale at its type section is relatively fossiliferous throughout, but the fossils are not sufficiently short-ranged to determine a precise age. Nevertheless, it is possible to arrive at an approximate age for this formation. First, the absence of typical Des Moinesian brachiopod species, such as *Desmoinesia muricatina* (Dunbar and Condra) and *Mesolobus mesolobus* (Norwood and Pratten) in the Belden, as well as the presence of *Fusulinella* of late Atokan age in the overlying Minturn Formation eliminates the possibility of Des Moinesian age for the Belden in the Minturn quadrangle. Brill (1944, p. 626) assigned a Des Moinesian (Cherokee) age to the Belden, but his faunal list from unspecified localities includes species that we have not found in the type Belden Shale. It would seem likely, therefore, that Brill's fossils came from areas where Belden-like lithology includes rocks of Des Moinesian age. In a later paper, Brill (1952, p. 814, 815) assigned a late Morrowan age to the lower part of the Belden as far south as Glenwood Springs. He assigned an early Des Moinesian (Cherokee) age to the uppermost part at Whiskey Creek Pass, Sangre de Cristo Mountains, and stated that the Belden seems to be a facies that crosses time lines.

The fauna of the Belden Shale in the Minturn region does not contain elements typical of either the fauna of the type Morrow Series of Arkansas or of its Lower Pennsylvanian equivalents in the Great Basin in western Utah and Nevada. The nearest affinities are to be found in the fauna of the upper Pottsville Formation of Ohio and of the Kanawha Member in the upper part of the Pottsville Formation of West Virginia. Of 15 taxa listed in table 4 that have been either definitely or questionably identified to described species, 10 occur in the upper Pottsville of Ohio. A common Belden species has been compared with *Aviculopecten eaglensis* (Price) of the Kanawha Formation.

The available evidence points to an Atokan age for the type Belden, though it is not conclusive. Similarities between this fauna and that of the upper Pottsville may be controlled in part by facies. The possibility that the lower part of the Belden might be of late Morrowan age cannot be eliminated entirely.

Extensive search for fusulinids in the Belden of the type section and neighboring areas by L. G. Henbest, Ogden Tweto, and others was generally fruitless, although Henbest found very sparse *Millerella* sp. together with *Endothyra* sp. and *Osagia* or *Girvanella* sp. about 55 ft (17 m) above the Leadville Dolomite and 4 ft (1.3 m) below an ostracode-bearing limestone in the type section of the Belden (L. G. Henbest, written commun., Oct. 2, 1958). As noted by Thompson (1945, p. 42) and Henbest (in Bass and Northrop, 1963, p. J40), the mere presence of *Millerella* does not prove a Morrowan age. Henbest (written commun., Oct. 2, 1958) concluded as follows:

No significant foraminiferal evidence on the age of the Belden shale in the vicinity of the type section has been found. Foraminifera indicating Early(?) Pennsylvanian age have been reported, by me, from Glenwood Springs and Wellsville on the Arkansas River below Salida. The evidence from larger fossils for a Middle Pennsylvanian age of the Belden at the type section is not positive, but I think that it has greater weight than an age determination based solely on correlations with the Wellsville and Glenwood Springs areas. In other words, the Belden shale may, and probably does, differ locally in age. At the type section, a Middle Pennsylvanian age seems most likely.

TABLE 4. — *Fossils in the Belden Formation*

[X, several; R, rare; ?, questionable occurrence; A, abundant; C, common]

Name	Collection No.							
	9869–PC	9870–PC	9871–PC	9892–PC	12089–PC	13048–PC	13053–PC	14580–PC
Bryozoans:								
Rhomboporoid indet	X	...	X	...	...	...	...	...
Pelmatozoans:								
Crinoid columnals	X	X	...	...	...	...	...	...
Cidarid spines (Echinoid)	R	...	...	...	X	...	...	...
Brachiopods:								
Lingula carbonaria Shumard?	...	...	...	...	?	...	...	...
Lingula tighti Herrick	...	...	...	...	...	...	A	A
Orbiculoidea sp	...	R	...	...	X	...	...	...
Derbyia crassa (Meek and Hayden)	C	...	...	...	...	...	...	A
Derbyia? sp. indet	...	...	X	...	R	...	...	...
Eolissochonetes sp	C	C	C	C	C	X	...	A
Orthotichia schuchertensis Girty	C	?	...	...	...	...	...	...
Echinoconchus sp	...	...	...	R	...	...	...	...
Antiquatonia coloradoensis (Girty)	C	?	C	...	...	...	...	...
Linoproductus prattenianus (Norwood and Pratten)?	X	X	...	X	...	...	...	...
Linoproductus sp. indet	...	...	...	...	...	...	...	R
Anthracospirifer rockymontanus (Marcou)	...	...	X	...	...	...	...	...
Anthracospirifer sp. indet	...	...	R	...	...	...	...	...
Condrathyris perplexa (McChesney)	...	...	...	A	A	...	X	...
Pelecypods:								
Nuclopsis cf. *N. girtyi* Schenck	...	...	...	...	...	R	...	...
Nucloidea sp	R	...	...	...	...	...	...	...
Parallelodon tenuistriatus (Meek and Worthen)	R	...	C	...	...	...	...	...
Edmondia sp	...	...	...	...	...	R	...	...
Posidonia sp	...	...	...	...	...	...	C	...
Aviculopecten cf. *A. eaglensis* Price	X	X	X	...	...	C	R	...
Pernopecten cf. *P. ohioensis* Newell	R	...	...	...	...	...	...	...
Pectenoid, genus and species indet	...	...	...	...	R	...	...	...
Myalina sp	R	...	...	...	...	R	...	...
Septimyalina? sp. indet	...	X	X	...	...	...	...	...
Bakevellia sp	...	R	...	...	...	...	...	...
Schizodus sp	X	...	X	...	...	R	...	...
Schizodus sp. indet	...	...	X	...	...	...	...	...
Permophorus sp	...	C	X	...	...	X	...	A
Astartella concentrica (Conrad)	C	C	X	...	...	X	...	...
Pelecypod indet	...	X	...	...	...	X	...	...
Gastropods:								
Knightites (*Cymatospira*) sp	R	...	...	...	...	...	...	...
Knightites (*Retispira*) sp	C	...	...	...	...	...	...	...
Glabrocingulum sp. indet	?	...	...	...	...	R	...	...
Pleurotomaracean, gen. and sp. indet	X	...	...	...	...	...	...	...
Murchisonia? sp. indet	R	R	...	...	...	R	...	...
Straparollus (*Euomphalus*) sp	X	...	...	...	...	...	...	...
Cephalopods:								
Pseudorthoceras knoxense (McChesney)?	R	...	...	...	...	...	...	...
Trilobites:								
Pygidium undetermined	...	...	R	...	...	...	...	...

TABLE 4 COLLECTION LOCALITIES AND DESCRIPTIONS

9869–PC	In type section of Belden Formation, in roadcut of U.S. Highway 24 on north side of Rock Creek, opposite Gilman, in limestone and shale about 100 ft (30.5 m) stratigraphically above base of Belden. (Approximately unit 13 of emended type section.) Collected by J. S. Williams, T. S. Lovering, and Ogden Tweto, July 20, 1941.
9870–PC	Same as 9869–PC, but 100–150 ft (30.5–45.7 m) farther east along highway and about 60 ft (18.3 m) higher stratigraphically, or about 160 ft (48.7 m) above base of Belden. (Approximately unit 21 of emended type section.)
9871–PC	Same as 9869–PC and 9870–PC, but 100 ft (30.5 m) farther east along highway, near top of Belden. (Approximately unit 33 of emended type section.)
9892–PC	From shale above porphyry sill in Belden Formation, on mountainside north of high bridge carrying U.S. Highway 24 over the Eagle River one-half mile (0.8 km) southwest of Red Cliff. (Probably 20–30 ft (6–9 m) above base of Belden.) Collected by L. G. Henbest, Sept. 28, 1945.
12089–PC	From undetermined stratigraphic position in Belden Formation, on west slope of southern prong of Battle Mountain, between 9,200- and 9,300-ft contours, 0.4 mi (0.6 km) N. 40° W. of high bridge carrying U.S. Highway 24 over the Eagle River 0.5 mi (0.8 km) southwest of Red Cliff. Collected by L. G. Henbest, Sept. 1945.
13048–PC	In type section of Belden Formation, in uppermost part. Locality about same as 9871–PC. Collected by Ogden Tweto, E. L. Yochelson, G. W. Weir, and R. E. Davis, Aug. 11, 1952.
13053–PC	From Belden Formation in roadcut on U.S. Highway 24, 1.2 mi (airline) north of Gilman. In cut on west side of highway and about 75–80 ft (22.8–24.3 m) above Leadville Dolomite. Collected by E. L. Yochelson, G. W. Weir, and R. E. Davis, Sept. 12, 1952.
14580–PC	From 8-ft (2.4-m) unit of limestone with shaly partings (unit 4 in Tweto, 1949, p. 228), 49 ft (14.9 m) above base of Belden Formation, on south bank of Silver Creek, NE1/4SW1/4sec. 33, T. 6 S., R. 80 W., Holy Cross quadrangle, 2.5 mi (4 km) southeast of Red Cliff. Collected by Mackenzie Gorden, Jr., and E. L. Yochelson, July 25, 1953.

As shown on an isopach map by Brill (1944, fig. 2) the Minturn quadrangle is high on the side of the trough in which the Belden was deposited, and, as previously noted, the depositional margin of the Belden must lie no more than a few miles east of the type section. The age relations previously discussed are in accord with this distributional pattern. Near the center of the trough, in the Glenwood Springs area where the Belden is thick, the lower part is Morrowan in age and the upper part is Atokan. In the Minturn quadrangle, where the Belden is thin, sedimentation began later and only strata of Atokan age were deposited.

MINTURN FORMATION

The Minturn Formation comprises as much as 6,300 ft (1,920 m) of clastic rocks and subordinate interbedded carbonate rocks of Pennsylvanian age lying above the Belden Formation and below the Maroon Formation. Except as covered in places by the Maroon Formation, the Minturn occupies almost all the area between the Eagle River and the Gore fault, and it is thus the most widespread geologic unit in the quadrangle. Segments of the formation are well exposed in the walls of many of the canyons (fig. 12), but exposures are generally poor in the intercanyon areas. Thus, the formation is not exposed in its entirety in any one place in the quadrangle.

The main body of the Minturn Formation in the Minturn quadrangle is a coarse clastic facies lying between a shoreline of deposition along the flank of the present Gore Range and a fine-grained and evaporitic facies just west of the quadrangle. The formation thins in both these directions. Toward the Gore Range, which is at the western edge of the late Paleozoic Front Range highland, the formation thins by onlap, or the shingling-out of lower beds against the old highland. Near the Gore fault, the entire lower half, or more, of the formation is missing, as discussed in a following section. In the opposite direction, toward the evaporite basin, the thinning is far less pronounced and is internal, as shown by diminishing thicknesses between carbonate marker beds.

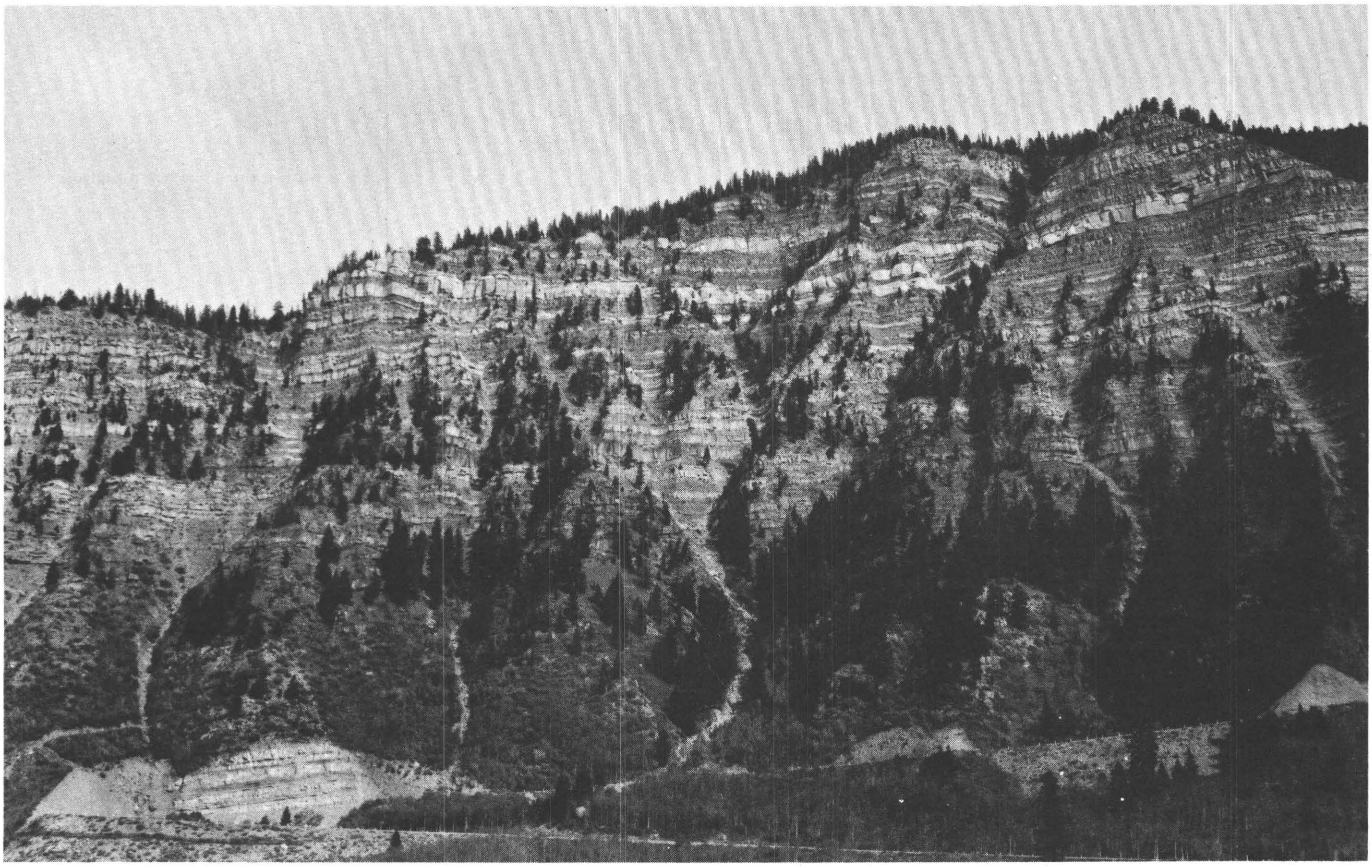


FIGURE 12.—Lower part of the Minturn Formation, in cliffs on the east side of the Eagle River near Two Elk Creek. Vertical distance from upper switchback in highway to skyline is 1,200–1,400 ft (365–427 m).

The clastic rocks that make up the bulk of the formation are varied but in general are highly arkosic, coarse grained, and poorly sorted. They are extremely lenticular and many of the beds or lenses change rapidly in lithology in short distances. The rocks are also poorly exposed over wide areas. Consequently, the clastic rocks present great difficulties in the tracing of stratigraphic levels and the determination of detailed geologic structure. In contrast, the limestone and dolomite beds interbedded with the clastic rocks are relatively persistent and are moderately well exposed. They constitute the only reliable stratigraphic markers in this thick formation. Though only a few of the carbonate beds have proved to be widely persistent, many others serve as local markers useful in stratigraphic bridging from area to area. In mapping, nearly all the principal carbonate beds were "walked out" as a means of establishing stratigraphic control and determining the presence or absence of faults.

SUBDIVISION

In defining the Minturn Formation, Tweto (1949) designated seven of the principal carbonate beds or zones as members in the Pando area (fig. 13). The lower three of these—the Wearyman, Hornsilver, and Resolution Dolomite Members—at about 2,600, 2,900, and 3,700 ft (793, 884, and 1,128 m), respectively, above the base of the formation, were newly named at that time. The upper four—the Robinson, Elk Ridge, White Quail, and Jacque Mountain Limestone Members—were named earlier in the adjoining Kokomo district, where they are the host rocks of ore deposits (Emmons, 1898; Koschmann and Wells, 1946). The Jacque Mountain, the highest persistent limestone in the Pennsylvanian-Permian sequence, is the uppermost unit of the Minturn Formation and defines the top of the formation (Tweto, 1949).

Not all of the seven carbonate members are persistent throughout the Minturn quadrangle. Further, the members were defined in the Pando area after most of the mapping in the Minturn quadrangle was completed, and no attempt was subsequently made to trace each one through the Minturn quadrangle. Consequently, only the Robinson, Jacque Mountain, and—to a lesser degree—the White Quail are distinguished widely on the geologic map (pl. 1). The other members are distinguished locally. In the Robinson, which consists of several limestone beds separated by clastic rocks, only

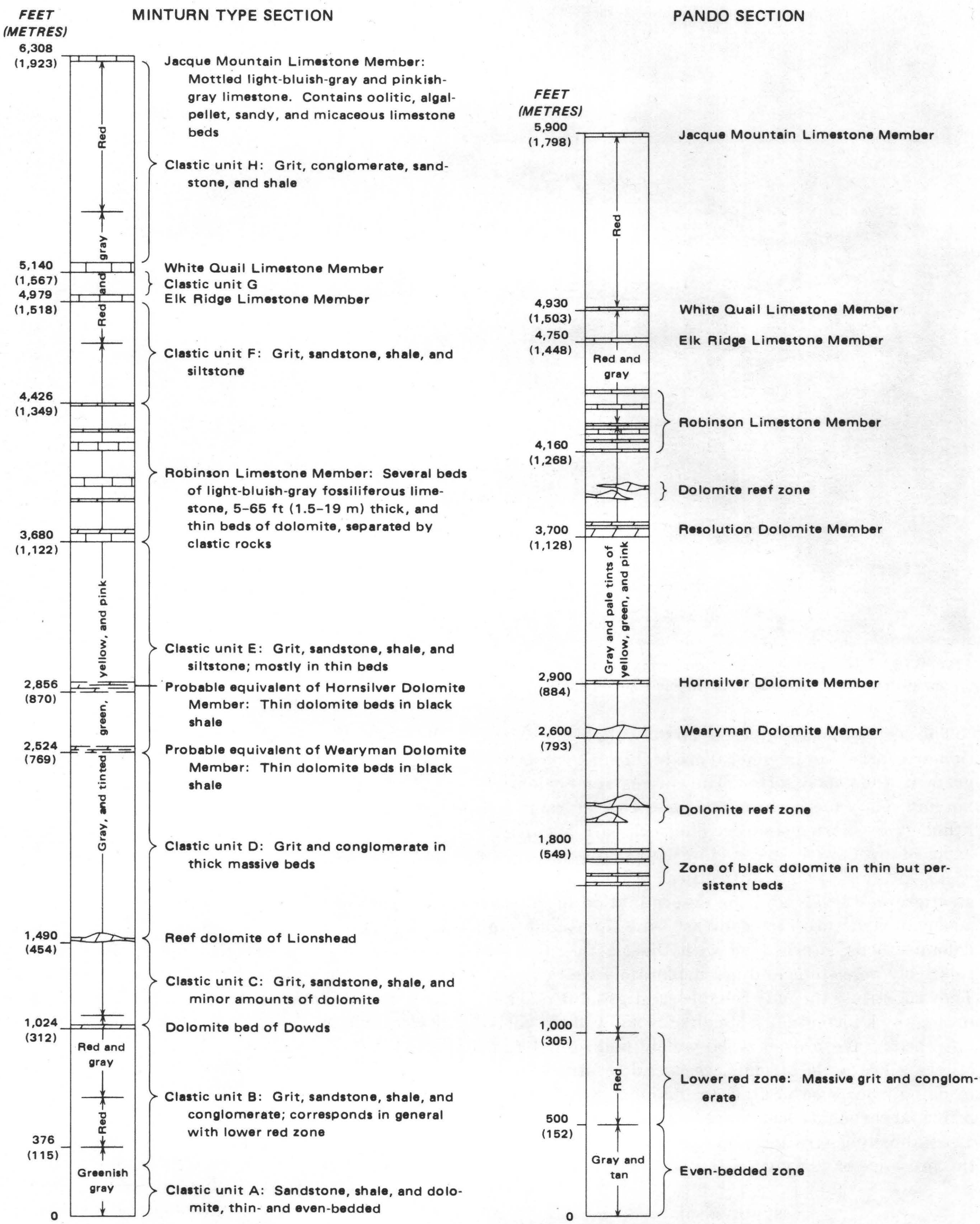


FIGURE 13.—Subdivisions and general character of the Minturn Formation in Minturn quadrangle, and comparison with stratigraphic section in Pando area, Holy Cross quadrangle.

the thickest and most prominent beds are distinguished. These beds are not necessarily the bounding carbonate beds of the member.

Clastic rocks between the various carbonate beds or members are all generally similar except that some of them differ in color, and some units have either more massive or thinner bedding than other parts of the formation. For purposes of reference, the clastic rocks are divided into lettered units A—H, bounded by the carbonate members or by certain carbonate beds of more local occurrence, as indicated in figure 13.

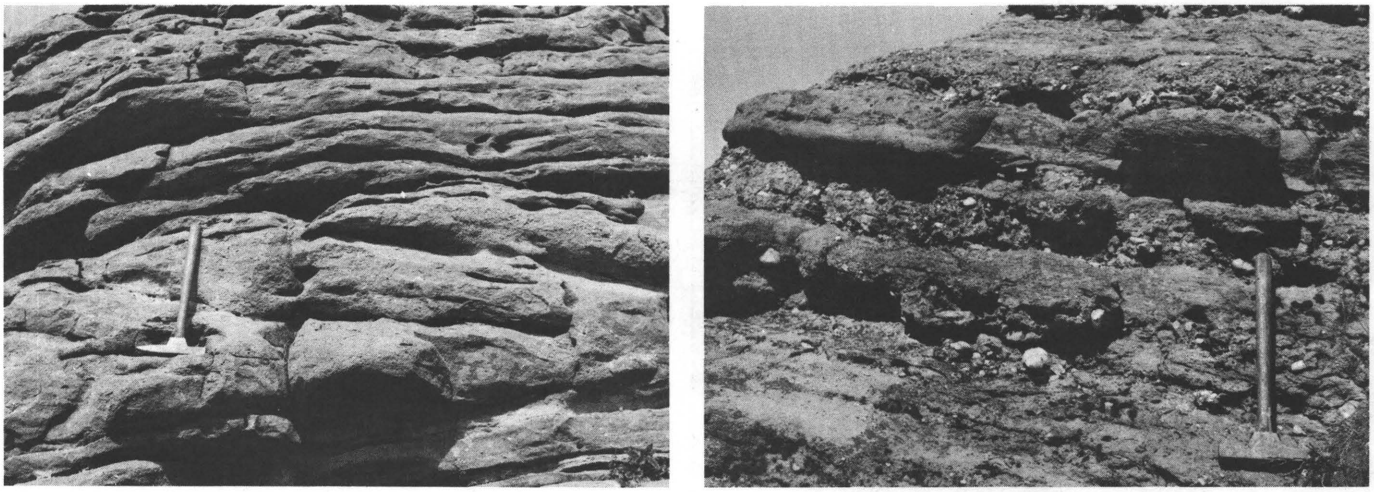
Attempts have been made in the past to subdivide the thick sequence of Pennsylvanian and Permian rocks in the region on the basis of color, as some of the rocks are gray and some are red, but the color boundaries migrate stratigraphically by as much as hundreds of feet in short distances and can be only indefinitely located in thick zones of interbedded red and gray rocks. Thus, except in a very general way, color is unreliable as an indicator of stratigraphic position. The Minturn Formation is predominantly gray, or pale tints of green, yellow, and pink, but it contains a dull red zone in its lower part and a zone of brighter red at its top. In the middle part of the Minturn quadrangle, the lower red zone extends from about 375 ft (114 m) above the base of the Minturn Formation to about 1,075 ft (328 m) above the base; the lower half of this zone is almost entirely red, and the upper half is alternating red and gray. In the Pando area a few miles to the south, in contrast, the lower red zone occupies the interval between 500 and 1,000 ft (152 and 305 m) above the base of the formation (Tweto, 1949, p. 194, 220–222). Similarly, in the Minturn quadrangle, the upper red zone lies about 4,750 ft (1,450 m) above the base of the formation and consists of 700 ft (215 m) of alternating red and gray rocks overlain by 800 ft (245 m) of almost entirely red rocks. In the Pando area (Tweto, 1949), the upper red zone lies 4,300 ft (1,310 m) above the base and consists of about 600 ft (185 m) of alternating red and gray rocks overlain by about 950 ft (290 m) of entirely red rocks.

LITHOLOGY

Exclusive of the volumetrically minor carbonate beds, the Minturn Formation consists of interbedded—or interlensed—grit, sandstone, conglomerate, shale, and siltstone, with grit the predominating and characterizing rock type. As applied here, grit is coarse grained, poorly sorted in size and shape of grains, markedly feldspathic, generally micaceous, and friable to firmly cemented. In most of it, a conspicuous fraction of the grains is very coarse sand (1–2 mm in diameter), and much of it contains abundant particles of granule size (2–4 mm), as well as scattered pebbles, or even cobbles several inches in diameter. Quartz is the most abundant constituent, but a large fraction of the grains is pink feldspar (microcline) derived from Precambrian pegmatites; plagioclase also is an abundant but less conspicuous component. Many of the feldspar grains are sharp-edged cleavage fragments. Coarse, ragged flakes of detrital muscovite are common in the grit; flakes of dark mica are somewhat less common. In a zone roughly 500–2,500 ft (150–760 m) above the base of the Minturn, the grit also contains rather abundant particles of dark-green chlorite phyllite. Pebbles in the grit are mainly quartz of the bull-quartz type, derived from Precambrian pegmatites and quartz veins, but some are feldspar fragments or rocks of various types, such as pegmatite, granite, and gneisses. The pebbles are well rounded to sharply angular. Pebbles of sedimentary rocks are rare and are found principally in the lower part of the formation.

Most of the sandstone in the Minturn Formation is also feldspathic, micaceous, and poorly sorted; it differs from the grit only in being finer grained and, commonly, in having a smaller proportion of angular grains. Though some relatively pure quartz sandstone is present in the Minturn, particularly in the lowermost part, most of the sandstone and grit is arkose by the definition of Pettijohn (1957, p. 291). Some beds of sandstone and grit contain abundant dark rock and mineral grains and might be called graywackes in the old sense of the term, but they lack the fine-grained matrix that is nowadays implicit in the term (Pettijohn, 1957, p. 301). Petrographic study by Boggs (1966, p. 1414) of 68 samples of sandstone showed very wide ranges in mineral compositions and a mean composition among the detrital grains of 50.5 percent quartz, 34.3 percent feldspar, 6.4 percent micas, 6.3 percent rock fragments, minor amounts of mud coatings and heavy minerals, and a trace of clay minerals. Boggs found that the cement is dominantly calcite but is silica in some samples. His samples apparently came from along Gore Creek and westward along the Eagle River, where rocks of the Minturn are generally finer grained and less feldspathic than those to the south.

Most shales and siltstones of the Minturn Formation are micaceous and sandy, though some gray to black clay shale is also present. Some of the micaceous shale contains as much as 50 percent of detrital mica in flakes 1–3 mm in diameter. Sand and silt in the shale and siltstone are generally arkosic. Boggs (1966, p. 1416) made X-ray diffraction studies of 26 samples of these rocks and found illite present in all samples, chlorite in about half the samples, and mixed-layer clays in several. No discrete kaolinite or montmorillonite were found. In a broader study of the clay mineralogy of the Pennsylvanian rocks in central Colorado, Raup (1966) found that the clay minerals in the finer grained rocks of the Minturn Formation are



A *B*

FIGURE 14.—Dolomite in the Minturn Formation in the Pando area. *A*, Crossbedded gritty dolomite 200 ft (60 m) below base of Robinson Limestone Member, 0.5 mi (0.8 km) south of Minturn quadrangle boundary. *B*, Conglomeratic dolomite, a local facies of the Hornsilver Dolomite Member, 1.5 mi (2.4 km) south of Minturn quadrangle boundary.

dominantly illite, mixed-layer illite-montmorillonite, mixed-layer chlorite-vermiculite, and, in the lower part of the formation, some kaolinite. The clay and mica fractions in the samples tested ranged from a trace to 100 percent and averaged less than 50 percent. A suite of 12 samples from near Gilman came mainly from the lower red zone in the Minturn.

Carbonate rocks of the Minturn Formation exhibit many unusual lithologic features resulting from the coarse-clastic environment of deposition. Almost all the carbonate beds are locally sandy or gritty, or even contain pebbles. Many grade laterally into grit, conglomerate, or sandstone, passing through such odd facies as conglomerate made up of quartz and pegmatite pebbles in a matrix of dolomite, or dolomite containing 50 percent by volume of coarse arkosic grit (fig. 14). The carbonate rocks are also prominently micaceous in places. Extreme examples are biotitic limestone that contains as much as 10 percent detrital biotite in a matrix of otherwise pure limestone and "schistose" muscovitic limestone that contains so much muscovite in coarse flakes oriented parallel to the bedding that the rock resembles a coarse mica schist.

The limestones of the Minturn are in part very fine grained or sublithographic and in part calcarenitic, consisting of limestone grains and fossil fragments. Most limestone beds or units contain both of these varieties. Boggs (1966), using the classification of Folk (1959), classified most of the limestone as micrite (lithified carbonate mud), biomicrite (carbonate mud with small fossils or fossil fragments), and oomicrite (oolitic carbonate mud). In a detailed study of the Robinson Limestone Member, Tillman (1971) identified four main facies of limestone: (1) oolite, (2) tubular Foraminifera micrite, (3) phylloid algae facies of biomicrite, and (4) stromatolite facies of laminated micrite. Bedding planes in the limestones are typically rough and scaly, and many near the tops of the limestone units are coated with films of yellowish- or greenish-gray argillaceous matter. In places, such bedding surfaces are studded with small fossils, such as fusulinids. Some limestone units locally contain chert. Most of the limestones are bluish or brownish gray on fresh fracture, but they weather a distinctive light bluish gray. In this respect particularly, the limestones closely resemble those in other Pennsylvanian formations of the region, as in the Hermosa Formation of southwestern Colorado and in the Madera Formation of northern New Mexico.

