OPEN-FILE REPORT 02-7

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FOREWORD

The Colorado Department of Natural Resources is pleased to present the Colorado Geological Survey Open File Report 02-7, *Geologic Map of the Breckenridge Quadrangle, Summit and Park Counties, Colorado.* Its purpose is to describe the geologic setting, mineral resource potential, and geologic hazards of this 7.5-minute quadrangle located in the mountains of north-central Colorado. Field work for the mapping project was led by C.A. Wallace, consultant, John Keller, CGS staff geologist, Jim McCalpin, consultant, and Paul Bartos, consultant, and was completed during the summer and early fall of 2001.

This mapping project was funded jointly by the U.S. Geological Survey through the STATEMAP component of the National Cooperative Geologic Mapping Program which is authorized by the National Geologic Mapping Act of 1997, Agreement No. 00HQAG0119, and the Colorado Geological Survey(CGS) using the Colorado Department of Natural Resources Severance Tax Operational Funds. The CGS matching funds come from the Severance Tax paid on the production of natural gas, oil, coal, and metals.

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ACKNOWLEDGMENTS

We are indebted to the staff at Breckenridge Ski Corp. for providing access to parts of Breckenridge Ski Area. Rick Sramek, general manager of the ski area, was particularly helpful in securing access for this project. The staff at the U.S. Forest Service office in Silverthorne provided access to areas within the Arapaho National Forest that were closed for administrative reasons. Jamie Connell, District Ranger for the Dillon District, provided permission for special access to a closed portion of the Forest. C.L. Williams and J.B. Turner assisted in Asarco's exploration effort in the Breckenridge quadrangle. Permission to release data was generously granted by Asarco, Incorporated. Asarco is now a division of Grupo Mexico. Karl Kellogg of the U.S. Geological Survey provided a beneficial geological tour of the Frisco quadrangle at the beginning of the mapping season. Helpful technical reviews by Vince Matthews (Colorado Geological Survey) and Karl S. Kellogg (U.S. Geological Survey) improved the map and report. Jane Ciener edited the text, map, and cross sections. Karen Morgan and Jason Wilson prepared the GIS data and Cheryl Brchan completed the digital cartography of the map and cross sections.

INTRODUCTION

The Breckenridge quadrangle is located in south-central Summit County and northwestern Park County, Colorado, mostly west of the Continental Divide (Fig. 1). The quadrangle includes numerous peaks that have elevations of 13,000 to more than 14,000 ft. The Breckenridge ski area is in the northern part of the intensely glaciated Tenmile Range. Quandary Peak, at 14,265 ft above sea level, in the southwestern quadrant of the map area, is a popular peak for hikers and climbers. The town of Breckenridge is located in the northern part of the quadrangle. The Blue River flows north through the middle of the map area in a glacial valley. The Breckenridge area has a long history of mining and mineral processing; lode mines produced gold, silver, zinc, lead, and copper, and placer mines produced large amounts of gold. Nearly $300 million worth of metal were produced from the Breckenridge mining district at approximate current metal prices.

Access to the quadrangle from the north is via I-70 and State Highway 9 south through Frisco to Breckenridge. From the south, U.S. Highway 285 provides access to State Highway 9 to the north via Alma and Hoosier Pass.

The oldest rocks are exposed in the western part of the quadrangle where Early and Middle Proterozoic metamorphic and igneous rocks are