Dolomite in the Minturn is of three main varieties: (1) Evenly and generally thin-bedded, finely crystalline, dark-gray to black dolomite, most of which weathers brownish gray; (2) massive, vuggy, light-gray to black, brown-weathering, crystalline reef (biohermal) dolomite; and (3) coarsely crystalline, light-gray, buff- to tan-weathering, vuggy hydrothermal dolomite formed either by replacement of limestone or by recrystallization of earlier dolomite. The thin-bedded dark dolomite is generally in layers only 1–5 ft (0.3–1.5 m) thick. This dolomite commonly is interbedded with black shale, and many of the dolomite beds grade on strike into black shale. Some of the dolomite contains abundant black chert, either as long lenticles or as very irregular, scraggly bodies. Also, some of the dolomite is appreciably phosphatic, for it reacts strongly to the qualitative ammonium molybdate test for phosphorus.

The dolomite reefs occur either as isolated bodies surrounded by clastic rocks or as abrupt bulges on thin layers of bedded dolomite or limestone. Most of the reefs have steep and ragged sides; a few have smooth and nearly vertical sides abutted by coarse grits. The reefs are typically a few hundred feet in diameter and 25–100 ft (7.5–30 m) high. However, some are as small as 25 ft (7.5 m) across and 5–10 ft (1.5–3 m) high; others are as large as 1 mi (1.6 km) in diameter. The largest reef in the quadrangle, partly exposed in the bottom of the valley of Two Elk Creek 3 mi(4.8 km) above its mouth, has a visible thickness of almost 500 ft (152.4 m) and a maximum horizontal dimension, including a projecting layer, of about a mile. This and many other reefs contain abundant fossil fragments, particularly in their outer part; some contain areas with concentrically laminated algal structures. The reefs evidently were deposited as algal and bioclastic limestone, and were subsequently dolomitized, perhaps diagenetically.

SEDIMENTARY FEATURES

Many of the lenses of clastic rocks in the Minturn Formation are crossbedded, some of them spectacularly so. Most of the crossbedding is high-angle, medium-scale planar in the classification of McKee and Weir (1953), but simple and trough crossbedding also occur. Scour structures, in addition to those recorded by planar crossbedding, are common also. The scours are of two general magnitudes: (1) small filled channels cut as much as several feet into underlying strata, and (2) channels hundreds of feet wide—seen in cliff exposures—filled by entire beds or lenticular bodies of grit or conglomerate.

Other sedimentary features present in some of the rocks are ripple marks of various kinds and sizes, mud cracks, mud-chip conglomerates, small clastic dikes, raindrop impressions, and, rarely, salt casts.

TYPE SECTION

In defining the Minturn Formation, Tweto (1949) designated the cliffs and area east of Minturn as the type locality but did not present a type section measured at that locality. Instead, he presented a representative section measured in the Pando area, about 10 mi (16 km) to the south. In 1963, T. S. Lovering measured a detailed section of the Minturn at the type locality, presented at the end of this report. That section is here designated the type section of the Minturn Formation, and the section in the Pando area (Tweto, 1949, p. 207–227) is designated a reference section. The main features of the two sections are compared in figure 13.

Because the type section was necessarily measured over a horizontal distance of several miles in rocks that are shingled against an old highland, the thicknesses measured in the type section are not necessarily a measure of the thickness of the Minturn at any given locality. As shown by cross sections (pl. 1), the distance between the Robinson Limestone Member and the base of the Minturn Formation decreases northeastward toward the Gore Range. This is due to progressive pinchout eastward of clastic beds in the lower part of the formation. The western boundary of the area affected by this pinching is not known but is almost certainly west of the outcrops of the major limestones. Therefore, the vertical distance from any given horizon to the base of the formation probably is less in most localities than that indicated by measurement of stratigraphic thickness along a horizontal course.

CLASTIC UNIT A

The basal unit of the Minturn Formation, here referred to as clastic unit A, is characterized by relatively fine-grained and evenly bedded clastic rocks. The rocks of the unit constitute a transition zone between the underlying shaly and limy Belden Formation and the overlying coarse-grained, lenticular, arkosic grits of the main body of the Minturn Formation. Unit A is 375 ft (115 m) thick in the Minturn type section and about 500 ft (150 m) thick in the Pando section. It consists largely of green-gray and tan sandstone and shale but includes many thin beds of dolomite and a little conglomerate. Grit is essentially absent, thereby distinguishing this unit from the remainder of the formation, and the sandstones and conglomerates are less feldspathic than those in overlying rocks. Raup (1966) found appreciable kaolinite in the shales of this unit, just as in those of the Belden Formation below.

CLASTIC UNIT B AND THE DOLOMITE BED OF DOWDS

Clastic unit B, about 650 ft (200 m) thick, consists of grit, sandstone, shale, and conglomerate lying between unit A and the top of a distinctive dolomite bed here referred to as the dolomite bed of Dowds. (Named for Dowds siding near the junction of Gore Creek and the Eagle River.) Unit B corresponds in general to the lower red zone in the area near Minturn and is characterized by alternating thin and thick strata. The dolomite bed of Dowds is about 6 ft (2 m) thick; it is mottled greenish gray and black and is cherty. This bed of dolomite is the lowest carbonate bed in the Minturn that is persistent and distinctive enough to serve as a stratigraphic marker.

CLASTIC UNIT C AND THE REEF DOLOMITE OF LIONSHEAD

Clastic unit C, about 450 ft (135 m) thick, consists of strata between the dolomite bed of Dowds and the top of

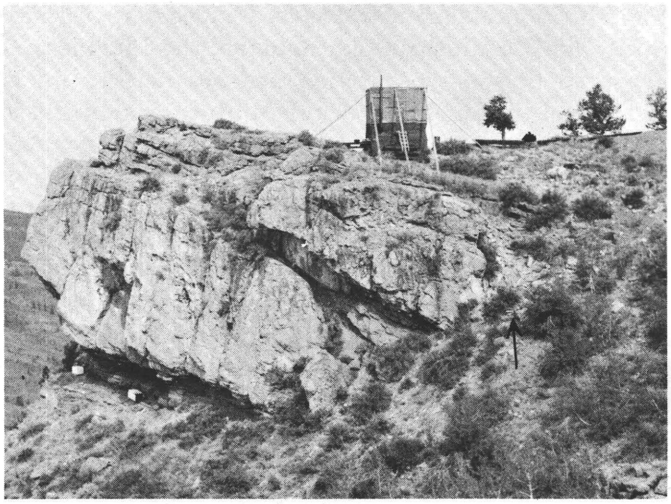


FIGURE 15.—Dolomite reef in Minturn Formation at Lionshead, on steep slope above Minturn. Note abrupt termination to right (arrow).

a reefy dolomite zone referred to as the reef dolomite of Lionshead. Unit C is similar in lithology to clastic unit B except that it is gray rather than red and contains a few thin beds of dolomite. The reef dolomite of Lionshead consists of discrete reefs strung at intervals along a thin and otherwise inconspicuous bed of dark dolomite. A typical reef in this unit forms the landmark of Lionshead on the slope above Minturn (fig. 15). This reef is 48 ft (14 m) thick but abruptly pinches laterally to two thin dolomite beds separated by several feet of grit.

CLASTIC UNIT D

Clastic unit D, about 1,000 ft (305 m) thick, consists of massive grits and conglomerates between the reef dolomite of Lionshead and the top of a massive grit bed about 200 ft (60 m) thick that is persistent through the cliffs on the east side of the Eagle Valley from Two Elk Creek to Gore Creek (grit marker bed of pl. 1). Clastic unit D constitutes the most massive part of the Minturn Formation. Many of the thickest beds are markedly lenticular; one bed that forms a cliff 200 ft (60 m) high on the shoulder north of Two Elk Creek pinches in a quarter of a mile (0.4 km) along strike to 5 ft (1.5 m). In the Pando area, thin beds of dolomite and also many dolomite reefs occur in this stratigraphic interval, but they are absent at Minturn.

CLASTIC UNIT E AND WEARYMAN AND HORNSILVER DOLOMITE MEMBERS

Clastic unit E, about 1,100 ft (335 m) thick, consists of varied clastic rocks in beds thinner than those in unit D. The base of the unit is marked by the Wearyman Dolomite Member or probable equivalent. The Hornsilver Dolomite Member—or equivalent—is about 330 ft (100 m) above the base. The Wearyman and Hornsilver both change in character northward in the Minturn quadrangle. The Wearyman is a light-colored reef (stromatolitic) dolomite 15–75 ft (4.5– 22 m) thick in the Pando area (Tweto, 1949, p. 198) and in the Wearyman Creek and Turkey Creek areas in the southern part of the Minturn quadrangle. On Battle Mountain the Wearyman thins, grades into bedded dolomite, and becomes discontinuous. Farther north, at the Minturn type section at Game Creek, its probable equivalent is a 27-ft (8-m)unit of dark-gray shale that contains thin beds of dolomite (unit 86, Minturn type section). Similarly, the Hornsilver, an 18–28 ft (5.5–8.5 m) of distinctive light-weathering dolomite in the Pando area and in southern part of the Minturn quadrangle, also thins and changes in character on Battle Mountain. In the part of the Minturn type section at Game Creek, the Hornsilver equivalent probably is a dolomitic sandstone and thin beds of dolomite in a predominantly clastic unit 54 ft (16.5 m) thick (unit 94, Minturn type section).

ROBINSON LIMESTONE MEMBER

The name Robinson was first applied by Emmons (1882, p. 220; 1898, p. 2) to a group of three limestone beds separated one from the other by 80–100 ft (24–30 m) of clastic rocks at the Robinson mine in the Kokomo district. Tweto (1949, p. 201) defined the Robinson as a member of the Minturn Formation in the Pando area and adjacent Kokomo district. There, the Robinson consists of 3–5 beds of limestone separated by clastic rocks in a zone 300–400 ft (90–120 m) thick and about 4,200 ft (1,280 m) above the base of the Minturn Formation. In the early mapping of the Minturn quadrangle, Lovering and Tweto (1944) called the limestones of this zone the "Lime Cliffs," but subsequent mapping in the area between the Minturn quadrangle and the Kokomo district (Tweto, 1953) established that these limestone beds are the same as the Robinson, and the term "Lime Cliffs" was dropped (Tweto, 1949, p. 201).

In the area of the Minturn type section in the Minturn quadrangle, the Robinson member is 746 ft (228 m) thick; it consists of six carbonate beds, each 5–65 ft (1.5–20 m) thick, separated by much thicker intervals of clastic rocks. The increased number of limestone beds and thickness of the member in this area as contrasted with the Pando area result from facies changes in the Resolution Dolomite Member of the Pando area. Northward from the Pando area, thin-bedded dolomite of the Resolution Member grades into thick-bedded to massive light-bluish-gray fossiliferous limestone characteristic of the Robinson, as does also an overlying zone of dolomite reefs and dolomitic grit (fig. 13). These lower limestone beds are accordingly included in the

Robinson, and the Resolution Dolomite Member is not recognized except in the southernmost part of the quadrangle.

The greatest amount of limestone known in the Robinson is along Gore Creek east of the mouths of Mill and Spraddle Creeks. In this area the member includes as many as four major limestone beds 25–75 ft (7.6–22.9 m) thick, as well as several minor beds. From this vicinity, the limestone beds decrease in number and thickness westward toward the evaporite basin, and the limestone also changes in character to a nonresistant and inconspicuous shaly, flaggy nonfossiliferous brownish-gray limestone. On the spur north of Dowds, the Robinson contains no more than two well-defined limestone beds and is a vaguely defined unit of interbedded shaly limestone, shale, and sandstone. Northwestward from this spur, gypsum appears in this limy-shaly zone and gradually supplants the limestone. Cross sections diagramming the changes in the Robinson from Booth Creek westward have been presented by Boggs (1966, fig. 5), and a facies classification of the Robinson over a wider region has been made by Tillman (1971).

Individual limestone beds within the Robinson extend for distances of a few thousand feet to several miles. Generally, as one bed pinches out, it is overlapped by another at a somewhat different stratigraphic level. Thus, the limestone beds have the form of broad lenses, and the member as a whole consists of overlapping lenses of limestone in a matrix of clastic rocks. In places, thin beds of dolomite are also present in the Robinson, and a few limestone beds have dolomite caps. Such dolomite is apparently of early, perhaps diagenetic, origin and is distinct from late hydrothermal dolomite, which irregularly replaces the gray limestone in many places in the southern part of the quadrangle.

In places, limestone beds of the Robinson swell abruptly into massive, vuggy bioherms or reefs consisting of algal bodies, shell fragments, and calcarenite. Most of these bioherms are dolomite, but some are limestone. Good examples, among many, are on the south wall of Gore Creek valley just east of Mill Creek, and on the west wall of the canyon of the Piney River near Moniger Creek.

The Robinson contains a large assemblage of fossils, as discussed under a following heading, but it is characterized particularly by brachiopods, pelecypods, and fusulinids.

CLASTIC UNIT F

Unit F (fig. 13) consists of about 450 ft (138 m) of grit, sandstone, shale, and siltstone, much as in clastic unit E. In the Minturn quadrangle, the lowermost light-red beds of the upper red zone in the Minturn Formation occur in the upper part of this unit, though most of the unit is gray. In the Pando area, in contrast, the lowest red beds of the upper red zone are in the middle part of the Robinson Limestone Member (fig. 13).

ELK RIDGE LIMESTONE MEMBER

The name Elk Ridge Limestone was first applied by Koschmann and Wells (1946, p. 67) to two beds of limestone separated by 175–225 ft (52–68 m) of red clastic rocks in the Kokomo district. The Elk Ridge was designated a member of the Minturn Formation by Tweto (1949, p. 202) who noted that in the Pando area it is a single limestone bed 7.5–21 ft (2.3–6.4 m) thick. In the Minturn quadrangle the member is also a single bed and, as elsewhere, is discontinuous, passing abruptly into black shale in places. In the area of the Minturn type section it is 30 ft (9 m) thick, but in most places it is no more than half this thickness. It has not been identified with certainty north of Gore Creek. The limestone in the Elk Ridge is in part dark, fine grained, and thin bedded, and in part bluish gray like the Robinson. This lighter variety is mottled pale pink in many places and is generally sandy and locally oolitic.

CLASTIC UNIT G

About 130 ft (40 m) of grit, sandstone, and shale between the Elk Ridge and White Quail Limestone Members constitutes clastic unit G. In the Minturn type section these rocks are gray or pink, but to the southeast in the Pando area and the Kokomo district they are predominantly red.

WHITE QUAIL LIMESTONE MEMBER

The name White Quail was first applied by Emmons (1898) to limestone beds that are the major host rocks of ore deposits in the Kokomo district. Koschmann and Wells (1946, p. 67) further described this unit in the Kokomo district as two, and locally three, beds of dark fossiliferous limestone 5–30 ft (1.5–9 m) thick, separated by clastic rocks, in a zone about 200 ft (60 m) thick. Limestones of this zone were designated the White Quail Limestone Member of the Minturn Formation by Tweto (1949, p. 203). In the Pando area, the zone is reduced to a single 10-ft (3-m) bed of dark-colored oolitic limestone or locally to about 10 ft (3 m) of dolomite and black shale. It thickens northward in the Minturn quadrangle, however, reaching 35–50 ft (10–15 m) in the general area of Mill, Booth, and Middle Creeks. From this area it thins westward toward the evaporite basin and also changes to silty limestone or calcareous siltstone, just as does the Robinson. It has not been identified farther west than the mountain spur north of Dowds.

Throughout the area, the White Quail contains lenses of black shale, and parts of it grade abruptly along the bedding into clastic rocks, causing marked differences in thickness from place to place. In general, the upper beds grade into grit, and the lower beds into shale or siltstone.

In the southern part of the quadrangle and in the Pando area, the White Quail is a dark-bluish- or greenish-gray, dark-weathering, irregularly oolitic limestone that in many places contains scattered gastropods, cephalopods, and pelecypods. It maintains these general characteristics northward to Gore Creek, except that the weathered surfaces gradually change to light grayish yellow. At Mill Creek the White Quail consists of a lower limestone unit about 15 ft (4.5 m) thick and an upper one about 20 ft (6 m) thick, separated by 10–12 ft (3–3.6 m) of dark shale. The limestones are in alternate thick and thin beds, and the thin beds are calcarenites consisting almost entirely of shell fragments.

North of Gore Creek the limestone changes from dark gray to light gray and assumes many of the characteristics of the Jacque Mountain Limestone Member higher in the section. For this reason, it was misidentified as Jacque Mountain in the original mapping (Lovering and Tweto, 1944) in the Spraddle Creek area, near the Gore fault. In this area much of the limestone is foraminiferal, accentuating the oolitic apperance, and on weathered surfaces it is characterized by very abundant pinhole cavities. It contains thin beds that consist largely of fossil fragments, and contains scattered coiled cephalopods in the thicker beds. It was classified in this general area by Boggs (1966, p. 1408–1410) as biomicrite, oomicrite, and algal oomicrite.

CLASTIC UNIT H

Grit, conglomerate, sandstone, and shale 1,000–1,200 ft (305–365 m) thick lying between the White Quail Limestone Member below and the Jacque Mountain Limestone Member above are referred to as clastic unit H. This unit is almost entirely red, though locally it contains some gray beds in its lower part. Through most of the area the red color is bright, ranging from orange red to maroon, but as the evaporite basin is approached, the color becomes dull red, or grayish red. The clastic rocks of the unit include much conglomerate and are in general coarser than in most of the other clastic units except in unit D.

JACQUE MOUNTAIN LIMESTONE MEMBER

The Jacque Mountain Limestone Member, which defines the top of the Minturn Formation (Tweto, 1949), is the most persistent and consistent limestone bed in the Pennsylvanian and Permian sequence. The limestone was named by Emmons (1898) for Jacque Mountain (later called Jacque Peak) in the Kokomo district. It has been traced from the Kokomo district northwestward beyond the northern boundary of the Minturn quadrangle, and it has been identified with reasonable certainty in a separate area of Pennsylvanian and Permian rocks 15 mi (24 km) farther northwest along the Colorado River near McCoy (Murray, 1958, p. 54). It also has been identified along the Continental Divide east of the Mosquito-Tenmile Range (observation by Tweto; also Singewald, 1951, p. 11; Brill, 1952, p. 819). Like all the limestones, the Jacque Mountain fades out in the evaporite basin just west of the Minturn quadrangle. Lovering and Mallory (1962) traced it from the Gore Creek area westward to a terminus on the north side of the Eagle River at a point almost exactly on the quadrangle boundary. Boggs (1966) reported that it extends discontinuously about 5 mi (8.1 km) farther west along the north side of the Eagle River, but W. W. Mallory (written commun., 1968) has stated that this extension cannot be confirmed.

The Jacque Mountain (fig. 16) is typically 20–25 ft (6–7.6 m) thick and consists of gray to light-bluish-gray fine-grained limestone with a distinctive combination of features. It is generally oolitic in some part, particularly in the upper beds. Some part or all of the limestone commonly contain clastic materials, such as grit, sand, or micas (fig. 17), and in many places the

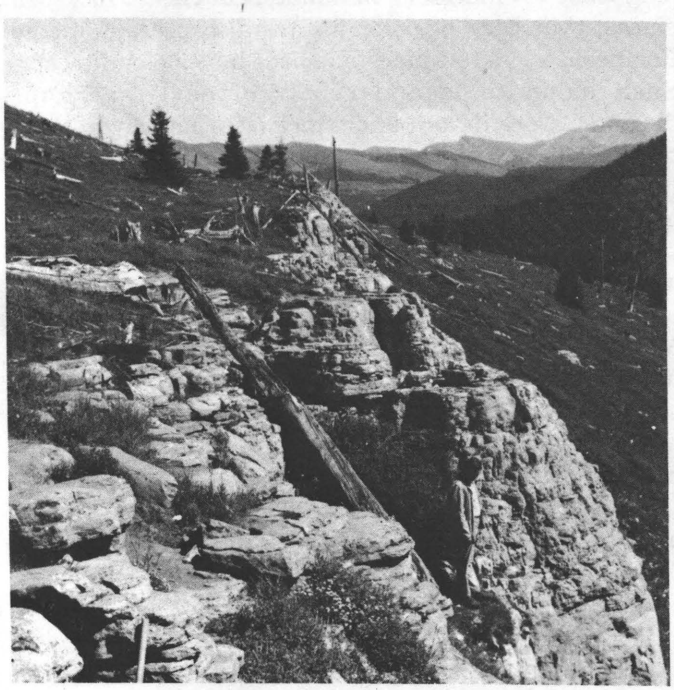


FIGURE 16.—Jacque Mountain Limestone Member of the Minturn Formation, on ridge between the heads of Mill and Two Elk Creeks.

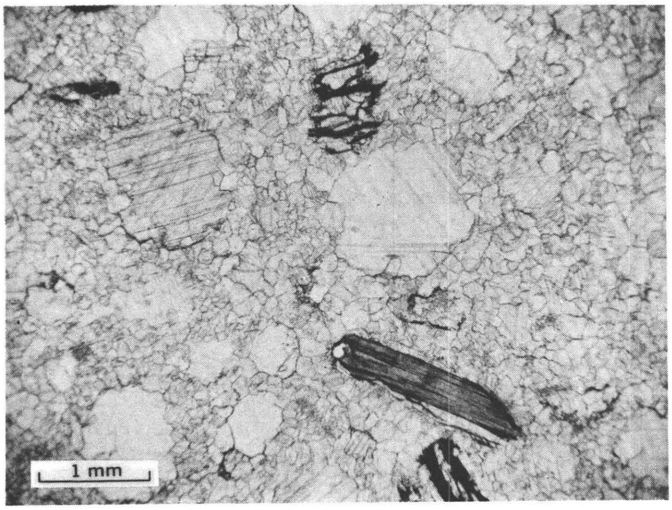


FIGURE 17.—Photomicrograph of biotitic oolitic limestone in Jacque Mountain Limestone Member of Minturn Formation, showing fresh and altered biotite flakes (dark), and oolites recrystallized to large single crystals. Crossed polars.

limestone contains lenses of grit, conglomerate, or siltstone. Locally, the oolites and clastic grains define a crossbedded structure in an otherwise sublithographic limestone (micrite). Beds of intraformational limestone conglomerate are common. Some beds are welded aggregates of irregular pellets a few millimeters in diameter, at least some of which seem to be algal. In places the limestone contains concentric algal structures a few inches to 2 ft (7 cm to 0.6 m) in diameter. In many exposures, some bedding planes are marked by cusps and hollows an inch or two across that look like disorganized cross-ripples. Pink mottling of the gray or bluish-gray limestone is common, particularly in the intraformational conglomerates, and locally some beds are pink throughout. Stylolites in the limestone are typically micaceous and are stained red by hematite. Throughout, but perhaps most commonly in the upper oolitic beds, the limestone contains widely scattered coiled cephalopods 2–4 in. (5–10 cm) in diameter, and locally it also contains straight cephalopods, high-spired gastropods, and fragments of pelecypods. These fossils are generally recrystallized to sparry calcite. In at least one occurrence, at the head of Mill Creek, oolites in the top bed of the Jacque Mountain are very soft but coarsely crystalline and were tentatively identified as gypsum. Boggs (1966, p. 1410) classified the limestone in the Jacque Mountain as biomicrite, oomicrite, and algal oomicrite in the east-central part of the quadrangle, and as micrite and intraclast and stromatolitic limestone near the evaporite basin. A series of sections of the limestone along Gore Creek and the Eagle River has been diagrammed by Lovering and Mallory (1962).

CHANGES IN THICKNESS AND FACIES

The Minturn Formation thins rapidly toward the Gore Range by onlap, or the shingling out of the lower units (pl. 1, secs. *A–A′*, *B–B′*, *E–E′*). On the mountain southeast of the junction of Gore and Black Gore Creeks, typical blue-gray fossiliferous limestone of the Robinson Member is separated from Precambrian rocks by only 50–100 ft (15–30 m) of grit. Similar relations are known on Copper Mountain, in the northern part of the Kokomo district (Tweto, 1949, p. 195; Bergendahl and Koschmann, 1971, pl. 1) where limestone of the Robinson member also lies within 50 ft (15 m) of Precambrian rocks. The same relations also are known or reasonably inferred at several places along the Gore fault north of Gore Creek, as at Bighorn and Pitkin Creeks and near the head of Middle Creek.

As the base of the Robinson Limestone Member lies 3,700–4,200 ft (1,130–1,280 m) above the Belden as measured from the valley of the Eagle River (fig. 13), the relations just described indicate that a minimum of about 4,000 ft (1,220 m) of clastic rocks beneath the Robinson pinches out between the Eagle River and the flank of the Gore Range. Much of the thinning evidently is localized near the Gore fault, for more than a thousand feet (305 m) of grit is exposed beneath the Robinson at Booth Creek, only a mile or two (1.6 or 3.2 km) from the fault. As discussed in the section on structure, the Gore fault is an ancient fault that in Pennsylvanian time formed an abrupt border between the highland area to the east and the basin of sedimentation to the west. In the area along the fault clastic rocks of the Minturn Formation are very coarse. Conglomerates exposed in fault slices on the south slope of Bald Mountain contain abundant 2-ft (0.6-m) boulders and some as large as 4 ft (1.2 m) in diameter.

Westward from the vicinity of the Gore fault, the clastic rocks become finer grained toward the evaporite basin. A partial section measured on the western side of the mountain spur north of Dowds showed predominant sandstone and siltstone and only 5 percent of grit in clastic unit E. Clastic units F and G contain no grit, 15 percent sandstone, 78 percent shale and siltstone, and 7 percent carbonate rocks. These proportions contrast with predominant grit and abundant conglomerate farther east, as described in the Minturn type section. The section near Dowds also illustrates the thinning between carbonate members of the Minturn. The White Quail and Robinson are separated by about 500 ft (150 m) of clastic rocks, in units F and G, in contrast to 700 ft (213 m) in the Minturn type section. Clastic unit E is reduced even more severely, from 1,100 ft (335 m) in the type section to only 350 ft (105 m). Clastic units C and D have the same thickness at Dowds as in the type section, but it should be noted that this part of the type section is the same distance from the depositional shoreline as in the locality near Dowds.

Westward from Dowds, the Minturn intertongues with, and grades into, gypsum of the Eagle Valley Evaporite (Mallory, 1971, pl. 2). On the north side of the Eagle River, thick units of gypsiferous shale and siltstone alternate with thin units of gypsum, most of which is silty. South of the river, near Stone Creek, gypsum is much more abundant, but its stratigraphic relations are obscured by slumps and landslides. This gypsum probably is the same as that in two beds that are exposed near Avon, 2 mi (3.2 km) to the west. Burchard (1911, p. 362) described these as a lower bed 130 ft (40 m) thick and an upper bed 50–75 ft (15–23 m) thick, separated by 40–50 ft (12–15 m) of clay, calcareous shale, and shaly limestone. Because of the small area of exposure and the obscurity due to slumping, Eagle Valley Evaporite is not distinguished on the quadrangle map (pl. 1).

FOSSILS, AGE, AND CORRELATIONS

The Minturn Formation and equivalents have been classed as mostly or entirely Middle Pennsylvanian in age by many workers (Roth and Skinner, 1930; Brill, 1944, 1952; Henbest, 1946; Tweto, 1949; Stevens, 1962; Bass and Northrop, 1963; Murray and Chronic, 1965). Extensive fossil collections from the Minturn quadrangle, Pando area, and Kokomo district establish that the lower five-sixths of the formation, up through the White Quail Limestone Member, is Atokan and Des Moinesian in age. The age of the uppermost part, comprising clastic unit H and the Jacque Mountain Limestone Member, is not so definitely established but is also classed as Pennsylvanian and very likely Des Moinesian, as indicated below.

Diagnostic fossils—both megafossils and fusulinids—are most abundant in the limestones of the Robinson Limestone Member. Megafossils are also found at various levels from the base of the formation up to the Robinson, but fusulinids have not been found lower than the Hornsilver Dolomite Member. Above the Robinson, the Elk Ridge has yielded a few megafossils and fusulinids. The White Quail has yielded diagnostic megafossils but the few fusulinids found in it are too poorly preserved for identification. Though searched extensively for identifiable fossils, the Jacque Mountain has yielded only a sparse molluscan fauna.

Data on fossils are summarized below from reports by Mackenzie Gordon, Jr., and E. L. Yochelson of the U.S. Geological Survey (written commun., Feb. 16, 1966) on 31 collections of megafossils, and by L. G. Henbest (written commun., May 5, 1958 and Oct. 2, 1958) on 44 collections of fusulinids. The localities of the fossil collections to which we refer in the present report are listed in table 5.

Gordon and Yochelson noted that colonies of the coral *Chaetetes* are the principal fossils in the lower part of the Minturn Formation, and that this form "ranges through about 3,000 feet of beds in this area, the lowest recorded occurrence being approximately 1,420 feet above the base of the Minturn."

From a shale bed about 40 ft (12 m) above the base of the Minturn (loc. 14582–PC) they reported:

Linoproductus cf. *L. prattenianus* (Norwood and Pratten)
Juresania nebrascensis (Owen)
Aviculopecten sp.