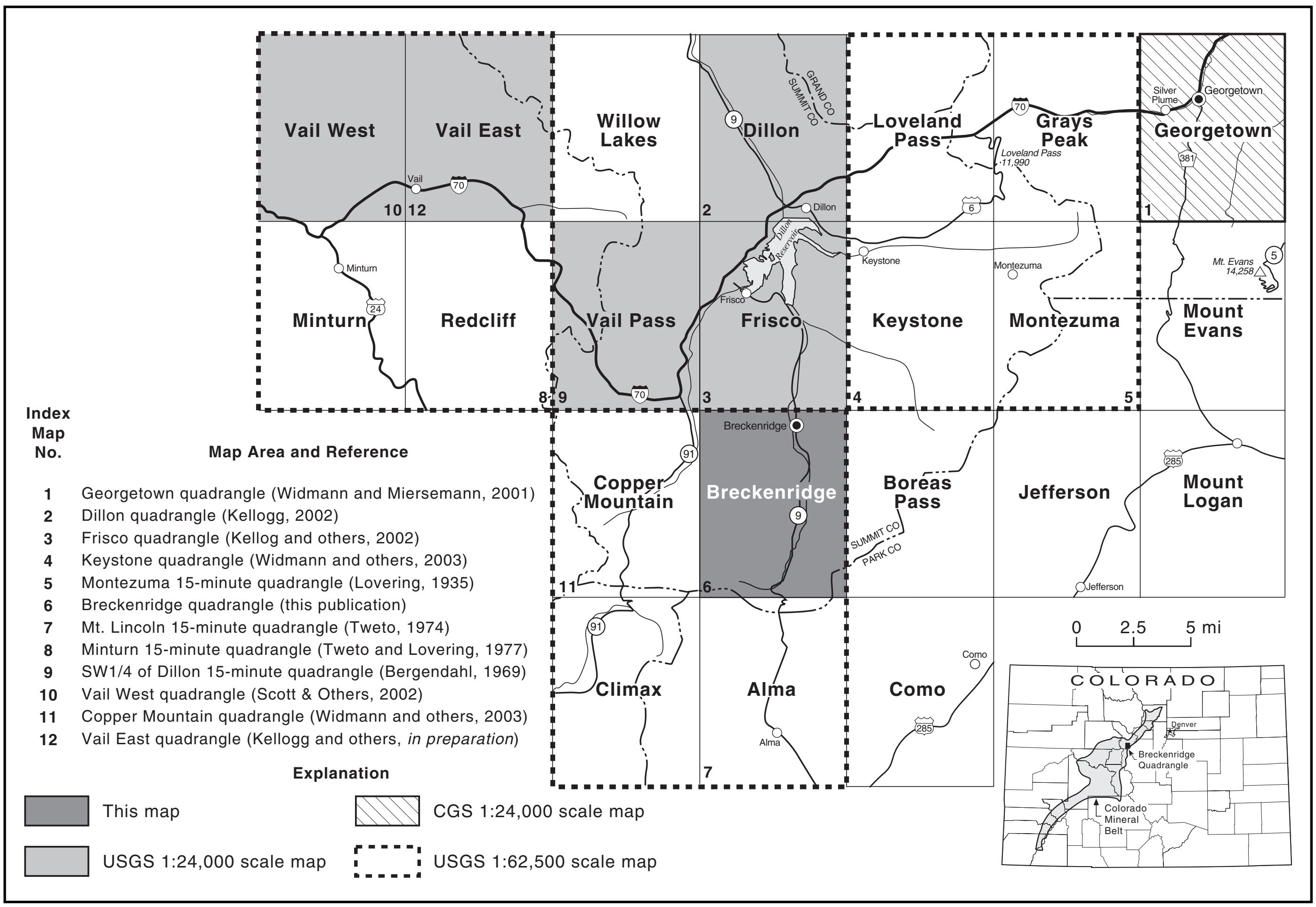

Figure 1. Location map and index of selected published geologic maps in the vicinity of the Breckenridge quadrangle. Inset map shows the location of the Breckenridge quadrangle within the Colorado Mineral Belt.

widespread. Proterozoic rocks are overlain unconformably by Paleozoic clastic and carbonate sedimentary rocks, which are exposed mainly in the eastern part of the map area. Mesozoic rocks occur mainly in the northeastern part of the map area and are composed of shale and subordinate limestone and sandstone. Intermediate and siliceous Tertiary sills and dikes intrude Paleozoic and Mesozoic sedimentary rocks, and lode and disseminated mineral deposits are commonly associated with these intrusive bodies. In the western part of the map area, Proterozoic rocks are intruded by a Tertiary stock and numerous Tertiary dikes. Quaternary deposits are common in valleys and are dominated by till, outwash, and lacustrine deposits. The topography of the Tenmile Range was sculpted by at least two alpine glacial events.

Northwest- and north-trending faults and shear zones that cut Proterozoic through Tertiary rocks, and in some cases Quaternary deposits, are the dominant structural feature of the Breckenridge quadrangle. At least two of these northwest-trending faults, in the western and northern parts of the map area, have large vertical separation. Many other faults in Phanerozoic rocks form a mosaic of intersecting faults of small separation. A less obvious but important east-northeast-trending zone of faults, dikes, and fracturing in the vicinity of the Humbug stock in the Tenmile Range likely represents a structural expression of the Colorado Mineral Belt and may have been active periodically since Proterozoic time. This zone appears to be continuous with several faults of similar trend in the Illinois Gulch area in the Breckenridge mining district east of the Blue River. Most faults east of the Blue River trend northeast, with a subordinate number of faults that trend northwest. Lower Paleozoic rocks rest unconformably over the Proterozoic basement and are exposed on east-facing dip-slopes on the east side of the Tenmile Range only in the southern half of the quadrangle. In the eastern part of the map area the Upper Paleozoic and Mesozoic sequences are generally homoclinal, dipping eastward, except where small fault blocks have locally rotated beds to other orientations. Prominent folds of regional scale occur in Paleozoic rocks in the Blue River Valley; these folds are covered by Quaternary deposits. Metamorphic rocks in the Tenmile Range exhibit strong foliation that has a well-defined and consistent north-northeast orientation.

The Breckenridge area has a well-documented history of placer and lode mining. Placer mines were active for one hundred years, from 1859 to 1959, with the greatest production occurring during the period 1906 to 1924 (Parker, 1974). Lode mining commenced in 1869 and eventually 25 to 30 mines produced ore of at least 1000 tons. The Wellington Mine, in French Gulch, was the most prolific producer, and gold, silver, lead and zinc were the principal metals extracted. None of the metal mines in the quadrangle are currently active.

Analysis of Quaternary deposits has identified four categories of geologic hazards in the Breckenridge quadrangle: (1) landslides and rock slides; (2) floods and debris flows; (3) abandoned mines and placer deposits; and (4) seismicity. Landslides are widespread in the map area, most commonly in till and in glaciated cirques. Rock falls and rock slides are common in rugged valleys of the Tenmile Range. Areas of incipient slope failure are identified by "sackung" structures, which are deep-seated tension gashes in bedrock caused by gravitational spreading on high ridges and mountains (Varnes and others, 1989). Floods are local hazards of known extent in the map area, but debris-flow hazards can occur in ephemeral streams or on Holocene alluvial fans. Abandoned mines pose a hazard from collapse, and areas that were dredged can form cavities at the surface. Mine water also poses a hazard because this water is usually acidic and can carry toxic elements. If it percolates into soil it may be corrosive to metal and concrete in foundations.

PREVIOUS STUDIES

Early geologic studies by the U.S. Geological Survey and by the Colorado Geological Survey in the Breckenridge area were mainly related to description and analysis of mineral deposits during the period that mining became the principal economic force in Summit County.

Regional studies of mining districts in the late 1800's and early 1900's established the stratigraphic and structural framework in which mineral deposits occurred. Emmons (1886) described rock units, structure, and mineral deposits of the Leadville district, located to the southwest of this map area (Fig. 2). Patton and others (1912) described the Alma mining district, and studies in the Alma district were continued by Singewald and Butler (1930, 1941). Singewald (1942, 1951) continued to study geology and mineral deposits of the Boreas Pass region and the upper reaches of the Blue River, as did Butler (1941). Bergendahl and Koschmann (1971) described the geology and mineral deposits of the Kokomo district to the west of the Breckenridge quadrangle. Mulienberg (1925) reported on the geology and mineral deposits of the Tarryall mining district.