From a dolomite reef at a stratigraphic level below the Wearyman Dolomite Member and above the reef dolomite of Lionshead (locs. 9875–PC and 9879–PC) Gordon and Yochelson reported:

Chaetetes sp.
Desmoinesia nana (Meek and Worthen)?
Linoproductus sp. indet.
Anthracospirifer rockymontanus (Marcou)
opimus (Hall)
Condrathyris perplexa (McChesney)
Streblochondria cf. *S. tenuilineata* (Meek and Worthen)
Lima? sp. indet.
Edmondia sp.
Weideyoceras sp.

From the Hornsilver Dolomite Member (loc. 14579–PC) Gordon and Yochelson reported:

Caninoid coral undet.
Chaetetes sp.
Multithecopora? sp.
Derbyia crassa (Meek and Hayden)?
Kozlowskia? sp. A
Anthracospirifer rockymontanus (Marcou)
Condrathyris perplexa (McChesney)
Crurithyris planiconvexa (Shumard)
Cleiothyridina orbicularis (McChesney)
Composita ovata Mather
Beecheria bovidens (Morton)
Glabrocingulum sp. indet.

From limestone about at the stratigraphic level of the Resolution Dolomite Member, or possibly of the Hornsilver Member (loc. 9874–PC) they reported:

Chaetetes sp.
Cidarid spines
Meekella striatacostata (Meek)
Antiquatonia coloradoensis (Girty)
Linoproductus prattenianus (Norwood and Pratten)?
Anthracospirifer rockymontanus (Marcou)
Condrathyris perplexa (McChesney)?
Composita subtilita (Hall)?

and stated:

> Occurrence of these fossils with a small tumid species of *Fusulinella* indicates a late Atokan age for the collection, according to Henbest (oral commun., 1966). The megafossils are all rather long-ranging Pennsylvanian species not restricted to beds of Atokan age.

TABLE 5. — *Fossil collection localities, Minturn Formation, Minturn quadrangle and vicinity, Colorado*

[Abbreviations for 15-minute quadrangle are: M, Minturn; HC, Holy Cross; ML, Mount Lincoln]

Collection No.	Quadrangle	Locality	Description and remarks
9864–PC	M	Turkey Creek, about 5.5 mi (9 km) northeast of Red Cliff, near mouth of tributary gulch from north that enters Turkey Creek at 10,050-ft contour.	Lower of two prominent beds of limestone of Robinson Member exposed at this locality.
9865–PC	M	Roadcut on U.S. Highway 6 southeast of junction of Gore and Black Gore Creeks, 0.25 mi (400 m) south of highway bridge over Gore Creek.	Limestone of Robinson Member.
9867–PC	M	Meadow at head of Spraddle Creek between 10,600- and 10,800-ft contours, and outcrops on slope on northwest side of creek; about 0.75 mi (1.2 km) southwest of top of Bald Mountain.	Limestone of White Quail Member.
9868–PC	M	Knob marked by closed 10,450-ft contour on ridge on southeast side of Spraddle Creek, about 1.7 mi (2.7 km) south-southwest of top of Bald Mountain.	Limestone of White Quail Member.
9874–PC	M	Crest of ridge between Spraddle and Booth Creeks, at 11,300-ft contour.	Limestone bed probably at about stratigraphic level of Resolution or Hornsilver Member.
9875–PC	M	Two Elk Creek, about 1.7 mi (2.7 km) from its mouth, near 8,750-ft contour at trail and creek.	Dolomite reef stratigraphically below Wearyman Dolomite Member.
9876–PC	M	Ledges in hay meadow on north side of Gore Creek and U.S. Highway 6, 0.5 mi (0.8 km) west of Red Sandstone Creek. (Locality was later covered by Highway I–70.)	Limestone of Robinson Member.
9879–PC	M	Same as 9865–PC.	
12062–PC	HC	Summit of Ptarmigan Hill (12,154–ft survey point) 0.35 mi (0.56 km) south of boundary of Minturn quadrangle. See Pando map (Tweto, 1953).	Dolomite and black shale of White Quail Member. Unit 101 of Pando stratigraphic section (Tweto, 1949, p. 208).
12063–PC	HC	Southwest shoulder of Ptarmigan Hill. See Pando map (Tweto, 1953).	Calcareous shale equivalent to fourth highest of five limestone beds in Robinson Member. Unit 55 of Pando stratigraphic section (Tweto, 1949, p. 212).
12093–PC	HC	Same as 12063–PC.	
12094–PC	HC	Same as 12062–PC.	
13049–PC	M	Two Elk Creek, at mouth of tributary gulch from north, at 9,100-ft contour.	Limestone boulders from ledges in Robinson Member higher in gulch.
13057–PC	HC	Same as 12063–PC.	
13058–PC	ML	Ridge crest outlined by 11,750-ft contours, 3,400 ft (1,020 m) east of common corner of Minturn, Holy Cross, Mount Lincoln, and Dillon quadrangles, and 500 ft (150 m) south of Dillon quadrangle boundary. See Pando map (Tweto, 1953).	Limestone of Jacque Mountain Member.
13059–PC	M	Same as 9864–PC.	
13060–PC	M	Same as 9867–PC.	
13061–PC	M	Same as 9867–PC.	
13062–PC	M	Same as 9865–PC.	
13064–PC	M	Ridge between Turkey and Wearyman Creeks, 200 ft (60 m) below crest of mountain with triangulation station Shrine on it at elevation 11,876 ft.	Limestone of Jacque Mountain Member.

TABLE 5. — *Fossil collection localities, Minturn Formation, Minturn quadrangle and vicinity, Colorado* — Continued

Collection No.	Quadrangle	Locality	Description and remarks
14578–PC	ML	100 ft (30 m) east of crest of ridge followed by Eagle County–Summit County boundary, at 12,250-ft contour; 1.4 mi (2.25 km) south of Dillon quadrangle boundary. See Pando map (Tweto, 1953).	Limestone of White Quail Member.
14579–PC	HC	Tributary gulch of Resolution Creek, NW1/4 sec. 36, T. 6 S., R. 80 W., at 10,700-ft contour. See Pando map (Tweto, 1953).	Dolomite and limestone of Hornsilver Member.
14582–PC	M	Roadcut on U.S. Highway 24 on north side of Rock Creek, 0.25 mi (400 m) north of Gilman.	Green-gray shale with limestone nodules, 40 ft (12 m) above base of Minturn Formation.
14583–PC	M	Same as 9867–PC.	
14584–PC	M	Same as 9867–PC.	
f5757–5760	HC	Southwestern shoulder of Ptarmigan Hill. See Pando map (Tweto, 1953).	Collections from limestone beds of Robinson Member in Pando measured section (Tweto, 1949, p. 211–212): f5757—unit 42; f5758—unit 39; f5759—unit 55; f5760—unit 60.
f5761–5766	ML	Type locality of Robinson Member, in Kokomo district, quarry at site of former town of Robinson. (Locality was later buried beneath tailings ponds).	From the three limestone beds present in the Robinson Member at this locality: f5761b–lower bed; f5761, f5762, f5762b— middle bed at base, middle, and top, respectively; f5765, f5766—upper bed at base and 5 ft (1.5 m) above base, respectively.
f5790	ML	Nearly same as 14578–PC, but on crest of ridge, between 12,300- and 12,350-ft contours.	Limestone of White Quail Member.
f7036–7039	M	Lime Creek, about 3 mi (5 km) above mouth, NW1/4 sec. 3, T. 6 S., R. 80 W., in clearing on slope above Lime Creek trail.	From three lowest limestone beds of Robinson Member: f7036—base of upper bed, 90 ft (27 m) above second bed; f7037—upper part of second bed; f7038—nodular limestone within second bed; f7039—lowest bed.

Megafossils from the Robinson Member are listed in table 6, which includes one collection, 13049–PC, from float judged to be from the Robinson but not included in the table as prepared by Gordon and Yochelson, who also stated:

Brachiopods characteristic of the Robinson Member and apparently restricted to it in this region are: *Mesolobus mesolobus* (Norwood and Pratten), *Chonetinella jeffordsi* Stevens, *Desmoinesia muricatina* (Dunbar and Condra), *Antiquatonia* aff. *A. hermosana* (Girty), and *Neospirifer coloradoensis* Stevens. These fossils suggest a correlation between the Robinson Member and units 7 to 9 of Stevens (1962) in the McCoy area, about 30 miles northwest of Minturn.

Fusulinids from systematic collections from the Robinson Member in three localities in or near the Minturn quadrangle are listed in table 7, as collected and identified by L. G. Henbest. Of a collection made earlier by Tweto at the same locality as megafossil collections 9864–PC and 13059–PC (table 5), Henbest said (written commun., April 29, 1941):

Two early species of *Fusulina* are present. One is new, and the other is either *Fusulina taosensis* Needham 1937, or a very closely related form. Though the stratigraphic record of these two species is but poorly known, the evolutionary status of these forms indicates early Des Moines age or perhaps a position in the upper part of the Lampasas Series of Cheney (1940). *Fusulina taosensis* was originally found in the lower part of the Magdalena Group east of Taos, N. Mex. I think that the evidence for an age at least as early as the early Des Moines is good.

Other Foraminifera noted by Henbest from the collections reported in table 7 are:

Bradyina sp.
Calcitornella sp.
Calcivertella sp.
Climacammina sp.
Cribrostomum sp.
Earlandia perparva Plummer
Earlandia sp.
Endothyra sp.
Globovalvulina sp.
Monotaxis sp.
Orthovertella sp.
Polytaxis sp.
Ozawainella sp.
Serpulopsis sp.
Spiroplectammina sp.
Tetrataxis millsapensis Cushman and Waters
Tetrataxis sp.
Trepeilopsis gnandis Cushman and Waters
Trepeilopsis sp.

TABLE 6. — *Megafauna of the Robinson Limestone Member of the Minturn Formation*

[X, present; ?, questionable occurrence]

Name	Collection No.: 9864–PC, 13059–PC	9865–PC, 9879–PC, 13062–PC	9876–PC	12063–PC, 12093–PC, 13057–PC	13049–PC
Corals:					
Caninia sp	...	X	...	...	...
Lophophyllidiid corals	X	X	...	...	...
Chaetetes cf. *C. milleporaceous* Milne-Edwards and Haime	X	X	...	...	...
Bryozoans:					
Fenestellid	...	X	...	...	...
Echinoderms:					
Crinoid stems	X	X	X	X	...
Echinoid spines	...	...	X	...	...
Brachiopods:					
Derbyia crassa (Meek and Hayden)	...	X	...	X	...
Derbyia? sp. indet	X	...	...	...	...
Meekella striatocostate (Cox)	...	X	X	...	...
Mesolobus mesolobus (Norwood and Pratten)	...	X	...	...	...
Chonetinella jeffordsi Stevens	...	...	...	X	...
Krotovia maccoyensis Stevens?	...	...	...	...	X
Krotovia? sp	...	X	...	...	...
Desmoinesia muricatina (Dunbar and Condra)	...	X	...	X	...
cf. *D.* ingrata (Girty)	...	X	...	...	...
Antiquantonia aff. *A. hermosana* (Girty)	X	...	...	X	...
sp	...	X	...	X	...
Linoproductus prattenianus (Norwood and Pratten)	?	X	X	X	...
sp. indet	...	...	...	...	X
Punctospirifer kentuckensis (Shumard)	...	X	...	...	...
Anthracospirifer rockymontanus (Marcou)	X	X	...	X	...
Neospirifer coloradoenis Stevens	...	X	...	X	...
Crurithyris planiconvexa (Shumard)?	...	X	...	...	...
Condrathyris perplexa (McChesney)	X	X	...	X	X
Composita subtilita (Hall)	X	X	...	X	...
sp	...	X	...	X	X
Beecheria cf. *B. bovidens* (Morton)	X	...	...	...	...
Kozlowskia? sp. A	...	...	...	...	X
Pelecypods:					
Pernopecten cf. *P. ohioensis* Newell	...	...	...	...	X
sp	...	X	...	...	...
Concardium sp	...	X	...	...	...
Schizodus sp	...	X	?	...	...
Sphenotus? sp	...	...	X	...	...
Astartella sp	...	X	...	...	...
Gastropods:					
Bellerophontid indet	X	X	X	...	...
Knightites (*Cymatospira*) *montfortianus* (Norwood and Pratten)	...	?	...	...	...
Worthenia tabulata (Conrad)	...	X	...	...	...
Platyceras (*Orthonychia*) *parva* (Swallow)	...	X	...	...	...
High-spired gastropod	...	...	X	...	...
Gastropods indet	...	X	...	...	...
Cephalopods:					
Pseudorthoceras knoxense (McChesney)	...	X	...	X	...

NOTE: In reports prepared later than this table, E. L. Yochelson (written commun., Nov. 14, 1966) and Mackenzie Gordon, Jr., and W. J. Sando (written commun., Nov. 21, 1966) reported the brachiopods *Antiquatonia coloradoensis* (Girty) and *Crurithypis* sp., the gastropod *Cinclidonema* sp., and indeterminate corals in collections from red-mottled cherty limestone of the Robinson Member 1 mi (1.6 km) west of Bald Mountain.

In summarizing the results of studies of the Foraminifera, Henbest said:

All of the fusulinid bearing units, except those with the problematic fauna of f7036, have foraminiferal faunas that indicate a Middle Pennsylvanian age. Of these, none younger than the middle part of the Middle Pennsylvanian was recognized. The fauna represented by f7036 suggests an early Late Pennsylvanian age, but the foraminiferal evidence is opposed by field evidence. Tweto observed that the zone of f7036 is overlain at another locality by beds containing *Mesolobus* sp. A definite solution of this problem remains to be determined.

In addition to the fusulinid species from the Robinson reported by Henbest, other species were reported by Tillman (1971, p. 599) as identified by G. J. Verville: *Fusulina curta*, *F. distenta*, *F. truncatulina*, *F. plattensis*, and *Wedekindellina coloradoensis*.

Fauna of the White Quail Member is shown in table 8 as reported by Gordon and Yochelson (written commun., 1966), who noted that:

"*Maximites cherokeensis* was described originally from the Mulky coal of the Cherokee Shale in Henry County, Missouri, and except for the White Quail specimens this genus and species is not known elsewhere." Regarding *Mesolobus euampygus*, they also noted that:

this is the only bed in the Minturn section in which this species has been found. This occurrence suggests a correlation between the White Quail Member and unit 15 of the section recorded by Stevens (1962, p. 618–624) in the McCoy area, the only bed in which he encountered *M. euampygus*.

Most collections of microfossils from the White Quail proved to be devoid of identifiable fusulinids, but in one collection (f5790) Henbest identified "*Profusulinella* sp. or immature specimens of a higher fusulinid."

Fossils in the Jacque Mountain Limestone Member as reported by Gordon and Yochelson (written commun., 1966) include (locs. 13058–PC, 13064–PC):

Schizodus sp.
Permophorous sp.
Dolorothoceras sp.
Domatoceras sp. indet.

Gordon and Yochelson stated:

The *Domatoceras* * * * is distinct from the species in the White Quail Member. It is too poorly preserved to name formally but probably is the same species that was collected by Koschmann and Williams near the head of Searles Gulch in the Kokomo district [Koschmann and Wells, 1946, p. 69]. This earlier specimen was described and figured as *Domatoceras* sp. (of Colorado) by Miller and Youngquist (1949, p. 46, 47, pl. 15, figs. 1–7) in their volume on American Permian Nautiloids. Despite this implication of Permian age, Gordon regards the Jacque Mountain species as rather closely related to Cherokee age forms such as *Domatoceras umbilicatum* Hyatt and *D. williamsi* Miller and Owen and rather unlike most known Permian species.

The genera so far recorded from the Jacque Mountain Member range widely through Pennsylvanian and Permian rocks. There is no demanding reason, especially when one considers the rapidity of sedimentary accumulation in the Minturn section, to regard the Jacque Mountain Member as any age but merely slightly younger than the White Quail Member.

In summarizing the age of the Minturn Formation, Gordon and Yochelson stated:

the Minturn Formation is regarded as Middle Pennsylvanian in age, and includes beds of Atokan and Des Moinesian age. The Robinson and White Quail Members are dated as Des Moinesian in age by the

TABLE 7. — *Fusulinids in the Robinson Limestone Member of the Minturn Formation*

	Ptarmigan Hill (Holy Cross quadrangle)		Lime Creek (Minturn quadrangle)		Robinson Member type locality (Mount Lincoln quadrangle)	
Limestone No.	Locality No.	Name	Locality No.	Name	Locality No.	Name
4	f5760	*Fusulina pristina* Thompson				
3	f5759	*Fusulina* sp.	f7036	?*Iowanella* sp. aff. *I. winternensis* (Thompson, Verville, and Lokke)	f5766	*Wedekindellina euthysepta* (Henbest) *Fusulina rockymontana* Roth and Skinner
					f5765	*Fusulina rockymontana* Roth and Skinner
2	f5757	*Fusulina* sp. (early form) *Fusulinella* or *Fusulina* sp. *Millerella* sp.	f7038	*Fusulina illinoisensis* Dunbar and Henbest	f5762b	*Wedekindellina euthysepta*? (Henbest) *Fusulina* sp.
			f7037	*Wedekindellina euthysepta* (Henbest) or *W. excentrica* (Roth and Skinner) *Fusulina* sp.	f5761 and f5762	*Fusulina rockymontana* Roth and Skinner *Wedekindellina* sp.
1	f5758	*Fusulina* sp. cf. *F. rockymontana* Roth and Skinner ? *Fusulinella devexa* Thompson *Wedekindellina euthysepta* (Henbest)	f7039	*Fusulina novamexicana* Needham *Wedekindellina euthysepta* (Henbest) *Millerella*-like foraminifer	f5761–b	*Wedekindellina excentrica* Roth and Skinner

megafossil content. The Hornsilver and Robinson Members are dated as early Des Moinesian in age by fusulinids. The presence of *Fusulinella* in a collection of unknown horizon dates at least some of the lower part of the Minturn Formation as late Atokan in age.

As indicated by the preceding statements of Gordon and Yochelson, and by Stevens (1962), some of the limestones of the Minturn correlate with limestones in the McCoy area, 12 mi (19 km) northwest of the Minturn quadrangle, where the term "McCoy formation" was formerly applied to the Pennsylvanian rocks (Donner, 1949). On the basis of fossils and, in some cases, physical stratigraphy, the Minturn also is approximately or in some part is equivalent to the Paradox Formation as used by Bass and Northrop (1963) in the Glenwood Springs area, to the Gothic Formation of Langenheim (1952) on the western side of the Sawatch Range, to the Morgan Formation of northwestern Colorado and northeastern Utah (Thomas and others, 1945) to the Hermosa Formation of southwestern Colorado (Bass, 1944; Henbest, 1946), to the lower part of the Fountain Formation of the eastern side of the Front Range (Mallory, 1958), and to the upper part of the Sandia and the lower part of the Madera Formations of the Magdalena Group of northern New Mexico (Henbest, 1946; Brill, 1952; Myers, 1968).

ORIGIN

The Minturn Formation records two alternating environments of deposition: (1) a marine facies, comprising carbonate rocks, black shales, intertongueing evaporites, and probably some even-bedded siltstones and sandstones, and (2) a nonmarine, largely fluviatile, facies comprising the bulk of the grits and conglomerates and at least some of the associated sandy and micaceous shales. A nonmarine origin of many of the coarse clastic rocks is not directly proved but is inferred from their extreme lenticularity, very poor sorting, general coarseness of grain, extensive crossbedding, channel structures, and the presence in some of them of land plants. The plant remains are not abundant but include fossil tree roots (stigmaria), *Lepidodendron, Sigillaria, Walchia,* fern impressions, and rare petrified wood. In addition, rush, reed, and twiglike impressions are fairly common. Although some of these are marine as indicated by their occurrence in fossiliferous dolomites, most are probably terrestrial, as also are thin coaly or carbonaceous seams in well-defined cyclothemic sequences (Tweto, 1949, p. 211–214; Brill, 1952, p. 820).

Distribution of the two general classes of rocks suggests that normal shallow-water marine sedimentation was interrupted repeatedly by floods of coarse clastic debris derived from the highland area immediately to the east. This debris probably was deposited in the form of shallow-water deltas, bar and back-bar deposits, river flood-plain deposits, and alluvial fans in a recurrent piedmont. When marine conditions prevailed, they extended literally onto the highland, as shown by the limestones on Precambrian rocks near the Gore fault, and when fluviatile conditions prevailed, they extended to the margins of the evaporite basin.

TABLE 8. — *Fauna of the White Quail Member of the Minturn Formation*

[X, present; ?, questionable occurrence]

Name	Collection locality and Nos.		
	Spraddle Creek	Ptarmigan Hill	Radio Ridge
	9867–PC 9868–PC 13060–PC 13061–PC 14583–PC 14584–PC	12062–PC 12094–PC	14578–PC
Plants:			
Reedlike plant	...	...	X
Lepidodendron sp	...	...	X
Echinoderms:			
Echinoid spines	...	X	...
Brachiopods:			
Derbyia crassa (Meek and Hayden)?	...	...	X
Mesolobus euampygus (Girty)	...	X	...
Linoproductus prattenianus (Norwood and Pratten)?	X	...	...
Anthracospirifer aff. *A. rockymontanus* (Marcou)	...	...	X
Condrathyris perplexa (McChesney)	...	X	...
Composita sp	X	...	...
Pelecypods:			
Nuculoidea? sp. indet	...	...	X
Polidevcia sp	...	X	...
Myalina sp	X	...	...
Aviculopecten sp	...	...	X
Schizodus sp. A	...	...	X
sp. B	...	...	X
Pleurophorus sp	...	...	X
Gastropods:			
Bellerophon sp. indet	X	...	...
Knightities (*Retispira*?) sp	...	...	X
Euphemites sp	...	X	?
Bellerophontid sp. indet	X	...	...
Glabrocingulum? sp	...	X	...
Cephalopods:			
Brachycycloceras sp	...	...	X
Kionoceras? sp	X	...	...
Mooroceras normale Miller, Dunbar, and Condra	X	...	X
Metacoceras sp. A	X	X	X
Domatoceras sp. A	X	...	X
Liroceras sp	X	...	X
Ephippioceras ferratum (Cox)	X	...	X
Maximites cf. *M. cherokeensis* (Miller and Owen)	X	...	...

Boggs (1966) and Mallory (1971) have interpreted the sediments of the evaporite basin as products of shallow hypersaline waters in the center of the trough that extended through west-central Colorado, and with this we concur. The open sea with normal marine conditions lay to the northwest, in the area of the Morgan Formation, which closely resembles the marine facies of the Minturn. Evidently, the waters of the Morgan sea repeatedly swept southeastward along the border of the Front Range highland, depositing the marine beds of the Minturn Formation, and just as repeatedly, they are forced back by deposition of the coarse clastic sediments. To what extent subsidence in the basin or trough, pulses of uplift in the highland, or climatic factors each controlled the interplay between spreading of the sea and the building of clastic dams in it is unappraised, but most likely, all three were involved.

From the absence of kaolinite in all but the basal part of the combined Belden and Minturn, and from the abundance of fresh feldspars, both Raup (1966) and Boggs (1966) concluded that the clastic sediments of the Minturn were derived from a source area—the highland to the east—that was undergoing rapid erosion under conditions of a semiarid to arid climate. Parallels in composition and sedimentary structure between the Minturn rocks and modern sediments in parts of the semiarid West suggest that this was so. Hubert (1960), however, concluded that because of the generally red color of the Fountain Formation—an analog of the Minturn—lateritic weathering under humid conditions prevailed. This interpretation of red sediments in the Minturn and Fountain has been refuted by Walker (1967).

MAROON FORMATION

STRATIGRAPHIC RELATIONS

The Maroon Formation as redefined by Tweto (1949) consists of the Pennsylvanian and Permian red beds lying above the Minturn Fromation. As applied in the Minturn quadrangle, the Maroon includes all the strata—as much as 4,200 ft (1,280 m) in thickness—between the Jacque Mountain Member of the Minturn and the Upper Triassic Chinle Formation. The base of the Chinle, which in most places is marked by a distinctive sandstone—the Gartra Member—was also recognized as the top of the Maroon Formation by Bass and Northrop (1963) in the Glenwood Springs quadrangle and, farther west, by Donnell (1954; 1958).

Throughout the area west and northwest of the Minturn quadrangle, however, other units have been recognized by various authors in the few hundred feet of strata immediately beneath the Chinle. Stratigraphically lowest of these, lying 100–750 ft (30–230 m) below the Chinle, is a distinctive white to orange sandstone called a tongue of the Weber Sandstone in the Maroon Formation by Donnell (1954) and Bass and Northrop (1963), called Weber Sandstone by Brill (1944) and Murray (1958), and called Schoolhouse Sand by Thompson (1949) or Schoolhouse Tongue by Brill (1952). About 50–150 ft (15–45 m) above the tongue of the Weber and 50–100 ft (15–30 m) below the Chinle, in the area west of Glenwood Springs is a cherty dolomite bed a few feet thick designated the South Canyon Creek Dolomite Member of the Maroon Formation by Bass and Northrop (1950), who recognized it as a probable tongue of the Phosphoria Formation.

All the strata between the tongue of the Weber and the Chinle, including the South Canyon, were assigned to the State Bridge Formation by Brill (1944; 1952), although in one measured section (1944, p. 643) he assigned these strata to the Dinwoody or Moenkopi Formations. At its type locality at State Bridge, 10 mi (16 km) northwest of the Minturn quadrangle, the State Bridge is distinguished from the underlying Maroon Formation by a change from the predominating coarse red sandstones of the Maroon to red siltstone and shale (Donner, 1949). A few miles northwest of State Bridge, Murray (1958) found that the tongue of the Weber ends abruptly; he inferred an erosional unconformity between the Maroon and State Bridge, and such an unconformity has subsequently been confirmed elsewhere in the region (Freeman, 1971).

The part of the State Bridge above the South Canyon Member (Stewart and others, 1972), or above an arbitrary datum 100 ft (30.4 m) higher (MacLachlan, 1959; Oriel and Craig, 1960), has been correlated on lithologic grounds with the Lower Triassic Moenkopi Formation.

It is not yet established whether equivalents of the Weber, South Canyon, and State Bridge or Moenkopi are included within the Maroon Formation as applied in the Minturn quadrangle. More likely, these units are younger than any of the Maroon in the quadrangle. The tongue of the Weber pinches out about 12 mi (20 km) west of the quadrangle, in the area between Walcott and Eagle. The South Canyon or a probable equivalent—the Yarmony Limestone Member of Sheridan (1950)—has not been identified closer to the quadrangle than Walcott or the State Bridge area. The Maroon within the quadrangle contains much siltstone in its upper part, and thus it might include strata equivalent to the lower part, at least, of the State Bridge. However, siltstone is abundant throughout the Maroon, even in the coarse-grained facies of the Pando and Kokomo areas. Therefore, the mere presence of siltstone in the red-bed sequence does not establish presence of the State Bridge.

THICKNESS

In the Minturn quadrangle the Maroon is largely restricted to the area north of Gore Creek, although a few small patches are present on high peaks south of the creek. The formation has a maximum thickness of about 4,200 ft (1,280 m) near Red and White Mountain, as determined from structure sections (pl. 1, secs. *A–A′*, *C–C′*), but it thins rapidly eastward toward the Gore Range. In the valley of the North Fork of the Piney River 2–3 mi (3–5 km) north of the quadrangle, the Maroon is only 1,700 ft (518 m) thick in the area just west of the Gore fault. East of the fault, where it lies on Precambrian rocks, only 100–300 ft (30–90 m) of it is present beneath the Chinle Formation (Tweto and others, 1970).

CHARACTER

The Maroon Formation resembles the Minturn Formation in lithology—except that it is almost uniformly red, contains only very minor carbonate beds, and grades irregularly upward into a predominating fine-grained facies. A measured section of the part of the formation preserved on Jacque Peak in the Kokomo district (Tweto 1949; 1958) shows that the lower 2,000 ft (610 m) of the formation consists of: sandstone, 35 percent; siltstone and shale, 25 percent; grit, 22 percent; and conglomerate, 18 percent. All these rocks are feldspathic and micaceous, just as are those of the underlying Minturn Formation. Some of the conglomerate beds contain abundant cobbles greater than 4 in. (10 cm) in diameter, and some contain 18-in. (45-cm) boulders. Many of the siltstone beds are calcareous, and some contain thin beds or lenses of fine-grained gray limestone.

In the area north of Gore Creek, the lower 3,000–3,500 ft (900–1,050 m) of the Maroon is moderately well exposed along Red Sandstone Creek and along the jeep road on the ridge to the west of this creek. The exposed rocks are principally brick-red sandstone, siltstone, grit, and conglomerate, just as on Jacque Peak, though collectively a little less coarse in grain. A few nonpersistent beds of gray dense unfossiliferous limestone 2–5 ft (0.6–1.5 m) thick are present among the clastic rocks. The upper 1,000–1,500 ft (300–450 m) of the Maroon is poorly exposed but seems to consist mainly of brick-red sandstone, siltstone, and grit. Much of the siltstone is limy, and some on the slopes above the Eagle River is gypsiferous. One thin bed of mottled gray and red algal limestone about 3,700 ft (1,130 m) above the Jacque Mountain can be traced with difficulty for several miles across the area (pl. 1). We consider it unlikely that this bed correlates with the South Canyon Member or the Yarmony Member of Sheridan (1950) because the red beds above it include much sandstone and grit.

Detrital material in siltstone and silty limestone in the upper part of the Maroon is of the same arkosic composition as that in the grits. In the siltstones, quartz, microcline, plagioclase, muscovite, and chlorite are principal constituents; magnetite is a rather abundant accessory mineral, and tourmaline and zircon are less abundant. The coloring matter is chiefly earthy red hematite or brown limonite concentrated at the grain boundaries. Some of the plagioclase grains are slightly altered, but many are fresh. In the silty limestones, the calcite matrix encloses abundant angular fragments of quartz and subordinate chert, microcline, plagioclase, muscovite, chlorite, and magnetite. The microcline and plagioclase are fresh. The magnetite is in rounded grains. Earthy red hematite coats the clastic grains and, in some of the limestones, this coating is accompanied by small but well defined crystals of red hematite.

FOSSILS AND AGE

No diagnostic fossils have been found in the Maroon in the Minturn quadrangle, and very few have been found in it or in closely associated units elsewhere in the region. A piece of fossil wood from a level about 200 ft (60 m) below the Chinle Formation on Red and White Mountain was tentatively referred to the genus *Dadoxylon* by R. A. Scott of the U.S. Geological Survey (written commun., 1961), who noted that this species occurs in all the post-Silurian periods of the Paleozoic. Limestone samples from two localites were examined by P. E. Cloud, Jr., of the U.S. Geological Survey (written commun., Feb. 7, 1961). Cloud found no microfossils in the insoluble residues. From thin-section study, he reported abundant fecal pellets 0.4–1.2 mm in diameter in a mottled pink and gray limestone from the saddle between Buffer and Indian Creeks. In a light-gray subaphanitic limestone from sec. 8, T. 5 S., R. 81 W., he found—in different specimens—tiny ostracods and "subspherical to bladder shaped objects about 0.3 mm in diameter and up to 1.2 mm long that suggest a siphonaceous alga similar to *Gymnocodium*." Cloud noted that if the objects are gymnocodian algae, they imply warm shallow water and a Permian age. The ostracods, which were examined by specialist G. I. Sohn of the U.S. Geological Survey, were unidentifiable.

Fossils found in the South Canyon Dolomite Member near Glenwood Springs indicate an age similar to that of the Permian Phosphoria and Kaibab Formations (Bass and Northrop, 1950; 1963). Poorly preserved fossils from the Yarmony Limestone Member of Sheridan (1950) were classed as Middle or Late Pennsylvanian or Permian in age by N. D. Newell (Brill, 1942). Far to the south, in the Salida area, reptilian remains occur in the Sangre de Cristo Formation at a level 1,800 ft (550 m) above a limestone unit that Brill (1952) correlated with the Jacque Mountain. The reptilian fossils were classed as Early Permian (Wolfcampian) in age by Brill (1952), but later collections from the same locality were classed as Late Pennsylvanian (Missourian) by Vaughn (1969).

Thus, the Maroon Formation of the Minturn quadrangle and neighboring areas probably is of Pennsylvania and Permian age. It is underlain without evident stratigraphic break by rocks of Middle Pennsylvanian (Des Moinesian) age and overlain by rocks of Early Permian (Leonardian) age, and reptilian fossils in the lower middle part of the generally equivalent Sangre de Cristo Formation have been assigned either to the Late Pennsylvanian or the Early Permian.

ORIGIN

The Maroon Formation records a continuation of the sedimentation that produced the Minturn Formation, but under somewhat changed environmental conditions. The average finer grain of the Maroon as contrasted to that of the Minturn and the general decrease in grain size upward within the Maroon suggest that the source land area to the east became progressively less mountainous. Presumably, the abrupt mountain front that existed along the Gore fault in Minturn time gradually was transformed by erosion to a gentler front which migrated eastward through Maroon time, thus continually increasing the distance between the main source of sediments and the site of deposition. The absence of fossiliferous marine limestones, such as those of the Minturn, and the absence of any strata indicating a marine origin—except near the evaporite basin—suggest that the pattern of alternating marine and terrestial conditions that characterized the Minturn gave way to dominantly terrestial conditions of sedimentation. The sediments of the Maroon in the Minturn quadrangle are interpreted as stream channel and floodplain deposits at the east and as grading westward into coastal plain or tidal flat and local lagoonal deposits. In the lower part of the formation, these deposits intertongue westward with marine evaporites. The thin and nonpersistent limestones in the Maroon probably formed in desiccation ponds or lagoons rather than in marine waters. Farther west, carbonate rocks, such as those of the South Canyon, represent marine conditions.

The consistent red color of the Maroon also indicates a change in environment from that of the bulk of the Minturn, though the uppermost part of the Minturn was also affected by the change. Raup (1966) concluded from the clay mineral assemblage and particularly from the absence of detrital kaolinite in the fine-grained red beds of the Minturn, Maroon, and State Bridge Formations that the source material could not have been laterite, as has been often assumed, but that the source material was a product of weathering in a semiarid to arid environment. Walker (1967) concluded from an extensive study of red beds in the Maroon and Minturn and from close mineralogic parallels with red beds that are forming at present in Baja California that the red color formed after the deposition of the sediments, by alteration of iron-bearing minerals, in an arid environment. We agree in general with these conclusions but would qualify them somewhat.

The widespread occurrence of evaporites and eolian deposits in the Upper Pennsylvanian and Permian rocks of the Rocky Mountain region (McKee, Oriel, and others, 1967) suggests a regionally arid climate, as does the absence of plant and animal remains in the Maroon

Formation. The abundance of fresh feldspars, even in the siltstones of the Maroon, and the presence of unaltered detrital magnetite and biotite suggest mechanical weathering in an arid environment rather than chemical weathering in a humid, laterite-producing environment. However, hematite does occur as discrete, apparently detrital flakes in company with unaltered detrital biotite and magnetite in some of the siltstones and impure limestones. Such hematite must have been transported to the site of deposition rather than forming there by alteration or by subsequent redistribution of ferric iron by ground water. Assuming, as the clay mineralogy seems to dictate, that lateritic soils did not exist as a source of the detrital hematite, a source might nevertheless be produced by normal weathering in an upland somewhat less arid than the environment of deposition.

One of the factors contributing to the redness of the red beds is the presence of films of hematite in minute fractures within quartz clasts, giving them a pink or red cast. Such quartz occurs as pebbles even in the gray, buff, and green conglomerates of the Minturn Formation. Reconnaissance of the entire Gore Range (Tweto and others, 1970) has revealed that quartz of this character occurs in many hematite-stained fracture zones in the Precambrian rocks of the range. Rocks of the Gore fault zone, for example, are stained red by hematite and contain the hematite-impregnated quartz through widths of hundreds of feet in places. Presumably, this hematite is a product of geologically recent weathering. However, the Gore fault and many of the numerous other faults in the range originated in Precambrian time (Tweto and others, 1970); thus, they were in existence and were exposed to weathering in Pennsylvanian and Permian time. Such faults or fracture zones might have been a source of some hematitic material in the red beds. Most of the hematite, however, probably resulted from alteration of iron-bearing minerals in the depositional environment, as demonstrated by Walker (1967), and from redistribution by ground water of iron liberated by alteration. Alteration of iron-bearing minerals and redistribution of iron need not have been, in their entirety, penecontemporaneous with sedimentation. Indeed, some evidently occurred much later. The lower red zone in the Minturn, for example, transects bedding in a wavy manner that suggests ground-water control; in part at least, this red color may be related to the present topography. On the other hand, the occurrences of typical red-bed rocks, such as pebbles or fragments in nonred conglomerates of the upper Minturn, and of red siltstone chips in dense gray limestone in the Maroon, though rare, indicate that red beds were in existence at the time these conglomerates and limestones were deposited.

TRIASSIC SYSTEM

CHINLE FORMATION

The Upper Triassic Chinle Formation is the only Triassic unit recognized in the Minturn quadrangle. The Chinle is preserved in the quadrangle only in an area of less than a square mile on the northeastern slope of Red and White Mountain. In this area, and also in the Mount Powell quadrangle to the north, it consists of a basal white sandstone or conglomerate 10–25 ft (3–7.5 m) thick overlain by red siltstone. The basal sandstone or conglomeate, earlier referred to the Shinarump Member (Lovering and Tweto, 1944), was later classed as the Gartra Member of the Chinle (Poole and Stewart, 1964). On Red and White Mountain the Gartra seems to be conformable with the underlying Maroon Formation, but a few miles to the northeast, in the Mount Powell quadrangle, it fills shallow channels in the top of the Maroon and in places shows an angular discordance of 1°–2° with the Maroon.

The Chinle is overlain unconformably by the Jurassic Entrada Sandstone. On the northeast shoulder of Red and White Mountain, the red siltstone of the Chinle is about 70 ft (21 m) thick. About a mile to the west, on the west and northwestern ridge of Red and White Mountain, Poole and Stewart (1964) measured 225 ft (68 m) of the siltstone between the Gartra and the Entrada. Thus, a significant unconformity between the Chinle and Entrada is indicated; this pre-Entrada unconformity has been widely recognized in Colorado.

As exposed within the small area on the side of Red and White Mountain, the Garta Member is about 10 ft (3 m) thick and consists of coarse-grained gray sandstone. On the northwestern side of Red and White Mountain, Poole and Stewart (1964; also F. G. Poole, written commun., 1956) found the Gartra to consist of 25 ft (7.6 m) of crossbedded conglomeratic sandstone. The pebbles consist of quartz, chert, and quartzite and are as much as 3 in. (7.6 cm) in maximum dimension. The sandstone also contains silicified wood in fragments or in segments of logs. A few miles north of the boundary between the Minturn and Mount Powell quadrangles, the Gartra is in some places a massive crossbedded coarse-grained sandstone and in others a conglomerate characterized by abundant silicified wood (Tweto and others, 1970).

The red siltstone of the Red and White Mountain area is divided by Poole and Stewart (1964) into a lower mottled member and an upper red siltstone member. The mottled member, about 25 ft (7.6 m) thick, consists of red and purple mudstone, siltstone, and sandstone. The red siltstone member consists of brick red siltstone, much of which is calcareous, and subordinate fine-grained red sandstone. As seen in thin section, the siltstone from Red and White Mountain consists of silt-sized angular fragments of quartz and equant grains of calcite, fairly abundant accessory leucoxene in rounded grains, and interstitial red hematite. Very sparse, small flakes of muscovite are also present but no detrital feldspar fragments were observed. The calcite appears to be detrital rather than a matrix cement as it is in the Maroon siltstones. The scarcity of mica and absence of feldspar suggest that the rock is more mature than the siltstones of the underlying Maroon and Minturn Formations; possibly the Chinle rocks were derived in part from the reworking of red beds in these older formations.

JURASSIC SYSTEM

Two Upper Jurassic formations, the Entrada Sandstone and the Morrison Formation, were mapped in the Red and White Mountain area, the only locality where rocks of Jurassic age are preserved in the Minturn quadrangle. The Morrison of this locality and also of the area immediately north of the quadrangle (Tweto and others, 1970) contains much sandstone in its lower part. Some of this sandstone may be equivalent to units of the Sundance Formation as recognized in the State Bridge area by Pipiringos, Hail, and Izett (1969) or to the Curtis Formation of Baker, Dane and Reeside (1936).

In the area just north of the Minturn quadrangle, the Entrada is absent and the Morrison rests, successively eastward, on Chinle, Maroon, and—a few miles east of the Gore fault—on Precambrian rocks (Tweto and others, 1970). Some part of the erosion that destroyed the Chinle or reduced it to thin remnants may be attributed to the pre-Entrada period of erosion discussed in the preceding section. A part, however, was caused by pre-Morrison erosion that removed the Entrada in a belt near the Gore fault and beveled an even surface across rocks of the Maroon Formation and remnants of the Chinle. East of the Gore fault, this surface beveled Precambrian rocks also.

ENTRADA SANDSTONE

As exposed on Red and White Mountain, the Entrada consists of about 60 ft (18 m) of cliff-forming, massive, bluff-to orange-weathering crossbedded sandstone. A generally similar character and thicknesses ranging from 62 to 109 ft (19 to 33 m) are reported in localities from 8 to 20 mi (13 to 32 km) west of the quadrangle (Sheridan, 1950). In outcrop, the Entrada appears to be conformable with the underlying Chinle Formation and the overlying Morrison, but regional relations indicate that both contacts are unconformities.

The sandstone of the Entrada on Red and White Mountain is compact, homogeneous, and fine grained. It consists of well-sorted subangular to subrounded equant sand grains about 0.1 mm in diameter and of small amounts of interstitial clay and orange goethite. The scattered coarse sand grains that characterize the Entrada in many places were not noted at this locality. The grains of the sandstone are mostly quartz, but chert is fairly abundant and a few grains of fresh microcline and slightly argillized plagioclase are also present. The interstitial clay is a mixture of hydromica and kaolinite, which locally contains small specks and irregular masses of goethite. No detrital heavy minerals were observed in thin section.

MORRISON FORMATION

In the small area of exposure on Red and White Mountain, the Morrison Formation consists of about 250 ft (76 m) of sandstone and shale unconformably overlying the Entrada Sandstone and unconformably underlying the Cretaceous Dakota Sandstone. This thickness is small as compared with about 500 ft (150 m) of Morrison in the southern part of the Mount Powell quadrangle (Tweto and others, 1970) and the 350–400 ft (105–120 m) shown on a regional isopach map (Craig and others, 1955). The abundance of sandstone in the Morrison at Red and White Mountain suggests that only the lower part of the formation is present and that the upper part was eroded prior to deposition of the Dakota.

The Morrison of Red and White Mountain, and the lower half of the formation as exposed just north of the Minturn quadrangle, consists of predominant sandstone, subordinate interbedded green and gray clay shale, and a few beds of fine-grained gray limestone. The upper part of the formation—north of the quadrangle—is mainly variegated shales.

The sandstone is characterized by uneven, lenticular bedding and by abundant particles of white clay that give the rock a chalky appearance. The clay occurs interstitially and also as discrete grains or granules. Some beds of the sandstone contain scattered granules and pebbles of chert and quartz. Thin sections show that the grains in the sandstone are poorly sorted, subangular to subrounded, and from 0.2 to 2 mm in diameter. In most parts of the rock these grains have the interlocking sutured grain boundaries of a quartzite, but in small irregular areas a few millimeters in diameter, the individual sand grains are separated by a matrix of fine-grained calcite. In the basal sandstone, the detrital sand grains consist largely of quartz, with subordinate chert, calcite, and fresh microcline, in order of decreasing relative abundance. A few rounded detrital grains of zircon and green tourmaline are present also. Sandstone above the basal bed is similar in character except that it contains chalky white grains of argillized feldspar and a few rounded masses as much as 2 mm in diameter of white clay. Specks of light-brown limonite averaging about 1 mm in diameter are abundantly and evenly disseminated through some of the rock.

Limestone of the Morrison is typically dense, thin bedded, lithographic, and medium gray to light bluish gray. Some of it contains irregular olive-gray chert nodules as much as one-half inch (1 cm) long. Some beds, and particularly a 5- to 10-ft (1.5- to 3-m) thick bed that is 10–15 ft (3–4.5 m) above the base of the formation, contain abundant spherical algal structures 1–3 mm in diameter that were identified as charophyte remains by Richard Rezak, formerly of the U.S. Geological Survey (oral commun., 1951). The presence of charophytes is conclusive evidence of the nonmarine origin of this limestone (Peck, 1957, p. 1).

CRETACEOUS SYSTEM

DAKOTA SANDSTONE

The Dakota Sandstone is the youngest formation in the sequence of consolidated sedimentary rocks preserved in the Minturn quadrangle. Only two small remnants of the Dakota—on the northeastern slope of Red and White Mountain—remain in the quadrangle, but the sandstone is widespread to the northwest and north. Just north of the quadrangle (Tweto and others, 1970), the Dakota is 150–160 ft (45–48 m) thick. Except for 25–35 ft (7.5–10.5 m) of dark-gray thin-bedded shaly sandstone at the top, it consists entirely of light-gray sandstone. In some places the sandstone is medium to thick bedded and contains thin argillaceous seams and nodules; in others it is very massive, crossbedded, and is composed of a clean quartz sand. Lenses of conglomerate a few inches thick occur locally at the base of the sandstone or scattered through the lower 5–10 ft (1.5–3 m) of it. At localities farther north, as much as 40 ft (12 m) of conglomerate is present at the base of the Dakota. Pebbles in the conglomerate are typically about one-half inch (1 cm) in diameter, are well rounded, and consist of chert, quartz, and white silicified volcanic rock.

The sandstone of the Dakota is brittle but is hard and resistant, and it has a tendency to fracture into blocks that slide on the shales of the underlying Morrison Formation and slopes below. An area of several square miles east of Red and White Mountain is littered with blocks of Dakota, and it is evident that the two small patches of Dakota bedrock near the top of the mountain are the last remnants of an extensive sheet that has been destroyed by sliding of detached blocks.

UPPER CRETACEOUS AND TERTIARY IGNEOUS ROCKS

Igneous rocks younger than Precambrian occur only in scattered areas in the Minturn quadrangle. They include (1) a persistent sill of quartz latite porphyry in basal strata of the Belden Formation along the canyon of the Eagle River; (2) scattered small dark dikes in the Gore Range; and (3) patches of basalt and tuff on the sides of the Piney Rivery valley in the northwestern corner of the quadrangle. The sill is a northern extension of the group of porphyry bodies that characterize the Colorado mineral belt at this general longitude. The northwestern edge of the main belt of abundant and varied porphyry bodies is in the Pando area, about 5 mi (8 km) south of the Minturn quadrangle.

PANDO PORPHYRY SILL

The quartz latite porphyry of the sill exposed along the canyon of the Eagle River was named the Pando Porphyry by Tweto (1951), who traced it to the Leadville area, where distinctive altered facies of it had been known as "White porphyry" and "Mount Zion porphyry" (Tweto, 1956). Throughout the area between Gilman and Leadville, the Pando Porphyry occurs principally in one or more sills near the base of the Belden Formation, but it also forms sills in the Sawatch Quartzite and the Minturn Formation. The sills become thinner and less numerous northward; from near Pando northward into the Minturn quadrangle, only one sill is present. This sill—in the Belden—is more than 100 ft (30 m) thick near the quadrangle boundary and about 80 ft (24 m) thick at Gilman. North of Gilman it tapers more rapidly and apparently comes to a wedge end in a covered area south of the mouth of Two Elk Creek.

Geologic relations show that the Pando is the earliest and most widespread of all the porphyries in the mineral belt in the southern Gore and Mosquito Ranges. Isotopic dating by the K-Ar method established a Late Cretaceous age of about 70 m.y. (million years) for it (Pearson and others, 1962).

The Pando Porphyry is altered wherever exposed in the Minturn quadrangle and through most of the region to the south. The only known unaltered occurrences of it are in the center of a source plug or stock north of Leadville. The widespread pervasive alteration is deuteric. In mineralized areas, a later hydrothermal alteration is superposed on the deuteric alteration, but as the chemistry of the two stages was generally similar, the second alteration merely accentuated the first one, and the two are difficult to distinguish.

The deuterically altered porphyry consists mainly of an aphanitic groundmass; phenocrysts constitute only 1–10 percent of the rock. The phenocrysts are principally altered plagioclase, typically in prisms 2–4 mm long, and smaller shreds of altered biotite. Quartz phenocrysts are generally present in smaller amounts, and potassium feldspar and smoky muscovite phenocrysts locally are scattered sparsely through the rock. The altered porphyry is light gray to orange gray or pinkish gray and weathers buff to yellowish gray.

As seen in thin section the deuterically altered rock consists of a slightly trachytoid groundmass and sparse phenocrysts. The phenocrysts are mainly plagioclase (oligoclase) and biotite, invariably strongly altered, but also they include quartz in rounded to subhedral grains and occasional grains of moderately fresh potassium feldspar. The groundmass consists of these same minerals together with anorthoclase. Sphene and apatite are minor accessory minerals.

In outcrop, sills of Pando Porphyry generally are characterized by a thin platy structure near and parallel to the contacts and by a crude columnar structure in the interior (fig. 18). Primary flow structures, described in detail by Tweto (1951), include textural layering, mineral orientations in the outer parts of a sill at right angles to the orientation in the body of the sill, intrusive-stage folds and faults, and the platy parting, which was produced by differential laminar flow. These features were interpreted by Tweto to indicate a relatively viscous magma as compared with other porphyries that do not show these features. The structural features indicate intrusion from the south-southeast, the general direction of the presumed source pluton near Leadville.

Chill zones in the Pando Porphyry sills generally are only a few inches thick, but locally they were thickened to as much as 3 ft (0.9 m) by the intrusive-stage drag folds and thrust faults. The contacts between the chilled and unchilled porphyry are sharp discontinuities that reflect differential flow while the sill magma cooled and solidified. The chilled porphyry is glassy in appearance, though microscopic study shows that most of it is finely crystalline.

Sedimentary rocks in contact with Pando Porphyry generally show only slight metamorphism. Black shale,

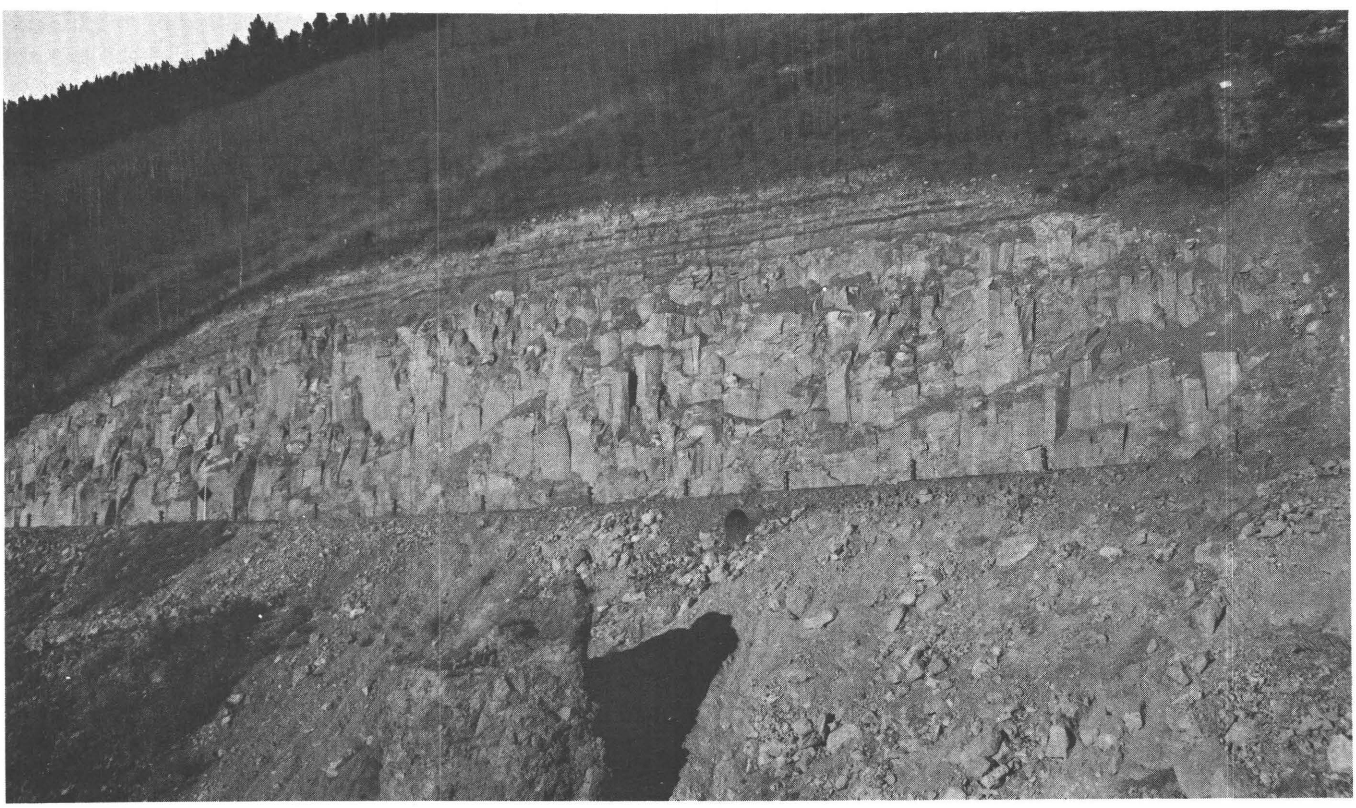


FIGURE 18.—Columnar structure in sill of Pando Porphyry exposed in cut on U.S. Highway 24, one-half mile (0.8 km) north of Gilman. Thin-bedded strata of the Belden Formation are above the sill, and a karst pinnacle of Leadville Dolomite casts shadow on embankment below highway.

the common wallrock of the porphyry, is only slightly hardened and slightly bleached for a few inches adjoining the contact. Black limestone is slightly bleached but otherwise unaltered. Where the Pando intrudes Leadville Dolomite 2–3 mi (3–5 km) south of Red Cliff, the gray dolomite is slightly reddened for about 2 in. (5 cm) from the contact. As seen in thin section, the dolomite is finely brecciated and is cut by minute veinlets of quartz and hematite. The dolomite also contains a few specks of hematite and a few blades of sericite that may have been introduced from the sill.

In contrast to the negligible effect of the sill on its wallrocks, the wallrocks seem to have affected the deuteric alteration within the sill, for the type of alteration seems to correlate with the type of wallrock. Where the Pando Porphyry sill intrudes shale of the Belden Formation, the sill is characterized by a sericite-anorthoclase type of alteration. In contrast, small sills of Pando in Sawatch Quartzite just south of the quadrangle in the Pando area (Tweto, 1953) are characterized by chlorite-allophane alteration. The difference in alteration with difference in wallrocks suggests that the wallrocks either influenced or caused deuteric alteration, probably by supplying water to the cooling sills which, as judged by metamorphic effects and structural features, were intruded as "dry" and viscous magmas.

Where the enclosing rock is shale, the dominant mineral in the Pando Porphyry is moderately coarse-grained sericite which makes up a large part of the groundmass of the porphyry. Biotite is altered to coarse sericite or muscovite accompanied by calcite, leucoxene, and small crystals of included apatite (fig. 19). Chlorite is absent. The feldspar phenocrysts are irregularly replaced by an isotropic clay identified microscopically as allophane. Both the feldspar and the allophane are veined by anorthoclase or by a more sodic plagioclase, which remains fresh. In the remaining allophanized portions of the feldspar grains, fine-grained sericite later formed abundantly. Except in the altered biotite grains, calcite or other carbonates are lacking in the deuterically altered porphyry, though they are generally present where the rock was further altered by late hydrothermal solutions. Pyrite is locally present in small amounts in the deuterically altered porphyry. Quartz and apatite are unaltered.

Where the Pando Porphyry has quartzite walls, biotite in the porphyry is changed to chlorite, and feldspars are extensively allophanized. The chlorite is accompanied by minor amounts of sericite, muscovite, montmorillonite, and leucoxene (fig. 20). Some chlorite is partly replaced by montmorillonite which, in turn, is replaced by sericite. Both the plagioclase and the potassium feldspar are strongly allophanized, and the allophanized plagioclase is partly altered to hydromica (about 10 percent) with some sericite. Potassium feldspar phenocrysts are strongly allophanized and contain many small irregular masses of chlorite which probably represent former inclusions of biotite. Moderately coarse sericite is abundant in the groundmass where it apparently represents groundmass biotite. Pyrite and carbonate are absent in the chloritized porphyry in quartzite and no evidence of silicification was observed.

The early allophane in both rocks and the accompanying chlorite in the one suggest only the addition of water and some leaching of iron. The abundant sericite and accompanying anorthoclase and late sodic

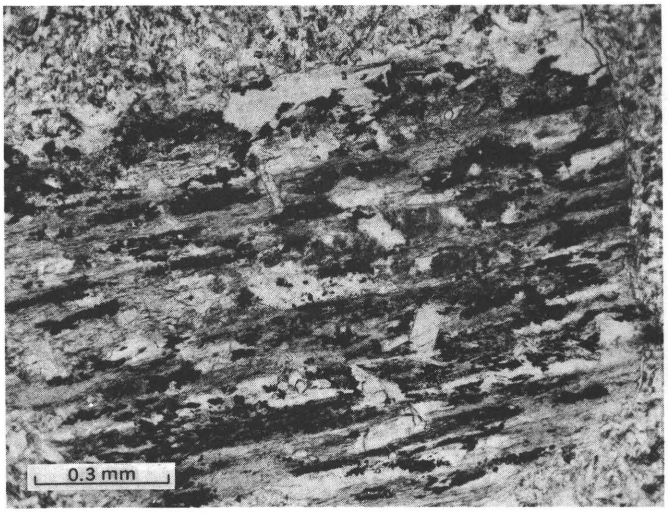


FIGURE 19.—Pando Porphyry showing phenocryst of biotite altered to sericite, leucoxene, and calcite, and sericitic groundmass. Crossed polars.

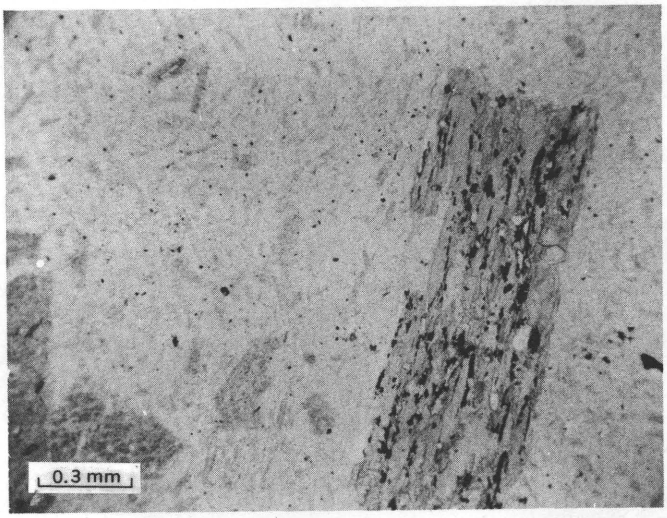


FIGURE 20.—Pando Porphyry showing biotite phenocryst altered to chlorite and opaque oxides. Potassium feldspar phenocryst at left is allophanized. Plain transmitted light.

plagioclase of the other rock suggest addition of alkalies at a later stage. At the time of intrusion, the wallrocks were almost certainly water saturated, as indicated by mudstone dikes near some porphyry contacts in the Pando-Leadville area; these dikes must have been emplaced as mud slurries. A sill of relatively dry magma intruded into saturated rocks might first absorb water nearly free of solutes, perhaps in the vapor phase, and then, with passing time and the transfer of heat farther into the wallrocks, water containing alkalies leached from shales might be supplied. Where the wallrocks consisted almost entirely of clean quartz sandstone or quartzite, alkalies were not available in quantity, and alteration stopped at the allophane-chlorite stage, except that alkalies liberated by allophanization of the feldspars and chloritization of biotite became available to form the relatively minor hydromica and sericite of these rocks. In the shale environment, the alkali-bearing solutions from the wallrocks probably contained a relatively high proportion of potassium, inasmuch as the potassium feldspar crystals are little sericitized, whereas biotite is completely altered to sericite and leucoxene.