Several studies concentrated on the Breckenridge quadrangle and adjacent areas. Ransome (1911) described the geology and ore deposits of the Breckenridge mining district, and Lovering (1934) followed that work with a more detailed analysis of rock units, structure, and mineral deposits of the Breckenridge district. Taranik (1974) produced a Ph.D. dissertation at the Colorado School of Mines that presented results of extensive geologic mapping, regional correlation, sedimentologic studies, and structural analysis of a large area that includes the Breckenridge quadrangle. Taranik's work provided a foundation for our quadrangle map, and we incorporated some data from his dissertation on our map. De Voto (1980) discussed in detail the stratigraphic and structural relations in the area of the Breckenridge quadrangle and established the regional framework for correlating these complex rock units. Bergendahl (1963) mapped the northern part of the Tenmile Range at a scale of 1:24,000. This map and report included detailed descriptions of the Proterozoic rock units of the Tenmile Range. Tweto (1974) published a reconnaissance geologic map at 1:62,500 scale of the Mt. Lincoln quadrangle, the northeast quadrant of which included the Breckenridge 1:24,000-scale quadrangle. More recently, Kellogg and others (2002) of the U.S. Geological Survey mapped the Frisco quadrangle directly north of the Breckenridge quadrangle.

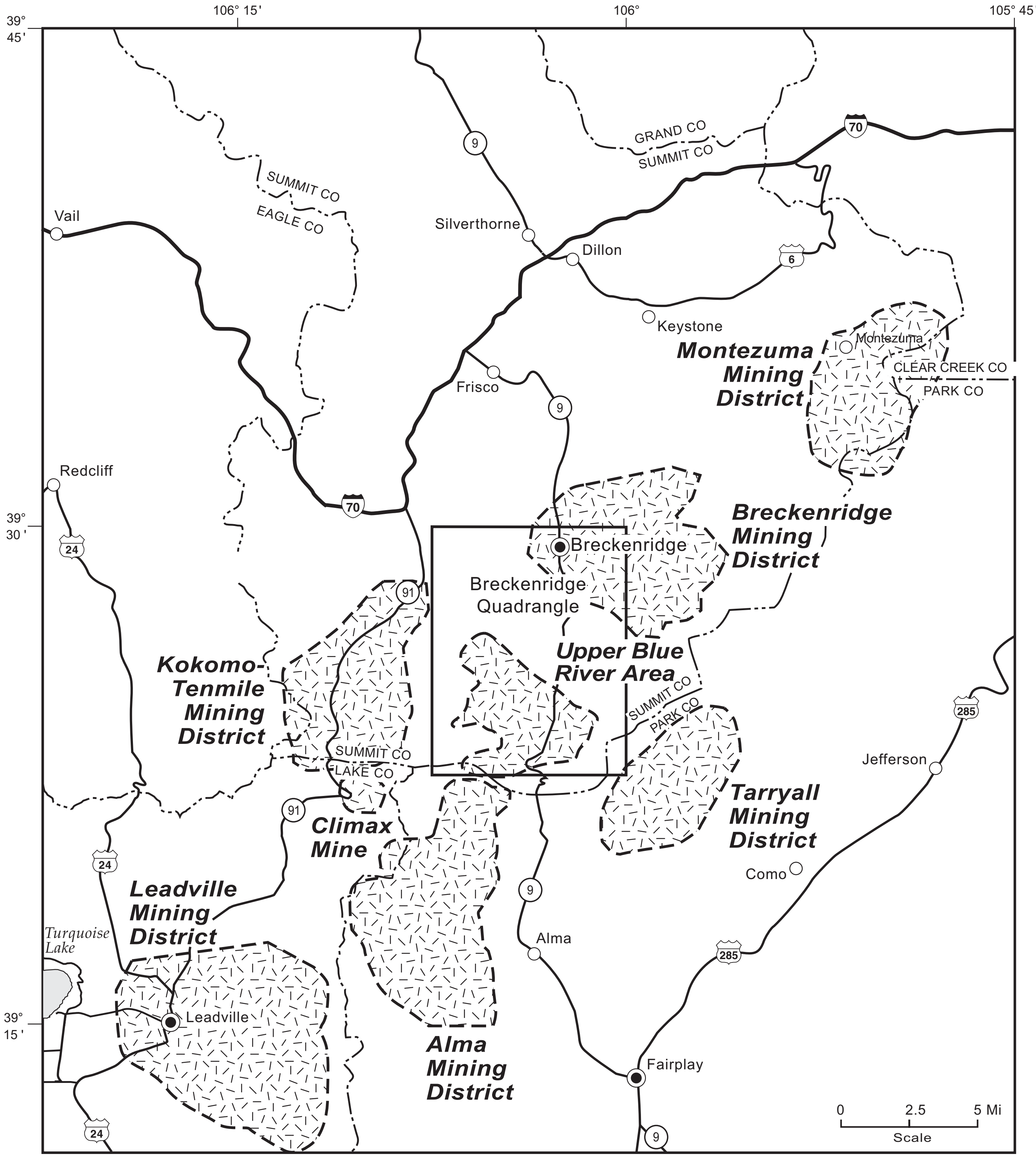

Figure 2. Index map showing historic mining districts in the Breckenridge region.