The formation of potassium and sodium feldspars would decrease the ratio of alkalies to hydrogen ion, and, as shown in the diagrams of Hemley and Jones (1964, figs. 1 and 2), this would shift the field of equilibrium from feldspar towards mica and ultimately to kaolinite-pyrophyllite. The shift from feldspar to mica is evident in the mineralogic relations in the altered porphyry; but the kaolinite-pyrophyllite stage was not reached, probably because equilibrium in saturation between wallrocks and sill was reached in a relatively short time, ending the transfer of solution to the sill. During the process of deuteric alteration, iron and magnesium were largely expelled, though some iron was fixed locally as pyrite or siderite.

DIKE ROCKS

Scattered small dikes of dark fine-grained igneous rocks occur along faults in the Precambrian rocks of the Gore Range, especially near the northern boundary of the quadrangle. The dikes are somewhat more abundant northward in the Mount Powell quadrangle but are absent southward through the remainder of the Gore Range (Tweto and others, 1970). Only one small dike has been found in the sedimentary rocks; this dike cuts grit of the Minturn Formation on Pitkin Creek about one-half mile (0.8 km) from Gore Creek.

The dikes are latite, dacite, and quartz basalt porphyries, some of which have lamprophyric characteristics. In the Slate Creek area and northward into the Mount Powell quadrangle, most of the dikes more than 4 or 5 ft (1.2 or 1.5 m) wide contain sanidine phenocrysts in their inner zones, but the small dikes are aphanitic. These dikes are inferred to be related to the trachytic intrusive and volcanic center at Green Mountain in the Mount Powell quadrangle (Tweto and others, 1970). The dikes are considerably altered deuterically and therefore cannot be closely characterized petrographically. They seem to have consisted originally of a groundmass of small andesine laths and magnetite grains in a matrix of low-index feldspar, possibly anorthoclase, and phenocrysts of labradorite, potassium feldpsar, hornblende, augite, and minor biotite and quartz. Some contain as much as 3 percent apatite. Calcite and chlorite are abundant alteration products, and one dike, 1.2 mi (1.9 km) southwest of Upper Slate Lake, contains the zeolite scolecite in abundance. The rock is classed as a lamprophyric latite.

Dacite porphyry dikes on the western side of the Gore Range, on the slopes above the upper Piney River, are characterized by abundant phenocrysts of andesine, some of which are as much as an inch (2.5 cm) in length and by small anhedral grains of hornblende. The groundmass is a very fine grained aggregate of oligoclase, quartz, potassium feldspar, biotite, and magnetite. Sphene is a relatively abundant accessory mineral, and apatite, epidote, and allanite are present in small amounts.

A short dike on the ridge between Bighorn and Pitkin Creeks and the dike in the Minturn Formation near the mouth of Pitkin Creek are quartz basalt. In the dike on the ridge, some of the quartz is in rounded grains that may be xenocrystic, although quartz occurs also in the groundmass. In the dike on Pitkin Creek, quartz occurs both in the groundmass and as 2–3 mm phenocrysts with square cross-section, suggesting original cristobalite. The plagioclase phenocrysts of the basalt porphyries are labradorite, An_{58-60}, and the plagioclase of the groundmass is andesine, An_{40}. The dike on the ridge contains about 25 percent of pyroxene in the form of aegerine-augite and pigeonite. The pigeonite rims and replaces the aegerine-augite. The dike on Pitkin Creek contains 11 percent augite and 5 percent biotite. The magnetite content of the two rocks is 5 and 8 percent, respectively.

The dike rocks are considered to be of middle to late Tertiary age. The basalts presumably are related to the basalts of the Piney River which, as shown in the following discussion, are Miocene in age. The latites and dacites seem to be related spatially and compositionally to the Green Mountain intrusive-volcanic center in the Mount Powell quadrangle. Geologic evidence suggests that this center is of late Tertiary age (Tweto, 1957), although a single fission-track age of about 30 m.y. (Naeser and others, 1973) suggests a late Oligocene age.

VOLCANIC ROCKS

Basalt and tuff or volcanic ash occur in patches high on the sides of the Piney River valley in the northwestern corner of the quadrangle. Basalt caps a ridge and knob northeast of the junction of Meadow Creek and the Piney River between the 9,500- and 9,800-ft contours, and it occurs also in a small patch high on the east slope of Red and White Mountain at the 10,300-ft contour. Tuff or ash crops out in a narrow belt at the top of the cliffs on the west side of the canyon of the Piney north of Dickson Creek, between the 9,400- and 9,750-ft contours. The tuff probably underlies much of the area covered by surficial deposits on the east and north slopes of Red and White Mountain (pl. 1).

These occurrences are erosional outliers of a moderately extensive basaltic volcanic field in the Piney River area and along the Colorado River north of the quadrangle. As mapped by Brennan (1969) and Donner (1949), this volcanic field extends from about 3 mi(5 km) north of the Minturn quadrangle northwestward about 14 mi (22 km) to Yarmony Mountain, north of the Colorado River. The volcanic sequence consists of superposed basalt flows which locally are separated by beds of volcanic ash or by lenticular fluviatile deposits. Donner (1949) distinguished at least nine flows, each 25–150 ft (7.6–45.7 m) thick, in the State Bridge area; he also mapped a persistent bed of tuff and breccia between the fifth and sixth flows. Taggart (1962) recognized more than 25 flows, each 5–40 ft (1.5–12.2 m) thick, on Piney Ridge, east of the Piney River, and he noted thin beds of calcareous tuff between some of them. In the lower valley of the Piney River, tuffaceous sedimentary rocks several hundred feet thick overlie the basaltic rocks (Brennan, 1969). On the basis of lithology, vertebrate fossils, and intercalated ash beds, the sedimentary rocks might be assigned to the Troublesome Formation of Middle Park, the North Park Formation, or the Browns Park Formation, all of Miocene age (Izett, 1968; also oral commun., 1970).

The tuff in the Minturn quadrangle crops out for about a mile (1.6 km) northwestward from the Dickson Ranch, at a level about 800–900 ft (240–270 m) above the Piney River. It lies on a gullied surface with relief of as much as 75 ft (22.8 m) cut over strata of the Maroon Formation. It is overlain by 50–75 ft (15–22.8 m) of surficial materials, which are discussed in the following section. Maximum exposed thickness of the tuff is about 200 ft (61 m). The tuff is light brown to yellowish white, coherent and tough but porous and friable, and distinctly "light" in weight, or specific gravity. Much of the tuff contains charcoal specks, and the upper 50 ft (15 m) contains abundant chunks of white opal as well as fragments of opalized twigs or rootlets. Bedding is faint or absent. As seen microscopically, the tuff consists principally of pyroclastic materials but contains a minor fraction of foreign materials, such as microcline, rounded quartz grains, epidote, muscovite, and probably some biotite. The pyroclastic fraction consists in part of faintly anisotropic, turbid, partly devitrified glass and in part of isotropic glass shards, crystal fragments of plagioclase, potassium feldspar, biotite, and hornblende. Refractive index of the glass is 1.49 as determined by G. A. Izett of the U.S. Geological Survey.

The basalt in the Minturn quadrangle is near andesite in composition and is notable for the presence of rather abundant potassium feldspar in the groundmass. The rock is dark gray, vesicular, and aphanitic, except for a few plagioclase phenocrysts as much as 4 mm long. These phenocrysts are conspicuously zoned and have cores of labradorite with rims of oligoclase. Grains of augite about 1 mm in diameter constitute about 25 percent of the rock. Olivine is present in scattered grains about the same size as the augite. Both the augite and the olivine are extensively altered to iddingsite and to a fine-grained low-index chlorite. The groundmass is a very fine grained mixture of twinned acicular andesine, tabular orthoclase, and sparse accessory magnetite. Flows near State Bridge were described by Donner (1949) as olivine-bearing hypersthene andesites and olivine basalts.

The stratigraphic relationship between the tuff and the basalt in the Minturn quadrangle is not evident, owing to the isolated exposures. Absence of basalt beneath the tuff suggests that the tuff may be the older, but the two rocks could intertongue, or if the basalt were discontinuous, the tuff could be the younger. Further, the precise relation of the tuff to the sequence of tuffs and siltstones farther north is unknown, but on the basis of general similarity in character, they are assumed to be of about the same age.

Fossil dog remains from the tuffaceous sedimentary rocks on the lower Piney River (E 1/2, sec. 1, T. 3 S., R. 83 W.) were described as *Cynodesmus casei* and assigned to the early Miocene by Wilson (1939). Reappraisal of this fossil and study of other vertebrate fossils found later in these strata led G. Edward Lewis of the U.S. Geological Survey (written commun., May 1, 1970) to assign a late Miocene age. Lewis referred Wilson's specimen to *Tomarctus thomsoni* (Matthew) rather than to *Cynodesmus casei* and, from other fossil collections in the area, identified:

1. The dogs *Amphicyon* sp. and *Tomarctus* sp.
2. The oreodont *Brachycrus* sp. close to *B. vaughani* Schultz and Falkenbach and *B. wilsoni* Schultz and Falkenbach
3. The horse *Merychippus* sp. close to *M. isonesus* (Cope)

Basalt from Yarmony Mountain in the Piney River

FIGURE 21.—Rugged topography formed by glaciation in Gore Range. View southwestward from Upper Slate Lake.

basalt field has been dated isotopically as 21–24 m.y. (early Miocene) in age (Mutschler and Larson, 1969). As the basalts underlie the fossiliferous tuffs and siltstones, this age is consistent with the late Miocene age of the vertebrate fossils.

PHYSIOGRAPHY AND UPPER TERTIARY AND QUATERNARY UNCONSOLIDATED DEPOSITS

Physiographically, the Minturn quadrangle consists of three main units, corresponding to the threefold division in its bedrock geology. The Gore Range, on the northeast, is characterized by deep canyons and knife-edge ridges created by intense glaciation (fig. 21). The flank of the Sawatch Range, on the southwest, is an area of shallower glacial canyons, separated by broad, evenly inclined dip slopes (fig. 22) that rise southwestward toward high and rugged peaks that lie outside the quadrangle. The broad area between the two ranges, corresponding in general to the area underlain by the Minturn and Maroon Formations, is an area of smooth ridges and slopes and deep stream valleys (fig. 23).

The fluvial and glacial erosional processes that produced these landscapes also produced deposits, such as stream gravels, moraines, and colluvial blankets. Although the preserved deposits are small in comparison to the volume eroded, they provide a record of the character and timing of the erosional processes. This record begins with local and generally scanty deposits of late Tertiary age and extends with increasing clarity through the Pleistocene Epoch to the present.

The earliest deposits related to the existing topography and physiography are the tuff and basalt of the Piney River area at the north edge of the quadrangle. These volcanic materials were deposited in a broad valley that was centered approximately over the pres-

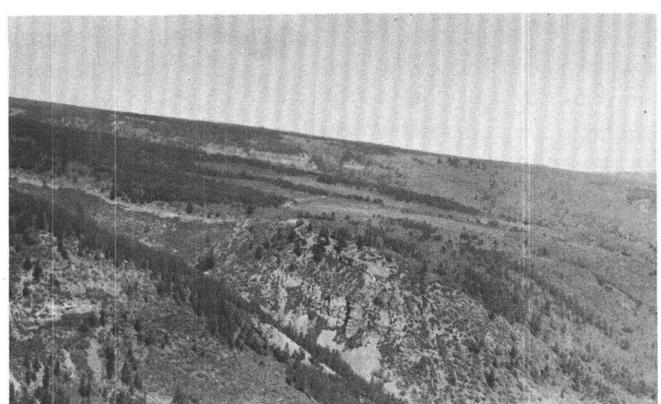


FIGURE 22.—Dip slopes on flank of Sawatch Range. View northwestward across mouth of Bishop Gulch; canyon of Cross Creek in middle distance.

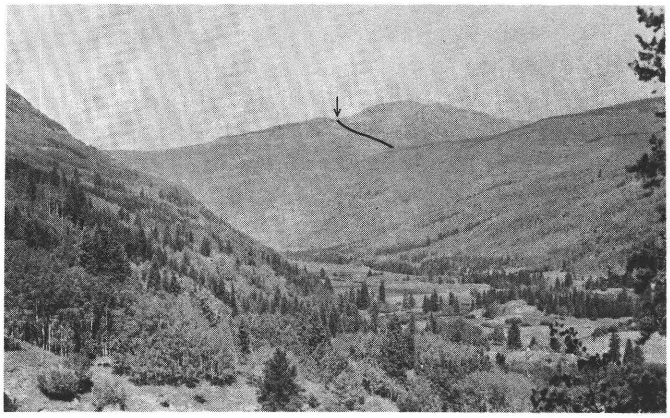


FIGURE 23.—Typical topography in area of Minturn Formation. View northwestward across valley of Gore Creek toward Bald Mountain (on skyline). Gore fault (arrow) is in front of crest of Bald Mountain; Precambrian rocks in back of the fault.

ent valley. Within the quadrangle, where the valley of the Piney River was greatly deepened by glacial erosion and related stream cutting, remnants of the old valley bottom as defined by the volcanic rocks are several hundred feet above the present stream (pl. 1, sec. *D–D'*). Farther north, however, the volcanic rocks extend to the bottom of the present valley, indicating that the valley was both wide and deep in Miocene time. Other streams in the sedimentary terrane, such as Gore, Red Sandstone, and Turkey Creeks and the Eagle River probably occupied similar valleys in a rolling upland of low relief in the Miocene, but no direct evidence of this has been found.

Aside from the volcanic rocks in the old valley of the Piney River, the oldest deposit related to the present physiography is a thick and old colluvium that mantles the high slopes in the northwestern part of the quadrangle. The colluvium covers some of the tuff along the Piney River; hence, it is younger than late Miocene. Shallow cirques of the earliest recognized glaciation are incised below some of the colluvium-mantled slopes, and in places the colluvium seems to extend beneath ancient glacial drift. The colluvium is, therefore, preglacial. It is judged to be Pliocene and possibly early Pleistocene in age.

The glacial history of the Pleistocene Epoch is represented by an exceptionally rich record, as almost every drainage of consequence in the quadrangle was glaciated at least once. This record takes the form both of erosional features, such as canyons and cirques, and of depositional features, such as moraines and valley trains of outwash gravels. Studies made subsequent to our main field work in the Minturn quadrangle indicate that as many as nine distinct episodes of glacial advance and retreat occurred in the mountains of central Colorado (Tweto, 1961). Of these, two are tentatively correlated with the pre-Bull Lake glaciations defined by Richmond (1960, 1964); two are correlated with the Bull Lake Glaciation; three are correlated with the Pinedale Glaciation (Blackwelder, 1915; Richmond 1960); and two are Neoglacial or Holocene. All nine are represented by deposits in the Minturn quadrangle, but they are depicted only in two main groups on the map: (1) pre-Bull Lake and (2) Bull Lake and Pinedale undivided, although deposits of these two glaciations are separately distinguished in a few critical areas. Deposits of the two Neoglacial episodes exist in many of the cirques of the Gore Range but were not mapped. Relicts of the later of these, if not of both, are represented by many ice-cored rock glaciers in the high cirques. The glacier shown on the map (pl. 1) at the head of Black Creek was active in 1942 when discovered by Lovering, but it had degenerated to a boulder- and snow-covered body of stagnant ice by 1969 when it was revisited by Bruce Bryant in connection with the study of the Gore Range Primitive Area (Tweto and others, 1970).

The glacial epoch was a time of pronounced erosion of valleys and canyons, both by glacial ice and by streams. At the time of the pre-Bull Lake glaciations, deep canyons, such as those of the Eagle River and upper Gore Creek, did not yet exist. The early Eagle Glacier, for example, occupied a broad valley whose bottom was at the level of Gilman and the present canyon rims, as shown by the relation of ancient glacial drift to the topography. By the time of the succeeding Bull Lake Glaciation, the canyon had been cut to a depth of about 400 ft (120 m) in hard rocks, as shown by the location of a till of early Bull Lake age on the canyon sides. By the time of the Pinedale Glaciation, the canyon had reached its present depth of 500–600 ft (150–180 m), or was even a trifle deeper. No deepening of the valleys has occurred since the Pinedale Glaciation and, in fact, many of the valleys have been aggraded by a combination of stream action, colluvial processes, growth of alluvial fans, and landsliding.

Some part of the canyon cutting was certainly accomplished by the glaciers, but the bulk of it seems to have been produced by stream erosion, as the cutting occurred after the valley or canyon was occupied by one glacier and before it was occupied by the next. Melting of ice many cubic miles in volume upstream from a canyon may have been a factor in the canyon cutting, but it probably was not the only factor. Canyon cutting occurred after early glaciation in many places in the Cordilleran region (Richmond, 1965), suggesting that climatic or orogenic factors might also have been involved.

TERTIARY AND PLEISTOCENE(?) COLLUVIUM

The upper slopes and tops of smooth ridges northeast and southeast of Red and White Mountain are mantled in places by thick colluvium that contains abundant blocks of light-colored sandstone from the Dakota, Morrison, and Entrada Formations. In other places, bedrock surfaces on the Maroon Formation are littered with the sandstone blocks, or with irregular masses or nodules of varicolored chert, or both. Gradation of sandstone-bearing colluvium into areas of isolated sandstone blocks resting on bedrock suggests that the isolated blocks are residual from the erosion of the colluvium. Some of the sandstone blocks are partly replaced by varicolored chert. The same chert has also locally replaced grit and thin limestone beds of the Maroon Formation at the erosion surface on which the blocks rest. This suggests that the chert-forming process was related to weathering at and following the time in which the sandstone-bearing colluvium accumulated.

The colluvium consists of angular and subangular sandstone fragments of various sizes up to several feet across, scattered limestone fragments, and pieces of chert in a brown sandy or clayey matrix. Gullies through the colluvium indicate that it is as much as 50–75 ft (15–22.8 m) thick. Because the colluvium is on slopes below the small area of Mesozoic rocks capping Red and White Mountain and contains no materials other than Mesozoic rocks and minor debris from the Maroon Formation, it is believed to represent an apron of debris that formed as cliffs of the Mesozoic sandstones retreated toward the crest of Red and White Mountain. The debris accumulated on the side of the broad old valley of the Piney River, and it extended over the volcanic rocks that also coat the sides of that old valley. Because these volcanic rocks are Miocene and possibly late Miocene in age, and because the colluvium predates the earliest recognized glaciation, the colluvium is regarded as Pliocene and possibly early Pleistocene in age.

The chert associated with the colluvium is distinctive in its varied color and in the extreme irregularity of the pieces or lumps in which it occurs. It differs markedly from the olive-gray chert that is present in minor amount in the Morrison Formation on Red and White Mountain and could not have been derived from that source. The chert is scattered over the broad, mature erosion surface that forms the divide between the Piney and the Eagle Rivers southeast of Red and White Mountain. It is especially abundant in the channel of an intermittent stream that joins Buck Creek from the north at about the 10,000-ft contour.

Most of the loose chert is free of matrix materials, but some pieces show remnants of sandstone, limestone, or grit. Chert in sandstone blocks is in globular or veinlike forms. Chert in limestone and grit of the Maroon Formation at the stripped erosion surface is in small, sharply angular, blocky bodies.

The chert is white to dark gray and various shades of yellow, red, and brown; much of it is variegated. Most of it is dense, but the larger lumps commonly contain vugs lined by quartz or—rarely—by calcite. In all types of occurrence, the chert generally shows several generations of deposition. As seen in thin section, chert that has replaced limestone at the outcrop of the Maroon Formation consists in large part of fine-grained quartz, the earliest silica mineral. Thin layers of fine-grained hematite coat this quartz. The quartz is cut by veinlets of coarser chalcedony in fibers that have an ordered arrangement and that maintain optical continuity across the hematite bands. The chalcedony is in turn coated by quartz in microvugs, and some of these openings contain still later growths of chalcedony, quartz, or calcite.

A good example of chert that has replaced arkosic red sandstone of the Maroon Formation was seen in a boulder near the head of Buck Creek. The chert, in an irregular body about 3 ft (1 m) long, has a dark-red hematite-rich core. This core is veined and is rimmed by salmon-pink chert that contains far less hematite. The sandstone adjoining the chert is pitted by solution cavities and is decolorized in a band about an inch wide.

The occurrence, character, and paragenesis of the chert together indicate that the chert formed under supergene conditions, at and near the base of the colluvium covering an old erosion surface. The successive generations of deposition recorded in the chert indicate fluctuating conditions that could well reflect fluctuations in amount and in composition of descending ground waters. The leaching of hematite in red beds by the chert-depositing solutions, and the wide ranges in iron content suggested by color contrasts in the chert, indicate that solutions that were able to dissolve hematite existed at times. Because hematite is stable in most natural solutions of inorganic composition, these features strongly suggest that the solutions contained organic compounds. Vegetation at the surface of the colluvium would have been a ready source for such compounds.

PRE-BULL LAKE GLACIATIONS

During the two pre-Bull Lake glaciations more of the quadrangle was covered by ice than in any subsequent time. Glaciers existed during one or both of the early glaciations in several areas that were never glaciated again: in tributary gulches on both sides of Wearyman, Two Elk, and Mill Creeks, and at the heads of Turkey, Timber, Lime, Willow, Game, Spraddle, Freeman, and Dickson Creeks. The largest of the early glaciers occupied the valley of the Eagle River from the southern edge of the quadrangle northwestward to Minturn. This glacier originated more than 15 mi (24 km) to the south of the quadrangle, and glaciers in the valleys of Fall and Cross Creeks were tributary to it within the quadrangle. Deeply weathered till that is the chief evidence of this glacier occurs in scattered patches, either as blanketlike deposits without morainal form or as damlike bodies in the valleys of sidestreams and gulches. One of the larger till bodies lies on the dip slope west of Gilman, where it extends from a little above the canyon rim upslope to about the 9,500-ft contour. Location of this and other remnants of the till indicate that the valley occupied by the glacier descended rapidly from the level of Gilman, 550 ft (170 m) above the present Eagle River, to the level of a rock bench on the north side of Martin Creek, 250 ft (75 m) above the valley floor at Minturn. Morainal remnants at this locality are the most distal that have been found; if the glacier extended farther, the evidence has been destroyed.

Trunk glaciers also existed in the Gore Creek and the Piney River drainages during the pre-Bull Lake glaciations. Along Gore Creek, evidence of these glaciations is in the form of scattered blanketlike deposits of till high on the valley walls, above the lateral moraines of Bull Lake age. The old glaciers in the Piney River drainage spread southward over the drainage divide into the drainages of Red Sandstone and Indian Creeks. The ridge between Indian and Freeman Creeks, for example, is capped by old till that contains boulders of Dakota Sandstone. The sandstone is thought to have been derived from an underlying colluvial blanket and to have originated on Red and White Mountain, though, conceivably, it could have come from remnants of a sedimentary cover on the Gore Range.

The older of the two pre-Bull Lake tills is typically red brown to brown and contains soft, weathered boulders in a tough, clayey matrix. Where extensively eroded, however, it is buff to light brown and sandy. The younger till has the same general characteristics but is a lighter shade of brown and not quite so clayey and tough. In many of the smaller old cirques and glacial valleys, these tills are heavily mantled with colluvium derived from the cirque walls, and hence they are shown on the map as "landslide and colluvium." Weathering and colluvial creep have destroyed or have buried any cliffs that existed in the old cirque walls, forming basins with characteristic steep smooth slopes at the heads of minor stream valleys. The Vail ski area owes the excellence of its ski runs to this modified glacial topography.

BULL LAKE GLACIATION

The Bull Lake Glaciation was characterized by the longest and thickest glaciers ever to occupy the Minturn quadrangle. The glaciation was in two episodes or stades, separated by a period of time long enough to allow appreciable modification of the moraines of the first stade and some weathering of the till before the second glacial advance occurred. Large lateral moraines along the valley sides hundreds of feet above the valley bottoms are the hallmark of these two glacial advances. Terminal moraines are inconspicuous because they were extensively eroded by the meltwater streams from younger glaciers with fronts farther up the valleys.

In general, the glaciers of the earlier stade extended farther down the valleys than did those of the later stade, but in many places ice of the later stade reached higher levels on the valley walls than in the early stade. Because of this and also because ice of the late stade extensively eroded the lateral moraines of the early stade in places, morainal evidence of the early stade of the Bull Lake is much less abundant than for the late stade.

Although the two sets of Bull Lake moraines differ preceptibly in degree of modification and weathering, together they are intermediate between the generally formless and deeply weathered pre-Bull Lake morainal deposits and the hummocky and bouldery moraines of fresh till characteristic of the Pinedale Glaciation. The Bull Lake moraines typically form benches on the valley walls, but where unimpeded by such walls, they form ridges. These ridges generally have smooth slopes with few or no boulders lying on them, in contrast to rough and bouldery morainal ridges characteristic of the Pinedale. Stream adjustment to the Bull Lake moraines is complete, and extensive segments of the moraines have been eroded in the process.

EAGLE RIVER AND TRIBUTARIES FROM SAWATCH RANGE

In the early stade of the Bull Lake, a glacier deep enough to have covered Iron Mountain at Red Cliff entered the quadrangle from the south and extended at least to Minturn. Morainal evidence of this glacier is scanty. Patches of lateral moraine lie just above the canyon rim west of the river and, near the lower end of the canyon, till of this age lies on bedrock 150 ft (45 m) above the river. Although the glacier was very large south of the quadrangle, it seems to have tapered rapidly between Red Cliff and Minturn. It may have reached Minturn only because of nourishment from the Fall Creek and Cross Creek tributary glaciers.

During the late stade of the Bull Lake, the Eagle

Glacier terminated about at Red Cliff. No terminal moraine remains, and probably none was formed, for all the drainage from a very extensive glacial system was here funneled into the narrow canyon of the Eagle River, presumably as a torrent that might have carried away almost all of the debris of the terminal area.

Bull Lake glaciers in the valley of Fall Creek formed prominent high compound lateral moraines that extend for 3–4 mi (5–6.5 km) along the valley. Ice of the early stade joined the Eagle Glacier at the level of a bedrock sill 250 ft (76 m) above the present canyon, and that of the second stade formed a small terminal moraine one-half mile (0.8 km) short of the mouth of this hanging valley. Ice of both stades also spilled prongs southward into the valley of Peterson Creek. The big lateral moraines lie on pre-Bull Lake tills, as along Notch Mountain Creek, and extensive blankets of the early tills extend upslope from them.

The Cross Creek drainage contained large Bull Lake glaciers that originated in cirques several miles southwest of the quadrangle. Unlike Fall Creek and many other valleys, Cross Creek valley contains only short segments of lateral moraines of any age, presumably because glacial movement and erosion were too vigorous to allow them to form or survive. In the terminal moraine area at the mouth of Cross Creek, only the northern portions of the Bull Lake terminal moraines are preserved. These are in the form of high morainal ridges. The older ridge curves northward, as if joining a glacier in the valley of the Eagle River, but the younger one extends straight eastward to a truncated front above the Eagle River where it rests on bedrock 60–75 ft (18–23 m) above the valley floor. Clearly, the late Bull Lake Cross Creek Glacier, and also the next succeeding Pinedale Glacier, forced the Eagle River eastward against the valley wall, causing erosion that accounts for the spectacular cliffs of the Minturn Formation between Minturn and the mouth of Eagle Canyon (fig. 12).

The valleys of Grouse and West Grouse Creeks were occupied by Bull Lake glaciers that were very narrow but had lengths of 5–6 mi (8–10 km). Moraine of the late stade of the West Grouse Glacier is at the level of the Eagle River below Minturn. An even narrower glacier of probable Bull Lake age descended the canyon of Stone Creek, at the western edge of the quadrangle, to a small terminal moraine between the 9,000- and 9,500-ft contours.

GORE CREEK DRAINAGE

The Gore Creek glaciers of Bull Lake time were the largest in the quadrangle. In both stades, ice reached levels 1,100–1,300 ft (335–400 m) above the present valley bottom in the vicinity of Black Gore, Bighorn, and Pitkin Creeks. The glacier of the early stade descended Gore Creek to a terminal moraine area just southwest of the Gore Creek School, or to a point about 1.5 mi (2.5 km) from the Eagle River. The terminal moraine is much dissected, and as shown in road cuts, it rests on a bedrock surface that is 40–50 ft (12–15 m) above the present stream. The glacier of the second stade was about 2 mi (3 km) shorter; it extended to a terminal moraine area in the vicinity of Red Sandstone Creek. This moraine is also extensively dissected. The largest remnant is a terraced deposit outlined by the 8,250-ft contour just east of Red Sandstone Creek. Other remnants to the south of this are knobs and ridges of till separated by channels cut into the till by Gore Creek, probably in Pinedale time.

In both stades, the glacier coming from the head of Gore Creek, 3–4 mi (5–6.5 km) east of the quadrangle boundary, was heavily augmented by tributary glaciers within the quadrangle. Massive glaciers also descended Black Gore Creek from sources in the West Tenmile drainage east of the quadrangle. The ice from this source spilled through Vail Pass, bearing a load of telltale porphyries that are foreign to the Gore Creek drainage. A prominent lateral moraine of this origin caps the ridge east of Timber Creek at the 10,500-ft contour.

Other major tributaries of the Gore Creek glaciers came from the Bighorn, Pitkin, and Booth Creek drainages. Smaller tributaries from Spraddle Creek, Middle Creek, and possibly from Mill Creek existed during the early stade of the Bull Lake. Middle Creek also contained a glacier in the late stade, but this failed by about a mile to join with the Gore Glacier. The two forks of Red Sandstone Creek contained glaciers in both stades that formed large moraines southeast of Lost Lake. These glaciers extended only to the forks of the stream; thus, they failed by 4–5 mi (6.5–8 km) to reach the Gore glaciers.

PINEY RIVER

The Piney River drainage contained very large glaciers in both stades of the Bull Lake. The bulk of the ice came from what is essentially a single elongated cirque extending 3.5 mi (5.5 km) from the Booth Creek drainage divide to the sharp bend in the Piney River. Smaller amounts came from a hanging valley or cirque on the south side of Mount Powell, just north of the quadrangle, drained by the stream that joins the Piney River at the big bend and from a cirque drained by East Meadow Creek. Massive lateral moraines that were formed in the two stades of the Bull Lake and in the earliest stade of the Pinedale border the Piney River valley from near the big bend southwestward and westward for 6 mi (10 km). At their upper ends, these moraines are 1,200–1,500 ft (360–450 m) above the present stream. Ice of the early stade of the Bull Lake spilled into the East Meadow Creek drainage on a wide front, forming extensive moraines in that valley. Ice of the second stade spilled into the East Meadow Creek drainage on a much smaller scale, through a saddle northwest of Piney Lake. The lower ends of the lateral moraines of the early stade, as well as any former terminal moraine, have been removed by erosion. The end of the eroded north lateral moraine is on the spur southeast of the mouth of Meadow Creek, 450 ft (135 m) above the Piney River. The end of the eroded south lateral moraine plugs the valley of Dickson Creek at Dickson Ranch, 550 ft (165 m) above the river. In contrast to the early moraines, the north lateral moraine of the late stade descends to a remnant of a terminal moraine in the canyon bottom. This indicates that the bedrock floor of this part of the canyon has remained at about the same level since Bull Lake time.

PINEDALE GLACIATION

With a few exceptions glaciers of the Pinedale Glaciation were far less extensive than the Bull Lake glaciers. The glaciation occurred in three episodes, or stades, of ice advance and retreat. Of these, the first was by far the most extensive, and in a few drainages in the region it equaled and even exceeded the late Bull Lake glaciers. Glaciers of the second and third stades of the Pinedale were everywhere much smaller than those of the first stade, and in many of the smaller drainages, they were absent.

Moraines of the Pinedale glaciers are hummocky, bouldery, and little modified. The till in them is sandy rather than clayey and, except as it might be colored by rocks, such as red beds, it is generally light gray in contrast to the yellow, buff, or brown colors characteristic of the older tills in surface or near-surface exposures. Soils are only weakly developed on the Pinedale Till and, practically speaking, are absent in many places.

The largest glaciers in the Minturn quadrangle during the Pinedale were in the valleys of Cross Creek and the Piney River. No glacier existed in the part of the Eagle Valley that is within the quadrangle, and Gore Creek Valley did not have a trunk glacier. An early Pinedale glacier did occupy the canyon of upper Gore Creek east of the quadrangle, but it terminated in the area between the mouths of Black Gore and Bighorn Creeks. Early Pinedale glaciers of Bighorn, Pitkin, and Booth Creeks reached the Gore Valley and deposited small moraines on its floor. Middle Pinedale moraines are a short distance up the canyons, and late Pinedale moraines are in the midportions of the canyons.

On Cross Creek, unlike all other drainages in the quadrangle, glaciers of all three stades of the Pinedale descended to the terminal moraine area near the mouth of the creek. On the north side of this morainal area, the early Pinedale glacier formed a morainal ridge almost as high as the Bull Lake ridges. The ridge descends more rapidly than the Bull Lake ridges, however, and turns into a broad, low, complexly ridged terminal moraine near U.S. Highway 24 and the Eagle River. The middle Pinedale glacier was split near its terminus by the hill of rock in the center of the morainal area (pl. 1) and formed two morainal lobes within the terminal moraine horseshoe of the early Pinedale. The southern lobe rests on a low valley flat excavated out of part of the early Pinedale moraine. The late Pinedale glacier formed small morainal loops immediately south and west of the bedrock hill.

In the Piney River valley, the early Pinedale glacier was as high on the valley wall as the Bull Lake glaciers near Piney and Lost Lakes. From about this place, however, it descended to a prominent southwestward-sloping morainal bench 1.5 mi (2.5 km) west of Piney Lake and formed a small terminal moraine on the floor of the Piney River valley just above the mouth of Dickson Creek. The small terminal moraines of the middle and late stades of the Pinedale are in the vicinity of Piney Lake.

LANDSLIDE

The Minturn and Maroon Formations contain many incompetent shaly beds that make ideal surfaces for landsliding where the beds dip toward valleys. Additionally, the weak and platy-weathering rocks of these formations readily form a heavy "slopewash" or colluvium that creeps down the slopes and accumulates in slidelike piles in the basins or valleys. All the major valleys that cut the Minturn and Maroon Formations and many of the smaller ones have their slides splattered with landslides and colluvial accumulations. The larger slides are mainly of the dip-slope slide type, but some follow ground broken by faults, and many are on slopes oversteepened by glacial erosion. Most of the conspicuous slides are postglacial in age, and some are very recent or modern.

Incipient slides are evident in many places where open tension fissures as much as several feet wide and 20 ft (6 m) deep occur on hillsides that slope in the general direction of the dip. Such fissures (pl. 1) are especially common in a belt that extends from the head of Game Creek to the slopes south of Mill Creek and were probably caused by glacial oversteepening of Gore Valley. Clear evidence of recent movement was seen at the east end of a fissure that starts at the 10,600-ft contour on the nose extending north from a knob on the

Game Creek–Gore Creek Divide 2.1 mi (3.38 km) N 78° E of the mouth of Game Creek. Turf extends across the eastern end of the slowly widening fissure, but a few feet to the west a bare root 2 in. (5 cm) thick from a pine tree growing on the north wall extends through the air horizontally into a crack in the south wall about 20 in. (50 cm) away. The pine was cut down in 1963 and the tree rings indicated an age of 68 years. The two walls of the fissure must have been next to each other when the root first crossed into the south wall, as otherwise the root would have grown vertically downward, if it grew at all. Either the walls have moved apart so gradually that the growth of the root has kept it from breaking as the separation proceeded or else the roots were strong enough to withstand the pull of faster movement that took place after the tree was partly grown. The data show that the walls have separated at a minimum rate of about one-third inch (8 mm) per year, and it is probable that the separation of the walls began many years after the pine seed first sprouted.

Elsewhere, as on the slopes south of Vail, many open fissures show evidence of very recent movement. The relation of the fissured area shown on the geologic map (pl. 1) to Vail indicates that the possibility of sudden mass movement of the ground on the northward-dipping bedding planes in this area should be carefully appraised.

The large landslide at Whiskey Creek and another opposite Dowds constrict the valley of the Eagle River for about a mile downstream from Dowds. These slides forced the Eagle River against the northeast wall of its earlier valley, causing steep and cliffy slopes to be formed there. The construction of I–70 across these slides in 1969–70 induced much heaving and slumping of the slide material, indicating that the slides are still unstable. The Whiskey Creek slide overrides glacial outwash gravels that probably are as young as Pinedale; hence, it is probably postglacial in age. Farther west, near Stone Creek, gypsum has slid or flowed over these same gravels, reducing the width of the valley bottom from its former extent.

ALLUVIUM

Morainal areas in the valleys have many pockets and channels filled with alluvium or reworked glacial drift, and most of the stream courses are bordered by alluvial deposits. The landslide just above the mouth of Gore Creek and the terminal moraine at the mouth of Black Gore Creek both have formed natural dams in the past that impounded lakes above them. Delta deposits of crossbedded sand have formed in these lakes, and remnants of such deposits remain along the sides of the valleys. These deposits are included with "alluvium" on the map (pl. 1) and so also are terrace gravels and fanglomerates.

STRUCTURE

The Minturn quadrangle contains elements of three major structural units—the Gore Range uplift on the northeast, the Sawatch Range uplift on the southwest, and a broad, northwest-trending, generally synclinal area of sedimentary rocks between the two major uplifts. The Gore Range is a fault-block range bordered on its southwestern side by the Gore fault—or fault zone—the largest and most complex fault in the quadrangle. The Sawatch Range, in contrast, is an anticlinal uplift of great size—90 mi (145 km) long and 40 mi (65 km) wide (fig. 24). The Minturn quadrangle includes only the eastern flank of the northward-plunging north end of the anticline. In this area, the flank of the anticline is disrupted only by minor faults, but several miles south of the quadrangle the eastern flank is disrupted by major graben faults of the upper Arkansas River valley (Tweto and Case, 1972).

Structural development of both the Gore Range and the sedimentary basin to the west was closely influenced by a long history of movement on the Gore fault. This fault was active in Precambrian, Paleozoic, Laramide (Late Cretaceous and early Tertiary), and late Tertiary times, and there is suggestive evidence of movement in Quaternary time. During the latter part of Paleozoic time, and perhaps intermittently earlier, the fault formed the western edge of a highland that extended eastward beyond the crest of the present Front Range—the Front Range highland of the Ancestral Rockies. (See Lovering, 1929.) As a structural and topographic unit created out of a part of the old highland, the Gore Range came into existence in Laramide time, but it was much modified and elevated as a fault block in late Tertiary time, accounting for its present relief (Tweto and others, 1970).

The Gore fault was also the border of the basin in which the Belden, Minturn, and Maroon Formations accumulated. Thus, it is not only a fault but also a zone of abrupt unconformity and wedgeout of sedimentary rock units. Folding or upturning of the sedimentary rocks along the fault may have begun in Pennsylvanian time. Folding that produced the present broadly synclinal structure of the sedimentary basin resulted from uplift of the Gore and Sawatch Ranges in Laramide time, but a minor part of it may have occurred in the late Tertiary, inasmuch as the volcanic rocks north of the quadrangle are synclinally folded.

In the Sawatch Range area, no evidence has been found anywhere of uplift prior to formation of the Sawatch anticline in Laramide time. This anticline was

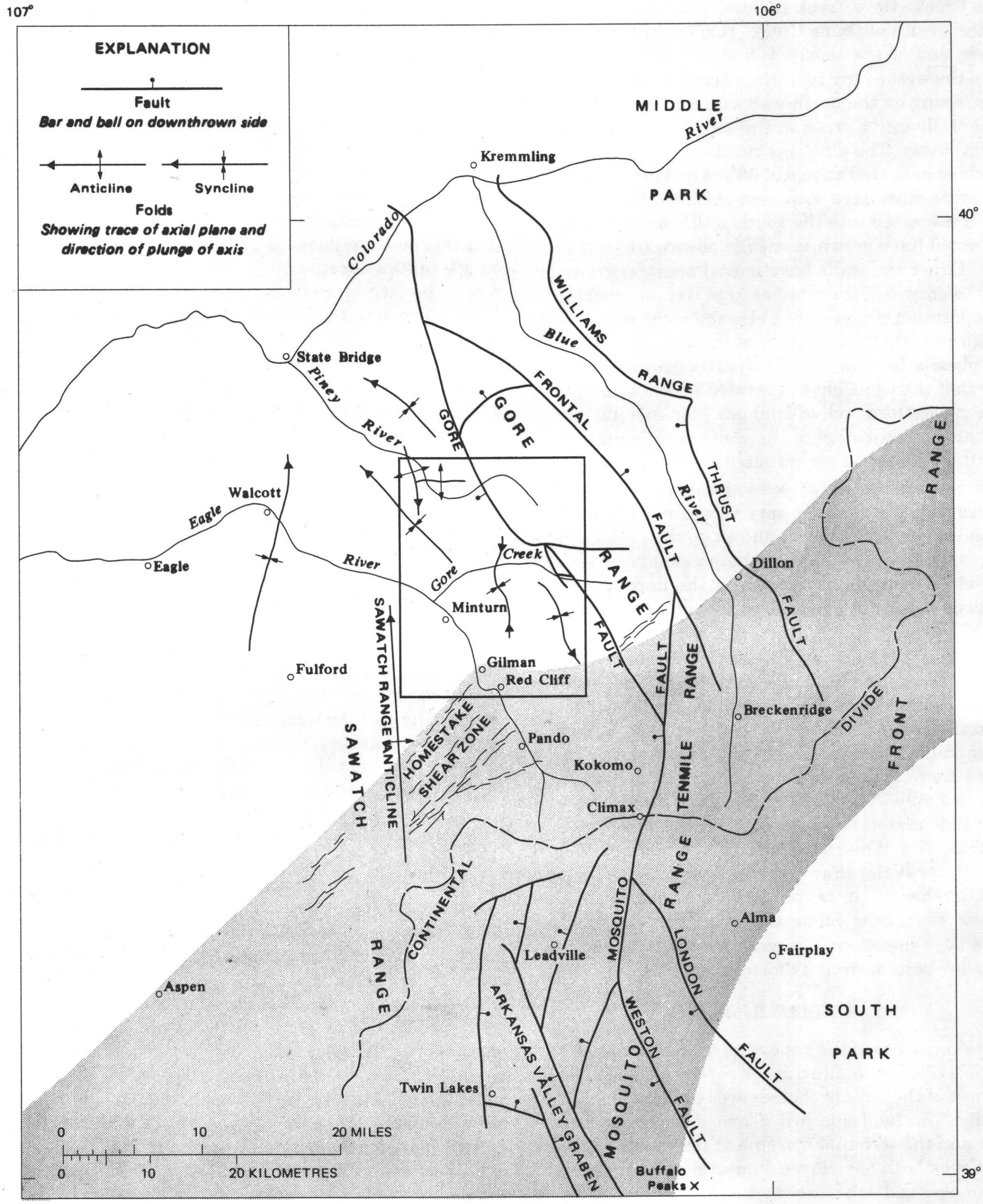


FIGURE 24.—Relation of Minturn quadrangle (outlined) to major structural features and Colorado mineral belt (patterned).

wedgeout of thousands of feet of sedimentary rocks elevated early in the Laramide orogeny, before the Gore Range (Tweto, 1975). Rise of the anticline tilted the sedimentary rocks northeastward through much of the Minturn quadrangle, forming the flank of the central syncline. This uniform tilt, or homoclinal dip, still characterizes a large area east of the Eagle River and south of Gore Creek. North of Gore Creek and, especially, from near the mouth of Gore Creek westward, a more complicated structural pattern now exists. Near the western border of the quadrangle, at least, this pattern is related to diapiric movement of gypsum as a result of excavation of the valley of the Eagle River. Folds and faults in this area probably have been developing almost continuously from the Laramide to the present.

GORE FAULT

The Gore fault delimits the western edge of the Precambrian terrane of the Gore Range for a distance of at least 45 mi (72 km), from the Mosquito fault in the Tenmile Range, several miles southeast of the Minturn quadrangle, to the Colorado River, 15 mi (24 km) north of the quadrangle (fig. 24). Through most of its course in the Minturn quadrangle the fault brings rocks of the Minturn Formation against Precambrian rocks, but in the north part of the quadrangle the Maroon Formation lies against the fault, and farther north various Mesozoic formations are against the fault.

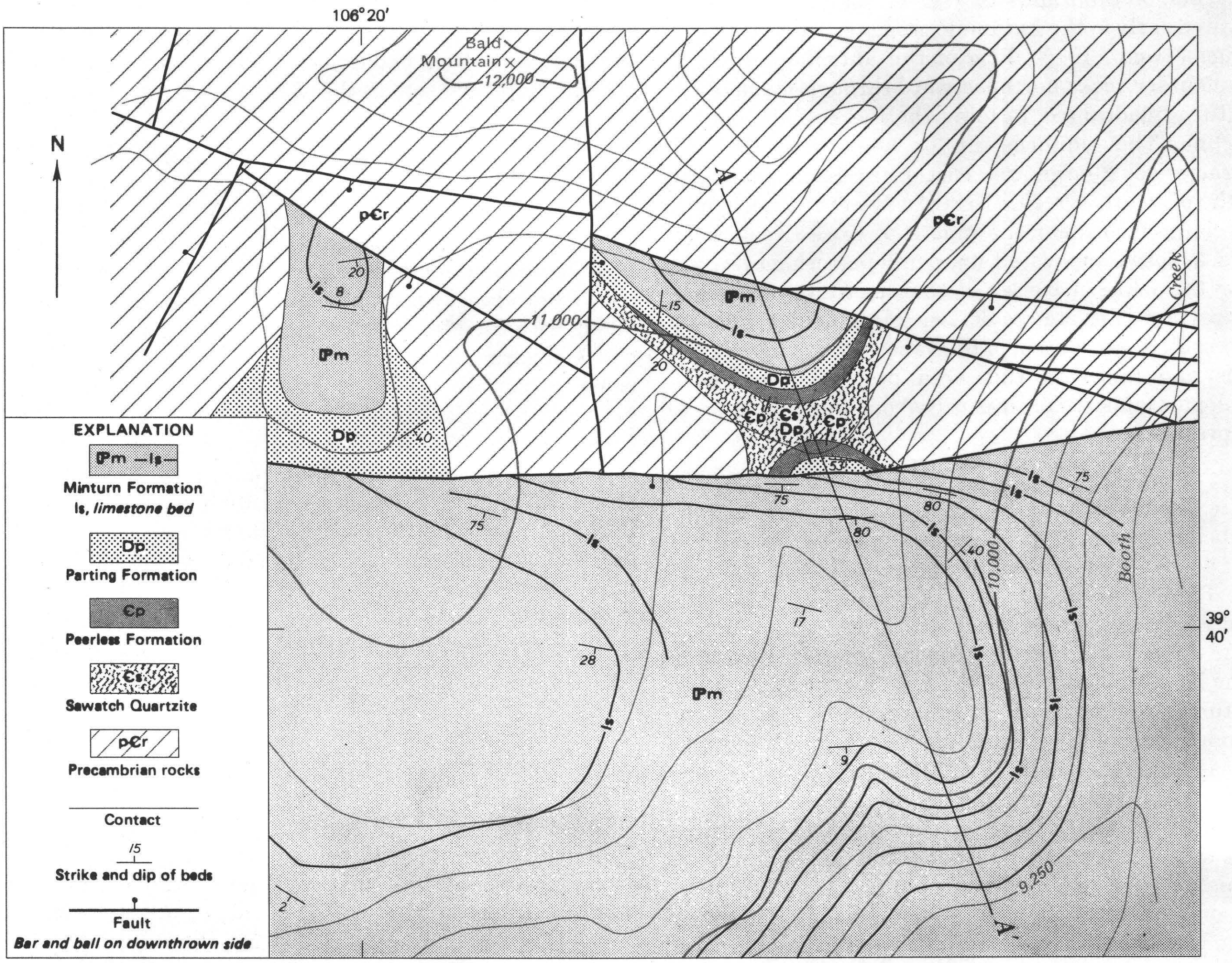
In most places the Gore fault is not a single fracture but a wide and complex fault zone. Most of the fractures in this zone are in the Precambrian rocks, on the northeast or upthrown side of the fault surface that separates the Precambrian and the sedimentary rocks, though strands of the fault are present also in the sedimentary rocks in places. Many of the fractures in the fault zone are of Precambrian age, as will be discussed further; others are younger, but it is difficult to establish the time of origin of most fractures. Main periods of later movement along the fault zone, whether on reactivated or newly formed faults, occurred in the late Paleozoic, the Laramide, and the late Tertiary.

Precambrian origin of many of the fractures in the Gore fault zone is indicated by several lines of evidence (Tweto and Sims, 1963; Tweto and others, 1970): (1) the occurrence of Precambrian intrusive rocks such as pegmatite, aplite, and mafic diorite as dikes along the faults in places, or intruded into mylonitic rocks; (2) the presence of mylonitic rocks of Precambrian aspect beneath undeformed Pennsylvanian rocks and the occurrence of cobbles of the mylonite in the Pennsylvanian conglomerates; (3) the presence of intensely sheared rocks beneath much less deformed Devonian(?) quartzite; and (4) the occurrence of little deformed dike rock dated isotopically at 1 b.y. on a fault of the Gore system at the Colorado River (Barclay, 1968).

Evidence of pre-Pennsylvanian Paleozoic movement along the Gore fault is shown by stratigraphic and fault relations. Of the pre-Pennsylvanian formations (table 1), the Harding Sandstone, the Dyer Dolomite, the Gilman Sandstone, and the Leadville Limestone are absent from upthrown fault blocks along the Gore fault. Along with the Manitou Dolomite of the area southeast of the quadrangle, they are concluded to have been erosionally truncated both in pre-Late Devonian and in pre-Pennsylvanian times and to wedge out beneath the Minturn Formation in a zone near and parallel to the Gore fault (Lovering and Johnson, 1933; Tweto and others, 1970). The Sawatch Quartzite, Peerless Formation, and Parting Formation reach the Gore fault (fig. 25), but the Sawatch is thinned to only 100 ft (30.5 m) beneath the Peerless, suggesting a possible "high" in the area of the Gore Range even in Cambrian time. The Peerless is only 20 ft (6 m) thick and tapers to a vanishing edge beneath the Parting Formation, indicating, along with absence of Ordovician rocks, extensive erosion before Late Devonian time. The Parting is exceptionally coarse grained and conglomeratic wherever exposed along the Gore fault, suggesting a land area in the vicinity of the Gore Range in Late Devonian time.

Fault relations suggest not only a land area but also active movement along the Gore fault zone in Paleozoic time. In the western of two fault blocks on the south slope of Bald Mountain (pl. 1; fig. 25), the Parting Formation lies on Precambrian rocks and is overlain by coarse Pennsylvanian conglomerate with an angular discordance of 17°. In the eastern fault block, one-half mile (0.8 km) away and 500 ft (150 m) lower, the Parting is underlain by the Peerless and Sawatch and overlain without angular discordance by strata of the Minturn Formation. The relations suggest that a north-trending fault—part of the Gore fault system—between the two blocks was active prior to deposition of the Parting and, again, prior to deposition of the Minturn. Similarly, in the valley of Black Gore Creek one-half mile (0.8 km) from Gore Creek, white quartzite and quartz granule conglomerate thought to be Parting but possibly Sawatch is turned up almost vertically, whereas rocks of the Minturn Formation 100 ft (30 m) away dip gently, suggesting a marked angular unconformity.

Major movement occurred on the Gore fault in Pennsylvanian and Permian time, as indicated by the



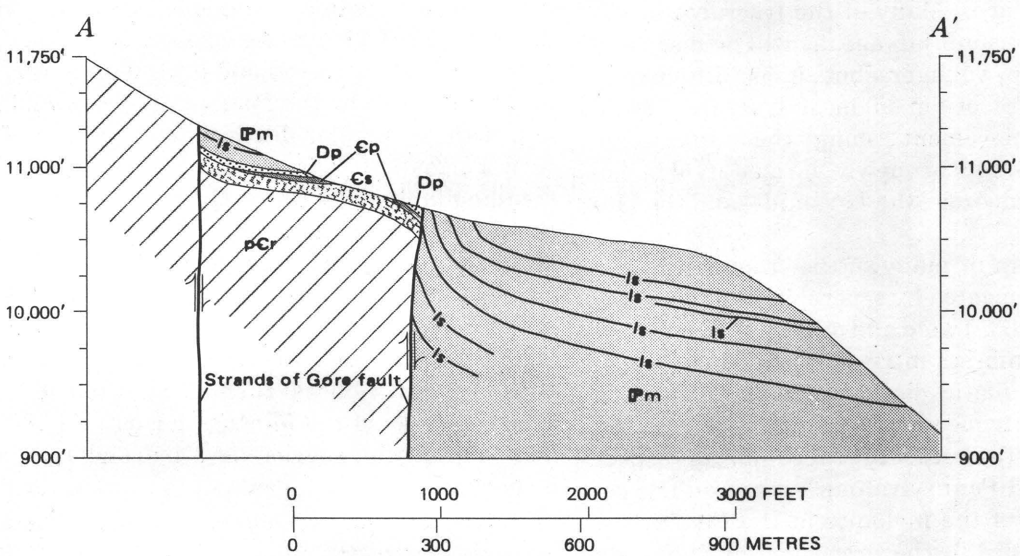


FIGURE 25.—Geologic sketch map and section of Gore fault zone on south slope of Bald Mountain.

against Precambrian rocks in and along the Gore fault zone (pl 1, secs. *A–A′*, *B–B′*, *E–E′*). The occurrence of the Robinson Limestone Member of the Minturn Formation only 50–100 ft (15–30 m) above Precambrian rocks—or above thin patches of the Parting Formation lying on Precambrian rocks—on the mountain southeast of the junction of Gore and Black Gore Creeks has been noted in the discussion of the Minturn Formation. The best example of the abrupt wedgeout of the sedimentary rocks against the fault-scarp front of the old highland is in the Mount Powell quadrangle 3–4 mi (5–6.5 km) north of the Minturn quadrangle, where sedimentary rocks are preserved east of the fault. There, the entire Minturn and all but the uppermost 100–300 ft (30–90 m) of the Maroon wedge out in a zone no more than 3–4 mi (5–6.5 km) wide along the Gore fault (Tweto and others, 1970). In this area, the fault may even have been active in Jurassic time, as suggested by a marked difference in thickness of the Morrison Formation on the two sides, but no evidence of a scarp in Late Triassic time is seen in the Chinle Formation.

Most of the movement that placed sedimentary rocks in fault contact with Precambrian rocks and that caused folding and overturning of the type shown in figures 25 and 26 is inferred to be of Laramide origin. However, it is difficult to separate with certainty the effects of Laramide fault movement from those of later Tertiary movements. Laramide deformation is proved more by regional geologic relations than by local ones, inasmuch as no sedimentary rocks younger than the Dakota are preserved within the quadrangle. On the northeastern side of the Gore Range, conglomerates of late Miocene(?) age show by their abundant content of Precambrian rocks that the range had been uplifted and had been stripped of its cover of Morrison and younger sedimentary rocks by that time, which was prior to the marked uplift in late Tertiary time (Tweto and others, 1970). The uplift that led to stripping of the sedimentary cover was almost certainly the Laramide in this range just as in most other major ranges in Colorado.

Extensive late Tertiary uplift and fault movement in the Gore Range has been documented by Tweto, Bryant, and Williams (1970). Some of this movement may have occurred along the strand of the Gore fault that separates the sedimentary and the Precambrian rocks, but most of it occurred along faults of the Gore

FIGURE 26.—Deformed strata of Minturn Formation in Gore fault zone at head of Spraddle Creek. View northwestward. One strand of fault lies in covered area between vertical strata of White Quail Limestone Member in center and inclined strata of Robinson Member and underlying Minturn rocks at right; main fault, which brings Precambrian rocks against the Minturn is just out of view to right.

fault zone within the Precambrian rocks. In the upper Piney River area, the late movement occurred on the series of long parallel faults of north-northwest trend (pl. 1). These are reactivated Precambrian faults. In the Gore Creek area, the late movement occurred on the fault strand that lies a short distance east of the sedimentary rocks. This strand is thought to be of Laramide origin.

From the north boundary of the quadrangle to Bald Mountain, the main strand of the Gore fault—separating the sedimentary and crystalline rocks—trends south-southeastward in a fairly straight line. At Bald Mountain, this fault intersects a west-northwest-trending fault zone in a complexly faulted area. The west-northwest-trending zone is a reactivated Precambrian fault zone that extends all the way across the range (pl. 1; Tweto and others, 1970) and is one of a family of persistent faults of this trend in the Gore Range. The line of displacement and upturning of sedimentary rocks turns eastward along the west-northwest-trending zone for about 2 mi (3 km) to beyond Booth Creek, and then it turns south-southeastward again. In the area of this bend, the fault is intersected by the faults with late displacement extending from the upper Piney River area. Southeast of the bend, an older unit of the Gore fault extends to a broad east-trending fault zone along Gore Creek, and the line of displacement jogs eastward along this zone. A younger strand of the fault—probably Laramide and Tertiary—cuts diagonally across the salient outlined by the two older faults in almost a straight line from Pitkin Creek to Gore Creek and beyond (pl. 1). In the area of the salient, near the mouths of Black Gore and Big Horn Creeks, other strands of the fault cut the sedimentary rocks. These are poorly delineated because of widespread cover of glacial deposits and uncertainties in distinguishing the effects of faulting as opposed to unconformity in an area with only scattered small outcrops.

A branch of the Gore fault extends south-southeastward up Black Gore Creek and then southward along Timber Creek, ultimately connecting with faults of the Pando area (Tweto, 1953). Also. old strands of the fault in Precambrian rocks near the mouth of Black Gore Creek project beneath strata of the Minturn Formation on the slopes east of the creek. From Gore Creek, the main young strand of the Gore fault extends into the adjoining Dillon quadrangle, where it intersects sedimentary rocks once again and forms a boundary between these and the Precambrian rocks (Tweto and others, 1970).

Most of the faults in the Gore fault zone are vertical or are steep normal faults (pl. 1, secs. $A-A'$, $E-E'$), and the zone as a whole is interpreted to be essentially vertical. However, reverse and even low-angle thrust faults are present locally. They probably formed in response to local stress conditions or in response to expansion of the Precambrian massif as it rose. Near Booth Creek, the fault strand between the Precambrian and the sedimentary rocks is a steep reverse fault that dips 80°–85° N. As shown in figure 25, section $A-A'$, this fault is inferred to steepen to vertical at depth; the northward dip near the surface is interpreted to reflect expansion of the upthrown block of Precambrian rocks. Near Middle Creek, low-angle reverse and thrust faults are present in a small area at the edge of the Gore fault zone (pl. 1, map and sec. $A-A'$). The reverse and thrust faults are in the tip of a wedge between southeast- and south-trending faults in the area where the main Gore fault begins to turn eastward. The south-trending fault has a displacement of several hundred feet in the Gore fault zone (pl. 1, sec. $A-A'$) but only a minor displacement farther south. Exposures are too poor in the small area of thrust faulting to reveal details of the complex structure there, but it is likely that the thrust fault is in a thin fault block underlain by an upward-steepening reverse fault as shown on plate 1 (map and sec. $A-A'$).