PRESENT STUDY

The present study focuses on geologic mapping in the Breckenridge quadrangle at a scale of 1:24,000. Geologic mapping was completed in July and August, 2001. John W. Keller and Erik E. Route mapped most of the Tenmile Range in the western part of the map area. Paul J. Bartos was responsible for compilation in the Breckenridge mining district in the northeastern part of the quadrangle, and he mapped between the Breckenridge mining district and Indiana Gulch. During the early 1980's Paul was in charge of exploration of the Breckenridge mining district for ASARCO, Inc., and was assisted by Cindy L. Williams. Parts of the map and report were modified from this earlier work. Paul also provided descriptive and interpretative information about mineral deposits in the Breckenridge quadrangle. C.A. Wallace and Natalie N. Jones mapped mostly in the southeastern and south-central parts of the Breckenridge quadrangle, and they mapped the isolated fault blocks of lower Paleozoic rocks scattered through the central part of the map area. James A. McCalpin mapped surficial deposits in the Breckenridge quadrangle and completed the geologic hazards analysis, and Matt Morgan and Francisco Gutierrez participated in part of the surficial mapping. C.A. Wallace and John Keller compiled the geologic map from data provided by these co-authors, and they assembled descriptive geologic data, descriptions of mineral deposits, and interpretations from these colleagues to produce this report.

Rock names in this report are field terms. Sedimentary rocks are named according to the scheme proposed by Pettijohn (1957), metamorphic rock names follow the system proposed by Best (1982), and volcanic and igneous rocks were named according to the I.U.G.S. classifications proposed by Strekeisen (1973, 1978). Field data were plotted on color aerial photographs from the U.S. Forest Service (1983) and from IntraSearch (1999), at a nominal scale of 1:24,000.

Thick forest cover below timberline, much of which is overgrown since Ransome (1911) and Lovering (1934) completed their pioneering studies, obscure rock units. In addition, Quaternary deposits and residual deposits combine to make outcrops rare in many areas of the Breckenridge quadrangle, except where road cuts provide fresh exposures. Exposure is better above timberline, except in areas where felsenmeer and solifluction deposits are widespread. Where felsenmeer and solifluction deposits are common, most of the rock is frost-riven blocks that are not in place. Proterozoic crystalline rocks are, in general, better exposed than the softer Phanerozoic sedimentary rocks.

STRATIGRAPHY

PROTEROZOIC ROCKS

The Tenmile Range, which is west of the Blue River Valley, is underlain by metamorphic and igneous rocks of Early and Middle Proterozoic age. Migmatitic (Xmg) to locally non-migmatitic biotite gneiss (Xb) is the most abundant of the Proterozoic rock types of the quadrangle. One small area of felsic gneiss (Xf) was mapped in the northern part of the map area. These units are part of the regionally extensive sequence of metamorphosed sedimentary and volcanic rocks that underlie much of the mountainous region of northern and central Colorado. This sequence of metamorphic rocks is known as the Proterozoic gneiss complex (Tweto, 1987) . The regional metamorphism and deformation occurred concurrently with the emplacement of syntectonic plutons during the Early Proterozoic in Colorado (Reed and others, 1987). Amphibolite and hornblende-plagioclase gneiss that were mapped over large areas by Kellogg and others (2002) in the Frisco quadrangle to the north do not occur in the Breckenridge quadrangle.

Proterozoic intrusive rocks in the Breckenridge quadrangle include small to medium-sized diorite and granodiorite intrusives (YXdi and Xgd), granitic plugs and small stocks (Xgg, Xg, Yqm), mafic dikes (YXm), and numerous small, irregular masses of pegmatitic granite, pegmatite, and aplite (YXp). These rocks were intruded during the late Early Proterozoic and the Middle Proterozoic. An Early Proterozoic intrusive unit of granitic gneiss that is exposed extensively in the Frisco quadrangle (Kellogg and others, 2002) was mapped in only one small area in the central part of the Breckenridge quadrangle. Intrusives of the Routt Plutonic Suite were emplaced about 1,700 Ma, and those of the Berthoud Plutonic Suite were emplaced about 1,400 Ma (Tweto, 1987). No intrusive rocks related to the Pikes Peak Batholith (1,000 Ma) are known to occur in this area (Tweto, 1974).

PROTEROZOIC GNEISS COMPLEX

MIGMATITIC BIOTITE GNEISS

The most widespread Proterozoic rock unit in the Breckenridge quadrangle is migmatitic biotite gneiss (Xmg), of Early Proterozoic age (Fig. 3). A photograph of an exposure of migmatite in Pacific Gulch, west of Pacific Peak along the western edge of the map area, was taken by Bergendahl and Koschmann (1971) and later used as a prime example of migmatite in an undergraduate petrology textbook (Ehlers and Blatt, 1982).

Migmatitic biotite gneiss is generally medium to dark gray, dark brownish gray, to locally dark reddish or rusty brown. Red or rusty coloration is from weathering or alteration of biotite, which results in the formation of iron-oxide minerals. The rock is well foliated (usually wavy), medium grained, hypidiomorphic to xenomorphic, and inequigranular to granular. Light-colored (felsic) pegmatitic to granitic layers and irregular veins consisting mostly of quartz and feldspar (locally quartz-only) are interlayered with the darker biotite-rich material. The felsic layers are typically coarse grained and range from about 0.5 cm to 20 cm thick. They constitute from 20 to 70 percent of the overall rock mass (Kellogg and others, 2002). The high percentage of the felsic material distinguishes the migmatite from non-migmatitic biotite gneiss. These felsic layers often show ptygmatic folding and boudinage structures. The felsic layers were caused by the processes of igneous injection and metamorphic segregation. At some places, especially near diorite or granodiorite intrusive bodies, some of the dark layers have an intrusive texture, with relict plagioclase phenocrysts as long as 1 cm. These intrusive-looking layers may be sills that emanated from the nearby intrusives prior to or during metamorphism.

Dark layers consist primarily of quartz, plagioclase, biotite, and microcline in varying proportions. Biotite is locally altered to chlorite. Thin sillimanite-bearing layers are present at a few places. Sillimanite is present as light-gray or colorless, fibrous to bladed clots and masses within the

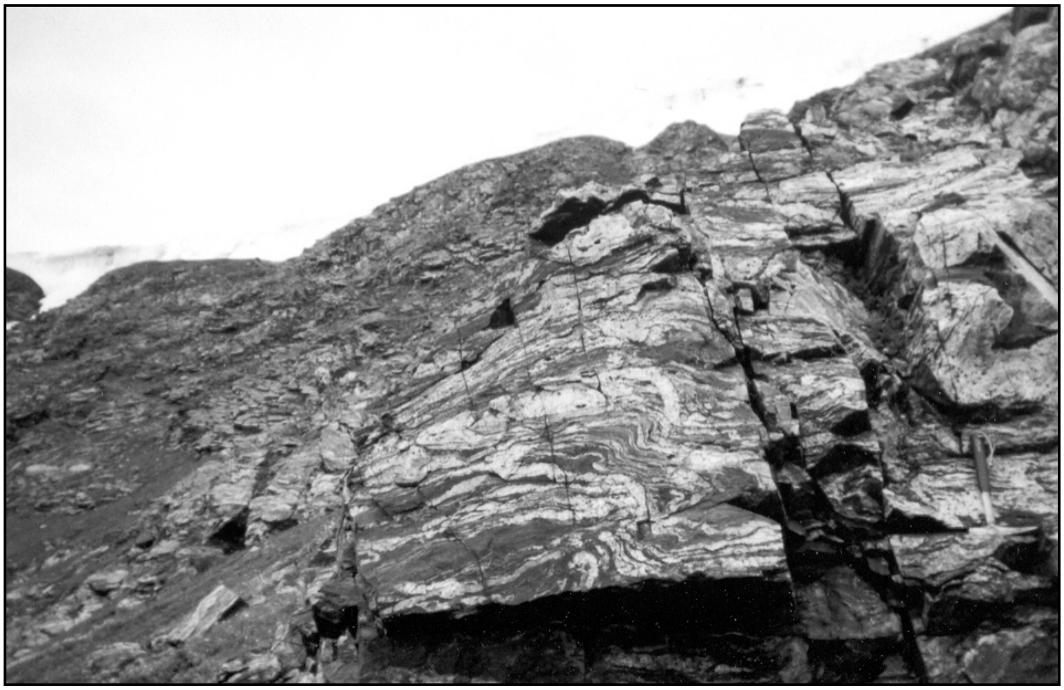

Figure 3. Proterozoic-age migmatitic biotite gneiss (Xmg) exposed on the south-eastern flank of Peak 8 in the Tenmile Range.

layers. Phlogopite and muscovite are locally present in small quantities (Kellogg and others, 2002) and may be alteration products of biotite. Traces of magnetite, garnet, zircon, and apatite also occur in the migmatite. Garnet, where present, occurs as fractured porphyroblastic crystals (Bergendahl, 1963). Epidote coats fractures at some places.

A few thin, discontinuous layers (<2 m) of metaquartzite occur within the migmatitic gneiss, especially in the Peak 10 and Crystal Peak areas. The metaquartzite was not mapped separately but serves as an additional indication that the biotite gneiss and migmatite have sedimentary protoliths. In the Front Range, biotite gneiss has been interpreted to be derived from the metamorphism of sandy shale or graywacke (Sheridan and Marsh, 1976).

Biotite Gneiss

Biotite gneiss (Xb) is Early Proterozoic in age and is lithologically and mineralogically similar to the dark layers of migmatitic biotite gneiss. However, biotite gneiss lacks the high percentage of felsic layers and degree of ptygmatic folding and boudinage exhibited by the migmatitic gneiss. The contact between biotite gneiss and migmatitic biotite gneiss is somewhat arbitrary and is based on guidelines provided by Kellogg and others (2002) for the Frisco quadrangle. Biotite gneiss was designated where the overall rock contains less than 20 percent felsic layers. Compared to the migmatitic gneiss, biotite gneiss has more parallel (less wavy) layering, often weathers in a more blocky fashion, and is less folded, at least at outcrop scale. Non-migmatitic biotite gneiss is less common than migmatite gneiss in the quadrangle. Biotite gneiss is most common in the lower, eastern side of the Tenmile Range.

Biotite gneiss is hard, medium-gray, medium-grained, and well-foliated. This unit consists of quartz (30 to 50 percent), plagioclase (20 to 30 percent), and biotite (10 to 15 percent). Microcline, muscovite, hornblende, and sillimanite occur as accessory minerals in variable proportions (Kellogg and others, 2002).

Felsic Gneiss

Felsic gneiss (Xf) was observed as a mappable unit in only one small and poorly exposed area near Peak 6 in the northwest part of the quadrangle. Felsic gneiss is light-tan to light-gray, fine- to medium-grained, moderately well-foliated gneiss consisting primarily of quartz and feldspar. Thin, dark-green, chloritic layers are present and appear to be derived from the alteration of biotite-rich layers. Tweto (1987) suggested that most felsic gneiss in the Front Range and Park Range was derived from silicic volcanic tuff protoliths.

ROUTT PLUTONIC SUITE

The Routt Plutonic Suite (Tweto, 1987) comprises the oldest of the igneous intrusive rocks in Colorado. Intrusives of this group were emplaced between about 1,660 and 1,790 Ma, during Early Proterozoic time (Reed and others, 1987). The Denny Creek Granodiorite (Barker and Brock, 1965), a foliated granodiorite of the Routt Plutonic Suite, occupies a large area stretching from a point about 18 km south-southwest of the Breckenridge quadrangle in the Mosquito Range southeast into southwestern South Park, and west into the central Sawatch Range. Granodiorite, granitic gneiss, alaskitic granite, and pegmatite dikes on the Breckenridge quadrangle have been assigned to the Routt Plutonic Suite. A few mafic dikes may also belong to this suite.