GORE RANGE

The Gore Range has two major categories of structural features—the internal structure of early origin in the Precambrian rocks and later faults. The Precambrian gneisses were highly deformed plastically and then were sundered by granite intrusion, forming a gigantic breccia of gneiss blocks in a matrix of granite (pl. 1). Thus, the gneisses are structurally disorganized, and no attempt was made to study them in detail. In general, a broken irregular tongue of gneisses extends south-southeast along the crest of the Gore Range to the head of Bighorn Creek. The Cross Creek Granite which surrounds and intrudes this mass of gneisses has a structure that is nearly concordant with the broad outline of the area of gneissic rocks. To the west and east the foliation or planar structure of the granite strikes north-northwest; south of the area of metamorphic rocks, the structure of the granite strikes northeast or easterly. The north-northwest foliation trend along the western side of the range is paralleled by fractures of the Gore fault zone and probably influenced the trend of parts of the Gore fault.

The many faults in the Precambrian rocks of the range are of two main orientations, north-northwest and nearly east–west. Faults of the set trending north-northwest are long and straight, and most of them dip almost vertically. The set that trends nearly east–west includes a few widely spaced persistent faults that extend across the entire range (Tweto and others, 1970) and many shorter faults that subdivide the long blocks outlined by the north-northwest-trending faults. Faults of both sets are typically fracture zones several feet to a few hundred feet wide, though a few narrow locally to a single fault plane. Many of the fracture zones are altered, and in general, the zones are marked by gullies and saddles on the slopes and ridges of otherwise hard rock. The density of the fault pattern in the Precambrian rocks contrasts markedly with the pattern of sparse faults in the bordering sedimentary terrane (pl. 1). This suggests that most of the faults in the range are Precambrian in age, as do other features noted in the discussion of the Gore fault. Many of the faults, however, were reactivated in late Paleozoic, Laramide, and late Tertiary time. One of the north-northwest-trending faults of the upper Piney River area, nearly 2 mi (3.2 km) east of the main Gore fault (pl. 1), contains in one area narrow slices of down-dragged red beds of the Minturn or Maroon Formation, indicating probable Laramide displacement of hundreds of feet.

SAWATCH RANGE

The part of the Sawatch Range included in the Minturn quadrangle consists of a core of Precambrian rocks covered by a thin mantle of sedimentary rocks that dip northeastward off the range, nearly in dip slopes (pl. 1, sec. *B–B'*). As in the Gore Range, the Precambrian rocks have an early fold structure and a later fracture structure, and the main elements of the fracture structure predate the Paleozoic rocks.

A major Precambrian structural feature, the Homestake shear zone, lies just south of the quadrangle (fig. 24). This master zone, which trends northeast and consists of several individual shear zones in a belt 7–8 mi (11–13 km) wide, separates a metamorphic terrane to the southeast from the granitic terrane of Cross Creek Granite to the northwest (Tweto and Sims, 1963; Tweto, 1974). Fringe shear zones or faults of the Homestake zone project into the Minturn quadrangle in the vicinity of Notch Mountain, Fall, and Peterson Creeks. They are exposed only locally, however, because of a widespread cover of Paleozoic rocks and glacial and colluvial deposits. The strongest of these fracture zones extends northeastward for about a mile along the slope northwest of Notch Mountain Creek and then disappears beneath the Sawatch Quartzite (pl. 1). It is probably represented in the canyon of the Eagle River by some of the northeast-trending faults and veins in the Precambrian rocks near Gilman. The Ben Butler mine (fig. 8), for example, is on small veins in or near a wide shear zone that resembles the Precambrian shear zones, and both the veins and the shear zone end abruptly upward against the smooth and unbroken basal bed of the Sawatch Quartzite. Similarly, the Santa Cruz vein (fig. 8) is a wide and strong fracture zone in the Precambrian rocks but barely affects the overlying Sawatch Quartzite. These fracture zones and mines are described in the report on the Gilman district (Lovering and others, 1977).

Among faults of Laramide or younger age in this part of the Sawatch Range, the largest are in the area north of the latitude of Minturn, at the north end of the Precambrian core of the range. A prominent fault of east-northeast trend, downthrown to the north, extends from the Eagle River at the mouth of West Grouse Creek, to a fault along Stone Creek; west of Stone Creek, an en echelon fault of the same trend and displacement extends west-southwestward out of the quadrangle at least 2 mi (3 km). The two echelon faults are north-dipping normal faults and have displacements of 200–300 ft (60–90 m). No sign of the eastern fault could be found east of the Eagle River at Game Creek; the fault is inferred to end against a fault along the river. Evidence of a northwest-trending fault, upthrown to the northeast, along the river is seen in the repetition of the Gilman Sandstone on the two sides of the river at Minturn, and in the position of the dolomite bed of Dowds near Dowds (pl. 1, sec. *B–B'*).

The fault along Stone Creek, very near the western border of the quadrangle, trends north-northeast and is upthrown about 250 ft (76 m) on its southeastern side. Its course along lower Stone Creek is uncertain because of slumping of shale and gypsiferous strata in the Belden and Minturn Formations.

In the area of the lower Stone Creek and Whiskey Creek, strikes and dips of the strata change erratically in short distances. A thrust fault that brings grits of the lower part of the Minturn Formation over gypsiferous strata cuts through this area (pl. 1). This fault probably is not a fundamental tectonic element of the Sawatch Range but is primarily a product of deformation and mass slumping at the edge of the gypsum basin. A fault along Whiskey Creek may be of the same origin. This fault is exposed only in a zone of vertical strata on the bank of the Eagle River. It projects southward beneath the landslide along Whiskey Creek but is not evident in the bedrock at the head of the slide. Neither is it seen to the north, across the Eagle River. There, it is inferred to end against east–west faults in a small area of landslide.

CENTRAL SEDIMENTARY BELT

The broad belt of sedimentary rocks between the Gore and Sawatch Ranges is predominantly synclinal in structure. Three northwest- to north-trending synclines, which are arranged echelon in a northwest-trending line, dominate the area structurally, though other folds are present. The southeastern syncline, called the Black Gore syncline (pl. 1), closely parallels the Gore fault in the area from upper Mill Creek to Turkey Creek. The middle syncline, called the Vail syncline, extends from the Spraddle Creek area southward to the Two Elk Creek drainage. The northwestern and largest syncline, called the Red and White syncline, extends from lower Buffer Creek northwest to and beyond Red and White Mountain. As shown in the cross sections (pl. 1), these synclines are more pronounced at depth than at the surface because of the thinning of all the Paleozoic formations—and particularly the Minturn Formation—toward the Gore Range.

The Black Gore syncline (pl. 1, sec. *E–E′*) is markedly asymmetric, with a wide, gently dipping southwestern limb and a narrow and steeper northeastern limb. Though interrupted by minor flexures, the southwestern limb is essentially homoclinal and is a part of the flank of the Sawatch anticline. The northeastern limb is a Gore Range structure and in part is due to drag along the Gore fault. As expressed in the rocks exposed at the surface—high in the Minturn Formation—the axis of the syncline is sinuous parallel to the Gore fault and lies less than a mile from the fault. As seen in cross section, however, the main synclinal axis is a mile farther southwest, owing to the thickening of the Minturn Formation in that direction. The Black Gore syncline dies out on the ridge between Mill and Gore Creeks, and it is overlapped on the west by the Vail syncline.

The Vail syncline (pl. 1) is a bowed, north-trending doubly plunging syncline that is prominently exposed on the sides of the valley of Gore Creek at Vail. The syncline is longitudinally faulted, and north of Gore Creek the east limb is turned up steeply against the fault (pl. 1). The northern part of the syncline, north of Gore Creek, is bounded on the west by a small anticline centered over Middle Creek. South of Gore Creek, the west limb is the homoclinal flank of the Sawatch anticline.

The fault zone that extends the length of the Vail syncline and beyond is called the Spraddle Creek fault zone. This fault zone extends south-southwestward from the Gore fault zone in the Bald Mountain–Spraddle Creek area nearly to Gilman. In the Bald Mountain area it is part of a complex of fault blocks where the Gore fault turns eastward. In this area it shows wide differences in amount of displacement, from as little as 100 ft (30 m) to more than 900 ft (275 m), reflecting both the differential movement of fault blocks and probable pre-Pennsylvanian and Pennsylvanian movements. From the head of Spraddle Creek, the fault extends southwestward into the eastern flank of the Vail syncline, separating steeply dipping beds of the synclinal flank from gently dipping beds to the east. At Gore Creek the fault bends southward, slicing across the eastern flank of the Vail syncline to Two Elk Creek. Farther south, a series of short en echelon faults in the Minturn Formation suggests that the zone of deformation in the basement rocks persists to the vicinity of Gilman and might even project to fractures of the Homestake shear zone. Through most of its length, the Spraddle Creek fault is downthrown to the east, and from Gore Creek southward the displacements are less than 100 ft (30 m).

The Red and White syncline is a large and nearly symmetric syncline that occupies most of the area between the mouth of Gore Creek and the Piney River (pl. 1, sec. *B–B′*). In much of this area, rocks of the Maroon Formation—and also of the Chinle and younger formations in a small area on Red and White Mountain—are disturbed by many gentle flexures; thus, the syncline is scarcely evident from the attitudes of the strata as observed on the surface. The southeastern nose of the syncline is blunt and is an abrupt northwest-dipping monocline (pl. 1, sec. *C–C′*) that extends along the north side of Gore Creek from the Eagle River to Red Sandstone Creek where it flattens somewhat and turns northward and then northwestward. On the spur north of Dowds, east–west faults with as much as 1,000 ft (305 m) of displacement increase the structural displacement along the monocline, inasmuch as they are downthrown to the north. In effect, the curving monocline or synclinal nose separates a southern area that is structurally a part of the flank of the Sawatch Range from a northern area that is part of a large structural basin in the area bordered by the Sawatch Range, White River Plateau, and northern Gore Range (figs. 1, 24).

In the vicinity of Dickson Creek, a small but sharp north-trending anticline—the Dickson anticline—is superposed on the lower northeastern flank of the Red and White syncline (pl. 1, sec. *A–A′*). The Dickson anticline enlarges northward and is a major structural feature along the Piney River near the quadrangle boundary (pl. 1, sec. *D–D′*). The anticline is cut acutely by two northwest-trending faults that have opposite displacements. The faults define a long narrow horst that is upthrown about 200 ft (60 m) on the northeastern side and nearly 1,000 ft (305 m) on the southwestern side (pl. 1, sec. *D–D′*).

The area between the Dickson anticline and the Gore fault is occupied by the East Meadow anticline, which trends east, almost at right angles to the Dickson anticline (pl. 1, map and sec. *B–B′*). At the intersection of the two anticlines, on the slope southwest of the mouth of Meadow Creek, the tight nose of the East

Meadow anticline forms a crossfold on the flank of the Dickson anticline (pl. 1). Much of the East Meadow anticline is concealed by glacial deposits, and its structure near the Gore fault could not be observed.

BEDDING FAULTS IN GILMAN AREA

The mine workings at Gilman and the cliffs in the canyon nearby expose many low-angle, or bedding-plane faults, and closely related small steep faults in the pre-Pennsylvanian rocks. Such faults probably are widespread in the quadrangle, but in the absence of near-perfect exposures they generally are not seen. The bedding faults record many different directions of movement and are interpreted as a complex system of adjustments to the regional flexural folding expressed by the Sawatch anticline and the synclinal region to the east.

The bedding faults occur persistently at certain stratigraphic horizons and also are scattered widely through the dolomites of the Dyer and Leadville. Stratigraphically, the lowest of the persistent fault zones is the Rocky Point zone near the top of the Sawatch Quartzite. The Rocky Point is a brecciated zone 2–10 ft (0.6–3 m) thick; it is subparallel to the bedding and is an important ore horizon in the quartzite. Slip surfaces within the zone indicate that the upper beds first moved northerly with respect to the lower ones and then, after or during fracturing that produced northeast-trending joints, they moved northeast down the dip.

One of the most persistent of the bedding faults follows the shaly layers in the upper part of the Harding Sandstone. It is exposed in a few places in mine workings and can be seen in a roadcut about 1.5 mi (2.4 km) southeast of Gilman. In the Eagle mine (fig. 8), the fault is marked by wet, gougy, "heavy" ground. Drag folds indicate that the upper block moved west; the amount of displacement was not ascertained but may amount to several hundred feet.

Persistent bedding fault zones also occur at the contact of the Parting Formation and Dyer Dolomite and in the Dyer at a horizon about 25 ft (7.6 m) above the contact. Both zones are altered and are mineralized in places, especially in the vicinity of some ore bodies. The faulted zone at the top of the Parting is a zone of thrust-fault movement; strata above the zoned moved southwest almost straight updip, suggesting response to regional folding. Two periods of movement are shown in the fault zone in the Dyer, an early strike-slip movement that carried the upper beds northwest and a later normal-fault movement that displaced these beds due east. The uppermost persistent zone of bedding-plane movement observed near Gilman is at the base of the Belden Formation. The fault zone is about 8 ft (2.4 m) thick where it is exposed beneath the porphyry sill in roadcuts just north of Rock Creek; drag folds and minor faults within the zone indicate a low-angle normal fault.

The bedding faults scattered through the Leadville Dolomite and Dyer Dolomite show movements of both the normal and reverse types. The amount and direction of movement on such faults is difficult to ascertain, but drag folds, grooves, striations, and gouge seams that displace conjugate systems of cross veinlets and that truncate folds and other structural features show the nature and the general magnitude of the movements. Bedding-plane thrust faults are apparently confined to relatively few surfaces; on these, the upper beds moved west and southwest updip relative to the underlying rocks. In contrast, normal-fault or downdip movement of upper beds on bedding-plane slips was widespread. In some places steep calcite veinlets are displaced along planes an inch or so apart through many feet of section, and although the displacement along individual slips is rarely more than a few inches, the aggregate movement amounts to several feet in a bed 10 ft (3 m) thick. Not all the normal-fault movement was of this pervasive type, however, and much of it was concentrated in shaly beds.

In some places bedding-plane or low-angle faults turn abruptly into vertical faults whose walls moved past each other along a line parallel to the low-angle slip. A fault block lying between two vertical walls, and roofed and floored by bedding-plane slips or low-angle faults, acts as a separate tectonic tongue whose movement may not be reflected in the enclosing rocks. We refer to the steep faults bordering such blocks as tongue faults in the report on the Gilman district (Lovering and others, 1977). In the district, the permeable zones created by bedding-plane slips and tongue faults were important factors in the circulation of ground waters and ore solutions.

ECONOMIC GEOLOGY

The principal mineral deposits known in the Minturn quadrangle are in the Gilman district; they are described in a companion report (Lovering and others, 1977). The Gilman district, which ranks fifth in total output among the metal mining districts in Colorado, is a major source of zinc and has also produced large amounts of silver, copper, lead, and gold. The total value of the production through 1972 was about $328 million. The main ore bodies of the district are replacement deposits in the pre-Pennsylvanian formations, principally the Leadville Dolomite. Rocks of the Belden and Minturn Formations above the mineralized formations show little evidence of mineralization or of the rich ore bodies that lie beneath them. Had the Eagle River not cut a canyon through the mineralized area, it is doubtful that the ore deposits of the Gilman district would yet be known.

If ore deposits are concealed beneath the wide expanses of Pennsylvanian rocks elsewhere in the quadrangle, evidence of them—to judge by the Gilman district—may be scant and subtle. Accordingly, even minor indications of mineralization or hydrothermal alteration in the Pennsylvanian rocks may be significant as evidence of "leaks" from potentially larger mineralized bodies in the underlying Leadville and older carbonate rocks. We discuss below the few localities showing evidence of mineralization or alteration noted in our mapping in the sedimentary terrane, particularly in the Minturn Formation. More detailed mapping and geochemical studies would almost certainly reveal others.

Most of the visible evidence of mineralization in the Minturn Formation is found in the carbonate beds, generally near faults. In such occurrences, the carbonate rocks are irregularly recrystallized to a coarse-grained vuggy light-brown to pearly-gray dolomite. Brown siderite occurs in some of the vugs and in scattered veinlets cutting some of the hydrothermal dolomite. White barite is present locally, either as vug crystals or as small veinlets. Sulfide minerals occur sporadically, either as crystals in vugs or as small lumps and veinlets. Chalcopyrite is the most common sulfide mineral in these occurrences, though pyrite, sphalerite, or galena may predominate locally. Quartz crystals are abundant in the vugs in some localities. Fluorite is present in vugs in a few places, occurring as small colorless to pale-green cubic crystals. Silver is present in an unidentified form in some of the altered carbonate rocks, as indicated by assays of 1–3 ounces of silver per ton from a few samples that contained no visible sulfide minerals.

Small bodies of carbonate rocks showing these characteristics occur on the top of Battle Mountain, along faults near the head of Rock Creek, in dolomite reefs on Willow Creek, in two thin dolomite beds at the mouth of Wearyman Creek, along faults at the head of Wearyman Creek, along the Spraddle Creek fault north of Gore Creek and south of Mill Creek, and along the long east–west fault (pl. 1) east of Gilman. Where this fault crosses Turkey Creek, veins of chalcopyrite an inch (2.5 cm) or more in width cut limestone just north of the fault in the valley bottom on the northwest side of the creek; on the southeast side of the creek, boulders of limestone in landslide debris are partly dolomitized, show zebra-rock structure, and contain disseminated siderite and chalcopyrite.

A small fluorite vein was noted on one of the en echelon faults at the southern end of the Spraddle Creek fault, on a shoulder south of Two Elk Creek, 3 mi (4.8 km) north-northeast of Gilman (pl. 1). The vein contains as much as 6 in. (15 cm) of pale-green fluorite through an exposed length of about 30 ft (9 m).

Uranium occurs in small amounts in red clastic rocks of the upper part of the Minturn Formation along the Black Gore Creek at the quadrangle boundary (Grossman, 1955). Exploratory drilling was done in the area in the 1950's, but little or no uranium production resulted. The drilling confirmed the unconformity beneath the upper part of the Minturn Formation in this area, as some of the drill holes passed into Precambrian rocks at shallow depth. Larger but low-grade deposits of uranium occur in the Gartra Sandstone Member of the Chinle Formation west of the quadrangle, near Red and White Mountain (Butler and others, 1962).

The Gore fault and many other faults in the Precambrian rocks of the Gore Range are accompanied in many places by hydrothermally altered zones, and, in a few places, by quartz or carbonate veins that locally contain traces of sulfide minerals. Many of the faults or veins are geochemically anomalous in one or more of several metals: copper, lead, zinc, gold, silver, molybdenum, bismuth, arsenic, antimony, cadmium, mercury, and tin (Tweto and others, 1970). Despite these anomalies, evidence of mineralization on a scale large enough to induce prospecting is scant. Quartz veins near the head of Deluge Creek, a northern tributary of Gore Creek a mile (1.6 km) east of the quadrangle boundary, locally contain the copper mineral bornite and are reported to have yielded a small amount of selected copper ore that was hauled out by pack burro. Similar but smaller copper-bearing quartz veins are exposed in cliffs beside Bighorn Creek between the 10,600- and 10,700-ft contours, but a prospect tunnel driven beneath the exposures encountered only tight unmineralized fractures. Narrow quartz-carbonate veins exposed in short prospect tunnels and trenches east of Pitkin Lake (lake at head of west fork of Pitkin Creek) contain silver-bearing copper and lead minerals in vuggy masses a few inches in diameter. At various places, but especially to the north of the Piney River, a few of the fracture surfaces in the Gore fault zone are coated with films of malachite or azurite a few square inches in area. About a mile (1.6 km) north of the quadrangle, malachite occurs as films on bedding planes and disseminated in sandstone of the lower part of the Morrison Formation upturned against the Gore fault. Though some of the sandstone contains as much as 1.2 percent copper and a little silver (Tweto and others, 1970, p. 91) the mineralized part is less than 100 ft^2 (9 m^2) in area and is not of itself of commercial significance.

The geochemical anomalies and most of the vein material found along the faults in the Gore Range were concluded by Tweto, Bryant, and Williams (1970) to be products of metal-bearing solutions that passed through the fracture system in the Precambrian rocks enroute either to hot springs at the surface or to mineral deposits in sedimentary rocks now eroded away. In part, at least, these solutions were introduced into the fracture system after the late Tertiary uplift of the Gore Range; thus, they reflect a mineralization epoch younger than those of major mining districts nearby. However, some part of the mineralization and most of the alteration probably are products of earlier Tertiary or Laramide hydrothermal activity.

In the part of the Sawatch Range included within the quadrangle, little evidence of mineralization is seen. Jasperoid that has replaced carbonate rocks of the Dyer and Leadville Dolomites is present near Minturn, as indicated on plate 1, but it is nearly barren of metals other than iron (T. G. Lovering, 1972, p. 79–81). In the area southwest of Gilman, where the carbonate rocks are no longer preserved, short veins of jaspery quartzite breccia or of hematitic breccia occur in the Sawatch Quartzite in several places. As judged from the small size of prospect diggings on many of these veins, the jaspery and hematitic materials are barren of metal values in the commercial range, but, to our knowledge, they have not been tested geochemically for trace metals. Except in the Gilman district, no evidence of mineralization was observed in the Precambrian rocks of the Sawatch Range.

The rapid urbanization of the valley of Gore Creek has created a large demand for sand and gravel. The quadrangle is not well endowed with these materials. Because of the urbanization, deposits in the valley of Gore Creek are eliminated from availability. Other stream valleys in the sedimentary terrane contain little gravel, and what exists is of poor quality because it is derived from weak and inhomogeneous sedimentary rocks. The only large and readily accessible potential source of sand and gravel of good quality is in the moraines near the mouth of Cross Creek. These moraines consist almost entirely of materials derived from Precambrian rocks; though containing boulders, they could become a source of sand and aggregate of good quality. Moraines in the valley of the Piney River area are also potential sources of sand and gravel. However, these moraines contain a fraction of red sedimentary rocks from the Minturn and Maroon Formations; hence, they might not be as suitable for aggregate as the moraines of Cross Creek. They are also far less accessible than those of Cross Creek.

TYPE SECTION

Type section of the Minturn Formation

[Section begins at small knob at elevation 11,500 ft on ridge between Mill Creek and Two Elk Creek, midway between the mountains with elevations 11,820 and 11,223 ft, approximately sec. 22, unsurveyed T. 5 S., R. 80 W., Minturn 15-minute quadrangle, 1934 edition (pl. 1). Section measured southward down spur toward Two Elk Creek. Section is successively offset, as indicated, and ends at intersection of U.S. Highway 24 and Rock Creek, 0.25 mi (400 m) north of Gilman, approximately SE1/4 sec. 13, unsurveyed T. 6 S., R. 81 W. Measured by T. S. Lovering, 1963]

	Thickness (feet)	*Distance above base (feet)*
Maroon Formation:		
Sandstone and siltstone, highly micaceous, thin-bedded; weather medium reddish gray.		
Conformable contact		6,308
Minturn Formation:		
Jacque Mountain Limestone Member:		
135. Limestone. Upper part contains oolitic beds that grade laterally into mottled light- and dark-gray pseudoconglomerate consisting of algal nodules in lighter limestone matrix; cephalopods and fragmentary or poorly preserved brachiopods present but uncommon. Middle part is light gray, medium grained, and medium bedded. Lower 10 ft is thin bedded and irregular bedded, fine grained, and mottled pale pinkish gray and pale green. Pink color cuts across bedding	31	6,277
Clastic unit H:		
134. Sandstone, siltstone, and shale. Sandstone and siltstone are red, weather pale grayish red; many sandstone beds are crossbedded; siltstone is micaceous and platy. Shale is light green, weathers green and medium grayish red; breaks in fissile chips	330	5,947
133. Shale, red and green; and minor interbedded red sandstone and siltstone	35	5,912
132. Conglomeratic grit in massive resistant bed	12	5,900
131. Grit and interbedded sandstone and minor shale, medium- to dark-grayish-red; some green mottling on fresh fracture; is thin to medium bedded. Grit is calcareous	108	5,792
130. Sandstone, dark-red; has some interbedded calcareous siltstone and 1/2-in. beds of silty limestone	25	5,767
129. Conglomeratic grit and interbedded sandstone and siltstone. Grit is light-greenish-gray; weathers light pinkish gray; is thin bedded; contains abundant 1- to 2-in. pebbles of quartz and felsitic Precambrian rocks and some pebbles of fresh mafic rock; grit is highly arkosic and some is calcareous. Siltstone is micaceous and greenish gray	100	5,667
128. Conglomerate; consists of pebbles, 4- to 6-in. cobbles and of a few 12-in.		

Type section of the Minturn Formation — Continued

Minturn Formation — Continued	Thickness (feet)	Distance above base (feet)
Clastic unit H — Continued		
128. Conglomerate — Continued boulders of Precambrian rocks in green-gray grit matrix	35	5,632
127. Grit and conglomeratic grit, and minor interbedded sandstone and siltstone, as in unit 128	115	5,517
126. Limestone, moderate- to pale-red; has light-green spots; weathers light pinkish gray; is thin bedded, flaggy, and medium grained; contains abundant muscovite throughout, and upper layers also contain abundant medium- to fine-grained biotite and pink feldspar	3	5,514
125. Siltstone, sandstone, and shale, interbedded. Siltstone and shale are light green and weather reddish gray; sandstone is medium grayish red; sandstone and siltstone are very thin bedded to thin bedded; weather in flaggy to platy ledges; most beds are limy; some sandstones are crossbedded. Thin-bedded conglomerate with pebbles 1–2 in. in diameter at 40 ft above base	**73**	**5,441**
124. Grit and sandstone, interbedded, light-pinkish-gray; weather medium to dark grayish red. Grits are about half feldspar and half quartz; contain scattered quartz and pegmatite pebbles 1½ in. in maximum size; are calcareous. Conglomeratic grit bed near top of unit contains limestone fragments and grades laterally into limestone and calcareous grit. In lower middle part, unit is interbedded grayish-red and grayish-green siltstone and moderate-red sandstone. Near base, unit is moderate-red to grayish-red, fine- to medium-grained thin-bedded sandstone; is calcareous; contains fresh mafic minerals grains	180	5,261
123. Shaly siltstone, sandstone, and grit, interbedded. Siltstone weathers medium grayish green. The sandstone weathers light brownish gray. Sandstones are medium to coarse grained, some grades into grit; consists of quartz and mica with some feldspar and mafic minerals. Both grit and siltstone contain abundant feldspar in a green, probably chloritic, matrix. Grit predominates in the interval from 10 to 50 ft above the base of unit.	70	5,191
White Quail Limestone Member:		
122. Dolomite, light-pinkish-gray, dense, thin-bedded; top 6-in. layer is reefoid, porous; weathers yellow brown	4	5,187

Type section of the Minturn Formation — Continued

Minturn Formation — Continued	Thickness (feet)	Distance above base (feet)
White Quail Limestone — Continued		
121. Limestone, medium-bluish-gray; weathers medium light gray, except light bluish gray at top; is fine grained, medium crystalline, and medium to thin bedded; Locally oolitic; where oolitic, is light brownish gray. Weathers in slightly rounded slabby blocks; forms low ledge	8	5,179
120. Gritty limestone and interbedded calcareous grit in about equal proportions. Limestone is medium blue gray; weathers medium light blue gray; contains feldspar, quartz, and mica; grades into grit by increase in clastic material. Both grit and limestone are crossbedded.	10	5,169
119. Limestone, mottled dark-gray and brownish-gray; weathers medium light bluish gray; is medium to fine crystalline and thin bedded; forms massive low cliff	14	5,155
118. Covered. Probably interbedded shale, shaly limestone, and thin-bedded grit	10	5,145
117. Limestone, dark-gray; weathers medium bluish gray; is thin bedded	5	5,140

[Section is offset 1 mile west on White Quail Limestone Member to spur extending south-southwest from 11,223-ft mountain on divide between Two Elk and Mill Creeks. Section continues south from this point down nose to base of basal limestone bed of Robinson Member, about 120 ft (37 m) above Two Elk Creek]

Clastic unit G:		
116. Sandstone, arkosic grit, and shale, interbedded. Sandstone is light greenish gray; weathers grayish green; is very thin bedded to thin bedded, fine to medium grained, micaceous, and arkosic; is dolomitic in lower part. Grit is pale greenish gray; weathers pinkish gray; has abundant fresh pink feldspar in fragments as much as ½ in. in diameter	131	5,009
Elk Ridge Limestone Member:		
115. Limestone, light-gray to dark-blue-gray; weathers light to medium blue gray; is fine grained to dense, thin to medium bedded, except thick bedded at base; some bedding in lower part distorted by domed algal structures. Uppermost bed is black, dark gray weathering. At 20 ft above base, is 8-in. dolomite bed; weathers brownish gray; has bunched parallel grooves on bedding planes.	30	4,979
Clastic unit F:		
114. Quartz grit, light-gray, well-sorted; consists almost entirely of gritty quartz grains in calcareous cement	8	4,971

Type section of the Minturn Formation — Continued

	Thickness (feet)	Distance above base (feet)
Minturn Formation — Continued		
Clastic unit F — Continued		
113. Sandstone, grit, and shale, interbedded. Grit predominates in upper third of unit; is light pinkish gray; contains abundant pink feldspar. Sandstone is light yellowish gray to light greenish gray, thin bedded to very thin bedded, fine to medium grained, except that it contains coarse mica; lowest bed contains abundant plant material	115	4,856
112. Shaly siltstone and shale. Dark-gray shale in upper part grades downward into shaly siltstone that weathers dark gray to brownish red and to platy to fissile chips. Grades upward into dark shale	145	4,711
111. Conglomeratic grit and gritty sandstone, pale-greenish-gray; weathers pinkish gray to light red; is very thin bedded and micaceous	90	4,621
110. Dolomite, pale-bluish-gray; weathers pale brownish gray; is medium bedded, medium grained, and fossiliferous	5	4,616
109. Shaly siltstone and arkosic sandstone, light-yellowish-gray to light-pinkish-gray, thin-bedded; at 30 ft above base is 15-ft ledge of coarse-grained crossbedded sandstone containing abundant muscovite flakes and angular quartz fragments as much as 1/2 in. in diameter. Unit forms sandy slope covered with thin platy fragments of the sandstone; coarse pebbles and cobbles about 120 ft above the base indicate a concealed conglomerate	190	4,426
Robinson Limestone Member:		
108. Limestone, medium- and irregular-bedded; weathers light blue gray blotched with irregular yellow-brown areas of argillaceous material. Unit is poorly exposed; forms low terracelike change of slope	5	4,421
107. Mostly covered but sparse outcrops show interbedded grits, conglomeratic grits, and yellowish-gray shaly siltstone	125	4,296
106. Limestone, light-blue gray, fine-grained, thin-bedded. Bedding is very irregular; contains abundant fossils and fossil fragments; fossils recrystallized to pinkish-white coarse calcite. Unit crops out in sporadic low ledges	15	4,281
105. Covered, probably sandstone and siltstone	65	4,216
104. Limestone, medium- to light-gray; weathers light bluish gray and is medium to thick bedded; contains		
Minturn Formation — Continued		
Robinson Limestone Member — Continued		
104. Limestone — Continued abundant fossils. In middle upper part, fossils dolomitized and yellowish and pinkish gray, giving rock a mottled appearance. Productids are abundant in lower layers. Upper part of unit forms smoothly rounded cliff 10–15 ft high	40	4,176
103. Shale and micaceous siltstone, interbedded, yellowish- to pinkish-gray. Upper part of unit is concealed in covered slope. Fault repeats 50 ft of section, and thickness of unit is corrected accordingly	150	4,026
102. Limestone and subordinate dolomite. Upper 8–10 ft is dolomite with reef structure, medium yellowish gray; weathers brownish gray; is medium coarse grained, thin bedded, and slabby; forms ledge 8 ft high. Remainder is light-bluish-gray, medium- to thick-bedded limestone; has nodular structure	43	3,983
101. Sandstone and siltstone, shaly, yellowish- to pinkish-gray	80	3,903
100. Dolomite, light-gray; weathers medium brownish gray; is thick bedded, medium crystalline; weathers in low rounded ledge	8	3,895
99. Micaceous sandstone and siltstone, interbedded, light-greenish-gray; weathers light yellowish gray to light pinkish gray. Sandstone is medium grained, moderately even grained, and thin to medium bedded; contains abundant mica and argillized plagioclase grains. Unit is poorly exposed	150	3,745
98. Limestone and dolomite, reefoid. Limestone is light brownish gray; weathers medium blue gray; is thin to thick bedded. Dolomite is granular, mostly medium grained but locally coarse grained; vuggy at base. Top of reef forms cliff 10–30 ft high	65	3,680

[Section is offset 4 miles northwest on limestones of Robinson Member to point at elevation 9,650 ft on ridge between Game and Gore Creeks. At this locality, limestone of unit 98 is 120 ft thick. Section continues southwest into valley of Game Creek and along jeep road in valley]

	Thickness (feet)	Distance above base (feet)
Clastic unit E:		
97. Sandstone, siltstone, and minor dolomite. Sandstone and intergrading siltstone are greenish gray; weather medium yellowish brown; are thin bedded, arkosic, and micaceous; many beds are dolomitic; some contain abundant mafic grains. Dolomite is brownish gray; weathers medium yellow; is fine grained;		

Type section of the Minturn Formation — Continued

	Thickness (feet)	Distance above base (feet)
Minturn Formation — Continued		
Clastic unit E — Continued		
97. Sandstone, siltstone, and minor dolomite — Continued contains fine quartz grains; occurs in scattered thin beds. Unit forms smooth slope; exposed only in jeep trail	234	3,446
96. Dolomite, medium-blue-gray; weathers light brownish gray; is very finely crystalline and thin to medium bedded	6	3,440
95. Sandstone, conglomeratic grit, shaly siltstone, and shale. Unit is mostly greenish-gray, thin- to medium-bedded arkosic sandstone, with minor interbedded siltstone, shale, and conglomeratic grit. Most of unit weathers gray to light greenish gray. Many of sandstone beds grade into arkosic grit; some appear to be gypsiferous; none are calcareous; all weather readily. Conglomeratic grit contains pebbles 1/2 in. or less in diameter and local lenses of conglomerate. Shale is dark gray to greenish gray and finely micaceous. Siltstone is greenish gray to medium green, shaly, highly micaceous, and chloritic. Beds range in thickness from a few inches to a few feet and alternate in a random way. Unit weathers to a smooth slope and is not well exposed	530	2,910
94. Probable equivalent of Hornsilver Dolomite Member of Pando area. Dolomite, grit, sandstone, and shale. Upper part is sandy dolomite grading into dolomitic sandstone; is very micaceous; weathers orange brown; breaks into angular blocks and slabs. Middle part is interbedded conglomeratic grit and dolomitic sandstone; weathers brown speckled with orange-brown spots; is strongly crossbedded. Gritty dolomite at base is overlain by black shale with interbedded black dolomite in thin beds, up to 10 ft above base	54	2,856
93. Sandstone and grit (80 percent), shaly siltstone (10 percent), shale and dolomite (10 percent). Unit weathers pale yellowish brown to light orange brown and is thin to medium bedded. Unit has a few lenses of quartz-pebble conglomerate; pebbles are mostly less than 1 in. in diameter, but a few are as much as 2 in. Unit forms slope with a few ledges of sandstone cropping out	70	2,786
92. Shale, shaly siltstone, sandstone, and grit. Shale is dark gray; weathers medium gray. Siltstone is gray; weathers medium gray to brown and		

Type section of the Minturn Formation — Continued

	Thickness (feet)	Distance above base (feet)
Minturn Formation — Continued		
Clastic unit E — Continued		
92. Shale, shaly siltstone, sandstone, and grit — Continued light brown. Both shales and siltstones contain abundant plant remains. Sandstone and gritty sandstone weather light bluish gray to light yellowish gray; are thin to medium bedded, and contain scattered plant remains. Thin sandstone beds have current ripple marks	60	2,726
91. Grit, conglomeratic, gray to brownish-gray, medium- to thick-bedded, unevenly calcareous. Pebbles are chiefly quartz	15	2,711
90. Siltstone, shale, and gritty sandstone, interbedded. Siltstone is micaceous, very fine grained, and grades into shale. Sandstone is arkosic and light green; weathers medium grayish green; is thin to medium bedded and medium grained to gritty. Unit has 1-ft bed of sandy calcareous dolomite about 30 ft above base. Unit forms smooth slope broken by ledgy layers of sandstone	55	2,656
89. Sandstone, dolomitic and gritty, yellowish-gray mottled with light yellowish-brown, medium-bedded	5	2,651
88. Grit, conglomeratic; weathers pale brownish gray to pale gray; is poorly cemented and poorly sorted; is medium to thick bedded; contains scattered pebbles 1/2 –3 in. in diameter that include wide variety of Precambrian rocks. Unit forms covered slope with sporadic outcrops in rounded forms	94	2,557
87. Siltstone and gritty sandstone, arkosic; weather brownish gray to light yellowish gray; are thin bedded to very thin bedded; contain abundant plant remains	6	2,551
86. Probable equivalent of Wearyman Dolomite Member of Pando area. Shale (80 percent), silty dolomite (10 percent), and micaceous sandstone (10 percent). Shale is dark gray; weathers light gray; is micaceous. Dolomite is gray; weathers brown; occurs as beds 1–3 in. thick. Sandstone is greenish gray; weathers brown; micaceous	27	2,524

[Section is offset about 1.4 miles south on contact between probable Wearyman equivalent and top of underlying grit marker bed (pl. 1) to point N. 6° E. of Minturn Ranger Station, at top of highest bold cliffs at approximate elevation of 9,975 ft. Section continues southward down cliffs]

Clastic unit D:

85. Grit marker bed. Conglomerate and grit are light gray to pale green;

Type section of the Minturn Formation — Continued

Minturn Formation — Continued Clastic unit D — Continued	Thickness (feet)	Distance above base (feet)
85. Grit marker bed — Continued weather pale pinkish gray to pale greenish gray; are medium bedded and crossbedded; alternate layers of fine- and coarse-grained conglomerate and interbedded grit give banded appearance. Most pebbles are less than 3 in. across, but some are as much as 1 ft; are mostly granitic and metamorphic rocks, subangular to subrounded, tending toward flat ellipsoidal shapes. Unit forms highest sheer cliff on upper slope of Eagle Valley east of Minturn	193	2,331
84. Sandstone, grit, and minor interbedded siltstone and shale. Sandstone and grit are arkosic, micaceous, reddish green; weather light brownish gray to light greenish gray; are mostly thin bedded and slabby or flaggy. Shale is dark olive gray and fissile. There are ripple marks about 3 in. from crest to crest at 27 ft above base of unit	33	2,298
83. Sandstone, grit, siltstone, and conglomerate, interbedded; are light green; weather pale greenish gray; are thin to thick bedded. Many beds contain coarse and poorly sorted fresh feldspar grains in a slightly dolomitic matrix of pyritic and micaceous sandstone. Some sandstone and grit beds show penecontemporaneous slumping and minor faulting. Conglomerates contain cobbles as much as 8 in. across; most conglomerate layers are nonpersistent and fill channels. Persistent conglomerate bed 2 ft above base of unit is overlain by very thin bedded micaceous sandstone or laminated siltstone	56	2,242
82. Siltstone, grit, and dolomite, interbedded, thin- to medium-bedded. Siltstone is pale green; weathers pale greenish gray; is shaly, coarsely micaceous; contains abundant grit. Grit is laminated; consists of coarse quartz grains in chloritic and micaceous matrix. Dolomite is medium gray; weathers light orange brown; ranges from dolomitic sandstone through sandy dolomite to conglomeratic dolomite with lenticular reefy masses of dolomite	17	2,225
[Section is offset 1,000 ft north on unit 82 and continues down cliffs]		
81. Grit and sandstone, pale-pinkish-gray to pale-yellowish-gray. Unit is mostly		

Type section of the Minturn Formation — Continued

Minturn Formation — Continued Clastic unit D — Continued	Thickness (feet)	Distance above base (feet)
81. Grit and sandstone — Continued thick bedded with a few nonpersistent layers of very thin bedded micaceous sandstone in upper half. Grit is conglomeratic, poorly cemented, and slightly dolomitic. Pebbles and cobbles in the grit are as much as 8 in. across, erratically distributed, subangular, and consist of Precambrian rocks and minor green micaceous arkosic sandstone and brown-weathering dolomite. In profile unit forms high cliff with rounded forms	101	2,124
80. Grit, sandstone, and shale. Grit is pale greenish gray; weathers light greenish gray; consists of feldspar, quartz, and abundant mica; is thin bedded and flaggy. Sandstone is coarse to medium grained. Shale is medium greenish gray; weathers light grayish green; is micaceous and laminated; weathers to fissile chips	55	2,069
79. Dolomite, micaceous, conglomeratic, medium-pinkish-gray; weathers light yellowish brown to medium orange brown; is medium bedded and slabby; contains subrounded to subangular pebbles of Precambrian rocks 1/2 –6 in. across	2	2,067
78. Grit, pale-bluish-gray; weathers pale yellowish gray to pale orangish gray; is arkosic, poorly cemented, and very thick bedded; has grains 2–8 mm in diameter; contains shales in small lenses both parallel to bedding and crosscutting at steep angle; steep lenses are 1 in. thick and 6–10 in. long	23	2,044
77. Grit (80 percent), shale (15 percent), and dolomite (5 percent), interbedded. Grit is light gray; weathers pale greenish gray to light yellowish gray; is conglomeratic and dolomitic, medium bedded; contains quartz pebbles as much as 3 in. in diameter. Shale is dark gray; weathers light gray; is laminated and fissile. Dolomite is dark-gray; weathers medium brown; is fine to medium grained; is thin to medium bedded and flaggy; occurs as lenticular beds	90	1,954
76. Grit, shale, and sandstone, interbedded, pale-yellowish-gray, thin- to thick-bedded. Grit is conglomeratic and calcareous; contains pebbles as much as 8 in. across; is in well-defined beds with irregular but nearly parallel tops and bottoms; grades into very thin		

Type section of the Minturn Formation — Continued

Minturn Formation — Continued	Thickness (feet)	Distance above base (feet)
Clastic unit D — Continued		
76. Grit, shale and sandstone — Continued bedded micaceous sandstone at top of unit. Shale layers are thickest in middle of unit	27	1,927
75. Shale, very dark gray; weathers gray; contains minor interbedded brownish-gray thin-bedded micaceous grit and siltstone. Unit is mostly covered	23	1,904
74. Grit and conglomerate, with siltstone and shale partings. Some layers are dolomitic, changing on strike to gritty dolomite that pinches and swells in thickness from a few inches to 2 ft. Unit weathers light greenish gray to light grayish brown; is platy to slabby; forms cliff. Upper part contains quartz pebbles 1/2 –3 in. across in matrix of poorly sorted sand and grit	33	1,871
73. Conglomerate, light-brownish-gray to light-greenish-gray, very thick bedded, poorly cemented, poorly sorted. Pebbles are subrounded to subangular, mostly of Precambrian rocks but a few of dolomite; matrix is coarse calcareous grit. Unit forms cliff pocked by caverns several feet high along vertical joints	46	1,825
72. Grit (60 percent), shale (25 percent), and dolomite (15 percent), interbedded. Unit is thin to medium bedded. Grit is greenish gray to brownish gray; weathers pale brown; contains brown-weathering carbonate grains. Shale is light gray. Dolomite is dark gray to brownish gray; weathers medium brown; is fine grained and gritty	36	1,789
71. Grit and conglomerate with a few shale partings. Unit is pale greenish gray to light brownish gray and thin to thick bedded. Conglomerate is poorly sorted; has pebbles 2–6 in. across in grit matrix. Unit forms prominent cliff 50 ft high	54	1,735
70. Shale, siltstone, grit, conglomerate, and dolomite, interbedded. Shale is dark gray; weathers medium gray; is laminated and fissile. Siltstone and grit are greenish gray to brownish gray; are thin to medium bedded and very micaceous; siltstone is laminated. Conglomerate is pale pinkish gray; weathers pale greenish gray; is poorly cemented; most of pebbles are quartz. Some fine-grained grit and siltstone contain abundant plant fragments, especially rushlike leaves	74	1,661

Type section of the Minturn Formation — Continued

Minturn Formation — Continued	Thickness (feet)	Distance above base (feet)
Clastic unit D — Continued		
69. Grit and sandstone, light-gray to nearly white; weather pale brownish gray to medium light grain; is thin to very thick bedded, coarsely crossbedded, poorly sorted, and poorly cemented. Some beds are dolomitic; are light brown and cavernous where weathered. Grit contains pebbles of quartz, Precambrian rock, and dolomite	28	1,633
68. Shale (70 percent) and dolomite (30 percent), interbedded. Shale is dark gray; weathers light to dark gray; is laminated to very thin bedded, and dolomitic near base. Dolomite in upper part is dark gray; weathers light yellow brown to light orange brown; is thin to medium bedded, dense, and almost lithographic; middle part is medium brownish gray, and gritty to conglomeratic; is pinkish gray, micaceous, and medium fine grained near base. Unit forms ledgy slope, mostly covered	95	1,538
Clastic unit C:		
67. Reef dolomite of Lionshead, dark-gray; weathers medium brown; is fine to medium grained, medium to thick bedded, and slabby or flaggy; contains poorly preserved fossils; is irregularly vuggy, with calcite crystals in the vugs. At 20–35 ft above base conglomeratic grit butts against side of reef in steep but sedimentary contact; dolomite above the grit contains abundant quartz pebbles. Upper surface of reef is irregular	48	1,490
66. Sandstone, siltstone, and grit, interbedded. Sandstone and grit are light greenish gray to pale red; weather grayish brown to orange brown and, locally, to bright red; are calcareous, dolomitic, thin to medium bedded, and flaggy; is crossbedded in middle of unit. Siltstone is dark greenish gray and dusky red to light brown; weathers dark greenish gray, medium reddish gray, and medium orange brown; is very micaceous and very thin bedded to fissile	38	1,452
65. Sandstone and minor shale, medium-light-gray; weather light yellowish gray; are micaceous, medium grained, medium well sorted, and medium to thick bedded	13	1,439
64. Shale (60 percent), siltstone (20 percent), and sandstone (20 percent), interbedded. Shale is dark		

Type section of the Minturn Formation — Continued

Minturn Formation — Continued	Thickness (feet)	Distance above base (feet)
Clastic unit C — Continued		
64. Shale, siltstone, and sandstone — Continued greenish gray; weathers medium greenish gray; is interlayered with laminated micaceous siltstone that weathers to fissile chips. Sandstone is medium light gray, weathers dark gray to orange-brown; is thin to medium bedded	57	1,382
63. Shale and dolomite. Shale is dark greenish gray; weathers dark grayish green; is silty, laminated, and fissile. Dolomite is medium grayish green; weathers medium grayish brown; is medium grained, medium bedded, and flaggy; contains abundant white-and-black mica and fine-grained sand	20	1,362
62. Grit, light-grayish-green; weathers light greenish gray; is arkosic, locally conglomeratic, medium bedded, and flaggy; contains a few siltstone partings	**45**	**1,317**
61. Shale, dark-gray to dark-greenish-gray; weathers dark greenish gray; is very thin bedded to fissile; contains plant remains in lower part. In middle of unit is 18-in. bed of medium-bluish-gray, medium-orange-brown-weathering dolomite	14	1,303
60. Grit, conglomeratic, pale-greenish-gray to pale-pinkish-gray, calcareous; weathers light pinkish gray; is very thin bedded and platy at top, massive in middle, and very thin bedded at base	18	1,285
59. Shale and minor shaly siltstone, black; weathers dark greenish gray to dark gray, in part is finely micaceous	10	1,275
58. Sandstone and grit, greenish- and pinkish-gray; coarse grit at top of unit and medium-fine-grained sandstone at base. Unit forms prominent continuous ledge with irregular profile	17	1,258
57. Grit (50 percent), shale (30 percent), and sandstone (20 percent), interbedded, light-grayish-green. Sandstone and grit are thin to medium bedded. Sandstone is medium fine grained and micaceous. Shale is micaceous and fissile	33	1,225
56. Shale, shaly siltstone, and grit, grayish-green; weather greenish gray. Grit is sandy to conglomeratic; forms ledges 2–4 ft thick on shaly slope	70	1,155
55. Shale and dolomite, interbedded. Shale is light greenish gray, micaceous, and fissile. Dolomite is in beds 2–4 in. thick, except 4-ft bed near top of unit	19	1,136

Type section of the Minturn Formation — Continued

Minturn Formation — Continued	Thickness (feet)	Distance above base (feet)
Clastic unit C — Continued		
54. Sandstone and conglomeratic grit, interbedded, pinkish-gray to light-gray except maroon to pink at base, medium-thin-bedded to massive, strongly crossbedded. Grit contains scattered pebbles, and a few lenses of conglomerate	20	1,116
53. Sandstone, shaly siltstone, and shale; top is approximately top of lower red zone in section in this area. Sandstone is hematitic and chloritic; weathers dark red; is very thin to medium bedded; forms ledges 1–2 ft thick. Shaly siltstone and shale are red and laminated or fissile	21	1,095
52. Sandstone and grit, mottled light-greenish-gray and light-green; weather light pinkish gray. Grit is arkosic, locally conglomeratic, very micaceous, slightly calcareous, and crossbedded	14	1,081
51. Sandstone (40 percent), siltstone (30 percent), and shale (30 percent), interbedded; weather medium red, except some ledges weather light grayish green. Shale is red to dark green and hematitic to chloritic. Sandstone is red to medium greenish gray. Coarse conglomerate layer 10 ft below top of unit contains pebbles of Precambrian rocks and of greenish micaceous shale and siltstone	51	1,030
Clastic unit B:		
50. Dolomite bed of Dowds: Cherty dolomite, medium-gray; weathers light grayish brown; is thin to very thin bedded and flaggy, with greenish-gray shale films on bedding planes. Chert is light to medium gray; some chert lenticles cut bedding in dolomite at low angle	6	1,024
49. Grit, sandstone, and siltstone, pinkish-gray to light-greenish-gray; weather medium red with light-gray streaks. Unit is medium to thick bedded; has local lenses of micaceous conglomerate. Upper part of unit is very thin bedded hematitic shaly siltstone	26	998
48. Sandstone (70 percent), shale (20 percent), and siltstone (10 percent) interbedded. Sandstone is partly hematitic and dark red, and partly arkosic, chloritic, and gray; is thin to medium bedded, poorly sorted, and fine grained to gritty; includes some graywacke. Shale is medium green to dark greenish gray; weathers light green; is laminated and fissile. Siltstone is shaly, finely micaceous, hematitic, and laminated; some		

Type section of the Minturn Formation — Continued

Minturn Formation — Continued Clastic unit B — Continued	*Thickness (feet)*	*Distance above base (feet)*
48. Sandstone, shale, and siltstone — Continued hematitic layers show ripple marks, rill marks, and possible raindrop impressions	52	946
47. Grit, sandstone, and siltstone. Poorly sorted conglomeratic grit alternates with well-sorted medium-grained arkosic sandstone containing abundant fresh pink feldspar grains. Grit is light greenish gray; weathers light gray to brownish gray; is thin bedded, but weathers in massive rounded forms. A little shaly siltstone occurs in middle of unit	37	909
46. Shale, mudstone, and siltstone, interbedded; are thin to medium bedded. Shale is green; weathers light green. Mudstone is light brownish green; weathers yellowish brown to medium red; contains abundant medium- to coarse-grained muscovite, black mica, and other mafic minerals in a very fine grained slightly chloritized matrix	8	901
45. Grit, conglomeratic, pale-gray; weathers light gray to yellowish gray; is thin to medium bedded and flaggy; contains fresh feldspar, chloritized mafic minerals, and scattered 1–3 in. quartz pebbles.	12	889
44. Sandstone (80 percent) and shale (20 percent), interbedded. Sandstone is medium gray; weathers light brownish gray to medium red; is poorly sorted and gritty; contains fresh pink feldspar, chloritized coarse hornblende and biotite, and abundant white mica. Shale is light greenish gray	23	866
43. Sandstone and grit,, light-greenish-gray; weather light yellowish brown; are thin to medium bedded, crossbedded, and flaggy. Layers of well-sorted, medium-grained arkosic sandstone alternate with grit containing abundant quartz and Precambrian pebbles in highly micaceous matrix. Some layers contain abundant limonite spots and carbonized plant remains; also contain minor thin interbeds of fissile greenish-gray shale	25	841
42. Shale (70 percent), and sandstone (30 percent), interbedded. Shale is micaceous, silty, and light green, except lower 6 ft is red. Sandstone is pinkish gray; weathers light brownish gray; is arkosic, medium bedded, and locally crossbedded	10	831

Type section of the Minturn Formation — Continued

Minturn Formation — Continued Clastic unit B — Continued	*Thickness (feet)*	*Distance above base (feet)*
41. Sandstone and minor interbedded siltstone. Uppermost bed is a medium-red fine-grained hematitic sandstone, Sandstone below is light greenish gray to light brownish gray; weathers pale greenish gray to pale pink; is medium to thick bedded, medium grained, well sorted, and arkosic; contains abundant brown limonite spots; has chlorite matrix. Siltstone is shaly, light greenish gray, very thin bedded to laminated, and contains abundant mica and chlorite	10	821
40. Covered	28	793
39. Sandstone, arkosic, conglomeratic, medium-gray; weathers dirty brownish yellow; is medium to thick bedded, faintly crossbedded; is interbedded with light-grayish-yellow fine-grained micaceous thin-bedded sandstone	14	779
38. Sandstone and grit, light-gray to light-yellowish-gray; weather light yellowish brown to medium grayish brown. Sandstone is medium grained, well cemented, and thin bedded; weathers to platy slabs. Grit is thin to medium bedded, flaggy, and locally crossbedded; contains small quartz pebbles. A 5-ft bed of conglomeratic grit 35 ft above base of unit shows both trough and planar crossbedding	44	735
37. Covered slope	35	700
36. Sandstone, grit, and shale, interbedded. Sandstone is light greenish yellow, and thin to very thin bedded; consists of fine grained quartz and abundant medium-grained mica. Grit is light grayish white, very arkosic, locally conglomeratic, thin to medium bedded, flaggy, and crossbedded. Shale is pale grayish yellow; weathers light olive yellow; is micaceous and very thinly laminated	55	645
35. Grit and interbedded shale. Grit is conglomeratic; contains green chloritic particles; is medium grayish red to medium grayish brown; weathers pale brownish yellow to dark grayish red; is thick bedded; contains 3/4-in. quartz pebbles. Shale is dark grayish red; weathers medium grayish red; is very thin bedded to fissile	**94**	**551**
34. Sandstone, gray, medium-grained, crossbedded	10	541

Type section of the Minturn Formation — Continued

	Thickness (feet)	Distance above base (feet)
Minturn Formation — Continued		
Clastic unit B — Continued		
33. Grit and conglomerate; has shale partings. Unit is light pinkish gray; weathers light grayish white to pale pinkish red with black seams; is very thick bedded; has planar crossbedding; contains many pebbles of green chloritic phyllite as well as pegmatite, granite, and metamorphic rocks; pebbles are as much as 3 in. across. Local channeling occurs between units ...	20	521
32. Grit and conglomerate, light-yellowish-brown to light-pinkish-gray; weather medium orange brown to medium grayish red; are medium to very thin bedded, flaggy, and crossbedded. Pebbles are similar to those in unit 33 ...	92	429
31. Grit and sandstone, arkosic, light-reddish-gray to light-yellowish-gray; weather dark orange brown; are thin to medium bedded, and flaggy ...	35	394
30. Grit, grayish-red; weathers dark grayish red; is thin to medium bedded, flaggy, and arkosic; contains minor muscovite and chloritic phyllite ...	18	376

[Interval between unit 30 and top of Leadville Limestone is largely covered. Section is offset 3.7 mi southward to slope on north side of Rock Creek, north of Gilman, to corresponding stratigraphic position above Leadville. Section ends at top of emended type section of Belden Formation. (See fig. 8)]

	Thickness (feet)	Distance above base (feet)
Clastic unit A:		
29. Grit; is in part conglomeratic; grades into quartz-pebble conglomerate, locally crossbedded ...	18	358
28. Shale, hematitic, dark-red; marks approximate base of lower red zone	5	353
27. Shale and sandstone, interbedded. Shale is green and fissile. Base of unit is 3-ft bed of brown-speckled gray sandstone ...	31	322
26. Sandstone and shale, interbedded. Shale is light green; forms 15-ft bed at top of unit. Sandstone is pinkish gray ...	71	251
25. Dolomite; contains abundant fossil fragments ...	2	249
24. Sandstone, greenish-gray; weathers dark orange brown; is medium to thick bedded, and, in part, crossbedded; is arkosic and sideritic. Greenish micaceous shale in beds 1 ft or less thick occur in lower 15 ft of unit ...	35	214

Type section of the Minturn Formation — Continued

	Thickness (feet)	Distance above base (feet)
Minturn Formation — Continued		
Clastic unit A — Continued		
23. Conglomerate and sandstone. Upper part is a light-pinkish-gray medium-bedded crossbedded medium- to fine-grained sandstone containing thin beds of conglomerate and lenses of green and red shale. This grades downward into pinkish-gray medium- to thick-bedded conglomeratic sandstone, and this grades into dark-red conglomerate at base. Conglomerate contains 1-in. pebbles of white and pink quartz, dark chert, and finely micaceous green shale fragments; matrix is micaceous ...	22	192
22. Shale, micaceous, green with dark-maroon-red streaks ...	1	191
21. Sandstone (70 percent), and shale (30 percent), interbedded. Sandstone is light greenish gray and thin to medium bedded; contains pebbles as much as 1/2 in. in diameter in a matrix of fine to coarse quartz grains. Shale is medium green; weathers light green; is very thin bedded ...	9	182
20. Grit, conglomeratic, light-green, weathers medium brown; is micaceous and poorly sorted; contains quartz pebbles 1/2 in. in diameter and minor feldspar ...	1	181
19. Shale, micaceous, green; mostly covered ...	17	164
18. Quartz-pebble conglomerate, light-gray; weathers light orange brown; is thick bedded; matrix is medium to coarse grained; pebbles are 1/4–1/2 in. in diameter ...	5	159
17. Dolomite, thin- to medium-bedded; is in persistent layers; has thin shale parting at top ...	2	157
16. Shale and sandstone, interbedded. Shale is fissile and thin bedded. Sandstone is medium bedded, fine grained to gritty, and micaceous; has clay cement ...	8	149
15. Conglomerate and sandstone, light-gray; weather light brownish gray; are medium to thick bedded; have pebbles up to 3/4 in. that are mostly quartz but some that are chert, sandstone, and quartzite. Sandstone at base has irregular upper surface	8	141
14. Shale, dolomite, and grit, interbedded. Unit is mostly dolomite and dolomitic grit in upper half and mostly shale in bottom half. Shale is platy and dolomitic in middle and fissile at bottom. Grit is very dolomitic; contains dolomite nodules	7	134
13. Dolomite and shale. 1.5-ft dolomite bed at top is medium bedded, medium fine grained, and nonmicaceous; has		

Type section of the Minturn Formation — Continued

Type section of the Minturn Formation — Continued

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