GRANODIORITE

Foliated granodiorite (Xgd), of Early Proterozoic age, forms small to medium-sized plutons in the Proterozoic terrane of the Tenmile Range. This unit is more common in the southern part of the map area. Plutons of granodiorite to locally quartz monzonite or quartz diorite composition are usually well foliated, with foliation parallel to the regional foliation of the migmatitic gneiss. Much of what we map as granodiorite was mapped by Bergendahl (1963) as "porphyroblastic migmatite". Our field work showed that this unit is not migmatitic in character. Near the margins of the well-foliated granodiorite bodies, concordant layers within the migmatitic gneiss (Xmg) take on a porphyritic or porphyroblastic texture. These layers are possibly metamorphosed sills that emanated from the intrusive body. This would indicate that this intrusive activity occurred prior to the regional metamorphic event. Feldspar phenocrysts as long as 4 cm are common along the outer margins of some of the granodioritic intrusives. The texture and composition is similar to Early Proterozoic rocks referred to as Denny Creek Granodiorite by Tweto (1987), which locally grades to biotite quartz diorite and quartz monzonite and is common in the Mosquito Range to the southwest of this quadrangle.

The granodiorite is medium to dark gray, medium to coarse grained, porphyritic, and is moderately to well foliated. It contains 15 to 35 percent biotite, 15 to 40 percent quartz, 30 to 60 percent feldspar (mostly plagioclase), and only minor amounts of hornblende and pyroxene. Accessory minerals include apatite, sphene, and rutile. Epidote is locally present as an alteration product, and biotite is often chloritized.

GRANITIC GNEISS

Granitic gneiss (Xgg) was mapped in one small area in the central part of the quadrangle. Granitic gneiss was mapped over a large area in the Frisco quadrangle and is interpreted to be intrusive in origin and part of the Routt Plutonic Suite (Kellogg and others, 2002). Bergendahl (1963) had previously interpreted the unit to be the stratigraphically lowest unit of a metasedimentary sequence. Our mapping and interpretations confirm that the unit is intrusive and not metasedimentary. Only one good exposure of granitic gneiss is present in the Breckenridge quadrangle, along a small landslide headscarp in Carter Gulch. The granitic gneiss is younger than biotite gneiss. The granitic gneiss is light gray, light pinkish gray, to pinkish green, medium to coarse grained, and moderately foliated to locally well foliated. It consists principally of 50 to 65 percent feldspar (mostly pink to white k-feldspar), 25 to 35 percent quartz, and 10 to 15 percent biotite, which is usually partially or completely altered to chlorite. Biotite aggregates commonly form clots and lenses. Small amounts of muscovite and opaque minerals are also present. Kellogg and others (2002) noted garnet, zircon, and apatite as accessory minerals. Thin (0.2 – 2 cm) shear planes composed mostly of chloritized biotite are common and give the rock a streaky appearance in places.

ALASKITIC GRANITE

A few irregularly shaped intrusions of alaskitic granite (Xg) are present in the Tenmile Range. The largest body of alaskitic granite is located on the northern side of Peak 10. Numerous, irregular, dike-like bodies of alaskitic granite emanate from the larger intrusive masses and intrude the migmatite gneiss. The granite is white to very light gray to light tan and consists of microcline and orthoclase (50 to 60 percent), quartz (30 to 40 percent), muscovite (5 to 10 percent), and minor plagioclase. Under the microscope, quartz displays prominent undulatory extinction. Bergendahl (1963) noted fine-grained magnetite, pyrite, chlorite, and biotite as very minor constituents. The texture is fine to medium grained and generally xenomorphic, and the rock sometimes appears aplitic. This rock has not been definitively age dated, but the authors speculate that it is Early Proterozoic in age due to its weak but consistent foliation.

BERTHOUD PLUTONIC SUITE

The Berthoud Plutonic Suite (Tweto, 1987) comprises the middle age-group of igneous intrusive rocks in Colorado. Intrusives of this group are thought to have been emplaced about 1,400 Ma, during Middle Proterozoic time. In the Breckenridge quadrangle, quartz monzonite, diorite, mafic dikes, and pegmatite/aplite dikes have been assigned to the Berthoud Plutonic Suite. The St. Kevin Granite comprises a batholith and associated smaller intrusions that extend from near the southwestern corner of the Breckenridge quadrangle southwest through the Sawatch Range and into the Elk Mountains (Tweto and others, 1978). The extensive Silver Plume Granite in the Front Range east of the Breckenridge quadrangle also belongs to the Berthoud Plutonic Suite.

QUARTZ MONZONITE

Intrusive rock of quartz monzonite to granite composition (Yqm), of Middle Proterozoic age, closely resembles the "Silver Plume Granite" (Ball, 1906). These bodies are present as irregular stocks along the western and southwestern margin of the quadrangle. Tweto (1974) also recognized the similarity and mapped the plutons as Middle Proterozoic granite. These rocks were later included as part of the St. Kevin Granite batholith by Tweto (1978).

The rock is light to medium gray to pinkish tan, medium grained, and porphyritic. It contains both biotite and muscovite, with biotite usually dominant. From a distance and in air photos, outcrops commonly appear to be rusty-pink colored. Euhedral, elongated, tabular phenocrysts of mostly microcline feldspar up to 2 cm long comprise 30 to 40 percent of the rock mass. These phenocrysts commonly display a rough alignment, especially near pluton margins. This phenocryst alignment has been attributed to primary flow structure (Tweto, 1987). The phenocrysts commonly display Carlsbad twinning. Plagioclase crystals, typically much smaller than the microcline phenocrysts, make up 25 to 35 percent of the rock. Quartz (sometimes smoky-colored) varies from 15 to 30 percent. Biotite and muscovite together comprise about 5 to 10 percent of the rock. Apatite and rutile are reported to occur as accessory minerals (Bergendahl, 1963). In small plugs, dikes, and irregular intrusions lying away from the larger stocks, quartz and muscovite generally increase in percentage, and overall grain size diminishes. The rock unit is not deformed by regional metamorphism.

Numerous irregular apophyses and dikes emanate from the quartz monzonite stocks and plugs. These often grade into pegmatitic granite, pegmatite, and aplite. In some places, such as the Crystal Peak area, these dikes are so numerous as to constitute nearly 50 percent of areas otherwise mapped as migmatitic biotite gneiss. In such cases, only the largest and most conspicuous dikes were mapped separately. Bergendahl (1963) had a separate map unit for this mixture of migmatite gneiss and younger granite and pegmatite.

PEGMATITE AND APLITE

Numerous discontinuous dikes and irregular masses of pegmatitic to aplitic rock (YXp) occur in the Tenmile Range, and these masses are especially numerous in the southern half of the range near mapped bodies of Proterozoic quartz monzonite. Pegmatites and aplites are undated but are probably Middle and Early Proterozoic in age. The long axes of the pegmatites are commonly oriented in preferred directions, especially east-west. Exposures often show a variety of textures, with coarse pegmatitic zones grading into medium-grained pegmatitic granite and fine-grained aplite. Pegmatites and related bodies range from 2 to 25 m in width, averaging about 7 m. Pegmatitic rocks in the map area are typically white to light pink and consist primarily of quartz, microcline, plagioclase, and muscovite and/or biotite. Rarely, large (~ 2 to 7 cm) masses of magnetite occur in pegmatite. Reddish-brown garnet locally is a minor constituent. Several pegmatites in the Mount Helen area contain several percent of a light-green mica, possibly the chromium-rich mariposite. Because they are so numerous and are often only exposed on extremely steep mountain faces, no attempt was made to differentiate the different types of pegmatites, aplites, and pegmatitic granites on the map. Due to their high color contrast with surrounding rock, these rocks were easily mappable from aerial photographs.

Mafic Dikes

In the Breckenridge quadrangle, narrow, mafic, fine-grained lamprophyre dikes (YXm) that discordantly intrude gneiss were mapped at a few places. At most places, the exposures were too small and discontinuous to be shown at map scale. These dikes are typically massive to weakly foliated. Their composition is variable, and many have undergone sausseritic alteration to varying degrees. In many exposures, rounded masses of recrystallized phenocrysts give the rock a spotted appearance. The spots can be either lighter or darker than the enclosing fine-grained material. The spots are not individual crystals, but fine-grained aggregates of alteration products. Dark aggregates are often hornblende that has replaced pyroxene. Relict plagioclase has in some cases been replaced by potassium feldspar. Uralite-chlorite intergrowths are present in most samples as an alteration product of mafic minerals.

The dikes are dark gray to black and display somewhat variable mineralogy and texture. The variation is due partly to alteration and partly to primary compositional differences. They consist principally of hornblende and/or biotite (30 to 60 percent), plagioclase and/or secondary potassium feldspar (20 to 40 percent), variable amounts of secondary epidote and chlorite (up to 15 percent), remnant pyroxene (less than 10 percent), rounded and resorbed quartz grains (5 to 10 percent), dolomite (up to 10 percent) which may be secondary, magnetite and other opaque minerals (2 to 3 percent), and traces of apatite. Secondary potassium feldspar is present in the groundmass in some dikes. A whole-rock geochemical analysis of one sample from a mafic dike showed it to be highly potassic, with almost no sodium. Along some mineralized fault structures in the southern part of the map area, mafic dikes contain up to 3 percent disseminated pyrite and have been explored by short mine adits. Migmatitic gneiss and pegmatitic material is locally present as inclusions within the dikes. Tweto (1987) grouped most narrow, mafic and intermediate dikes that are present in the Front, Sawatch, and Park Ranges into the Berthoud Plutonic Suite. Some of the dikes display more foliation than others and may be of the Routt Plutonic Suite. Kellogg and others (2002) mapped a small body of ultramafic material in the Frisco quadrangle and assigned it to the Routt Plutonic Suite.

Diorite

Small intrusions of diorite (YXdi) are present in the northern and north-central Breckenridge quadrangle. The diorite is dark gray, medium to coarse grained, and massive to very weakly foliated. Kellogg and others (2002) mapped similar intrusions in the southern part of the Frisco quadrangle. The lack of strong foliation indicates that these intrusives are probably of Middle Proterozoic age, but no definitive age date or cross-cutting relationships prove it. The diorite consists principally of plagioclase (40 to 60 percent), hornblende (30 to 55 percent), biotite (5 to 10 percent), and quartz (5 to 10 percent). Opaque minerals (mostly magnetite; 2 to 4 percent), pyroxene (trace), and variable amounts of secondary chlorite and epidote. Accessory apatite and sphene were noted in thin section.

PALEOZOIC ROCKS

Regionally, the complete stratigraphic sequence is, in ascending order, the Sawatch Quartzite and Peerless Shale (Late Cambrian), Manitou Limestone (Early Ordovician), Harding Quartzite (Middle Ordovician), Fremont Dolomite (Upper and Middle Ordovician), Parting Quartzite and

Dyer Dolomite Members of the Chaffee Formation (Late Devonian), Leadville Limestone (Lower Mississippian), Belden Shale and Minturn Formation (Pennsylvanian), and Maroon Formation (Pennsylvanian and Permian). The Sawatch Quartzite and Peerless Shale, and the Parting Quartzite and Dyer Dolomite Members are combined on cross-section B-B′.

In the map area, the Harding Quartzite and Fremont Dolomite are absent from the stratigraphic sequence; these units were not deposited in the map area or they were eroded before the Chaffee Formation was deposited. The Leadville Limestone thins from south to north and it disappears near the south border of the Breckenridge quadrangle. Most of the lower Paleozoic rock units are absent in the northern part of the map area where the Maroon Formation was deposited directly on Proterozoic rocks. Lower Paleozoic rock units are separated by disconformities that represent long periods of non-deposition, or after deposition, erosion. Lower Paleozoic rocks occur mainly west of the Blue River on local fault blocks unconformably above Middle Proterozoic metamorphic rocks. The Belden Shale is not mapped in the Breckenridge quadrangle. The Minturn Formation overlies the Manitou Limestone in exposures west of the Blue River, but nowhere is a complete section of Minturn present. The Maroon Formation is the uppermost Paleozoic unit, and it overlies the Minturn on an intertonguing contact in the southern part of the map area. The Maroon Formation is exposed mainly in the southeastern part of the quadrangle where this unit thickens drastically. The exposed Paleozoic sequence is estimated to be about 1,765 m thick in the map area, but nowhere is the sequence continuous.

SAWATCH QUARTZITE

In the south-central part of the Breckenridge quadrangle the Sawatch Quartzite (€s), of Late Cambrian age, overlies Middle Proterozoic metamorphic and igneous rocks. The Sawatch Quartzite is as thick as 43 m in the map area. This unit has a prominent basal conglomerate that is overlain by fine- and medium-grained quartzite. The base of the Sawatch Quartzite is marked by a feldspathic conglomerate that contains well-rounded quartz pebbles in a matrix of medium- and coarse-grained sand. The basal conglomerate is 18 to 32 cm thick, and it contains planar crossbeds. Most of the Sawatch Quartzite is a medium-grained, well-sorted quartzite with sub-rounded grains. Some beds are graded from medium-grained quartzite at the base to fine-grained quartzite at the top. The amount of feldspar decreases upward. The lower part of the quartzite is grayish white and the upper part of the quartzite is reddish brown and contains thin, laminated black shale interbeds. The Sawatch Quartzite has been eroded by a pre-Pennsylvanian unconformity in the northern part of the map area.

PEERLESS SHALE

The Peerless Shale (€p), of Late Cambrian age, is a sequence of coarse-grained quartzite inter-bedded with black shale at the base and fine- and medium-grained quartzite, interbedded with dolomite-cemented sandstone and sandy and silty dolomite. The Peerless Shale is as thick as 12 m in the map area. This unit is generally poorly exposed and it forms a recessive-weathering zone that contains clasts of rusty-weathering dolomite and dolomitic quartzite in soil above the resistant-weathering quartzite of the Sawatch Quartzite. The Peerless Shale disappears south of the Breckenridge quadrangle. Taranik (1974, p. 19) regarded the Peerless Shale as a transitional unit between the Sawatch Quartzite and the Manitou Limestone.

MANITOU LIMESTONE

The Manitou Limestone (Om), of Early Ordovician age, overlies the Peerless Shale on a disconformity and is mainly a dolomite in the map area. The Manitou Limestone is as thick as 27 m in the map area. This unit is composed of dark-, moderate-, and light-gray, thin- to thick-bedded dolomite and cherty dolomite, and rare beds of dark-gray limestone. Grayish-pink and light-grayish-red dolomite beds occur in the upper part of the unit. Taranik (1974) reported that the upper 6 m of the Manitou Limestone contains casts of crinoids, shell fragments, and stromatolites. Sand grains and sandstone beds increase in the upper part of the Manitou Limestone. Distinctive grayish-white chert nodules and rare black chert nodules are elongate parallel to bedding planes and mostly occur in the upper part of the Manitou Limestone. Silicification of dolomite is not common in the Breckenridge quadrangle, but silica replacement of dolomite beds and dolomite breccia is common about 90 km south of this map area between Trout Creek Pass and Salida, Colorado,(Wallace and others, 1997; Wallace and Keller, 2001). The Manitou Limestone is absent in the northern part of map area where this unit was eroded before Middle Pennsylvanian time.

CHAFFEE FORMATION

The Chaffee Formation (Dc) is of Late Devonian age and rests disconformably on the Manitou Formation (Taranik, 1974). This unit thins toward the north in the Breckenridge quadrangle and is absent north of McCullough Gulch. The Chaffee Formation is composed of the Parting Quartzite Member at the base and the Dyer Dolomite Member at the top.

The Parting Quartzite Member is a grayish-red, gray, dark-reddish gray, grayish-orange, and black weathering, fine-, medium-, and coarse-grained, silica- or dolomite-cemented orthoquartzite and slightly feldspathic quartzite. The base of the Parting Quartzite is marked by a conglomerate. Planar crossbeds are more common in the lower part than in the upper part of the unit. Generally beds are 3 to 30 cm thick. The Parting Quartzite is as thick as 6 m thick in the map area.

The Dyer Dolomite Member is a laminated, tan-weathering dolomite that is as thick as 14 m in the map area. This unit is light yellowish gray, grayish yellow, light brownish gray, mottled and contains wavy microlamination. Dolomite is very fine grained to fine grained and the rock has a conchoidal fracture. Where outcrops occur in the south-central part of the quadrangle, the Dyer Dolomite Member forms a prominent light-colored band above darker colored rocks.

MINTURN FORMATION

The Minturn Formation (IPm) is of Middle Pennsylvanian age (Des Moinesian) (De Voto, 1980), and either disconformably overlies the Dyer Dolomite Member in the southern part of the map area or unconformably overlies Proterozoic rocks in the northern part of the map area. The Belden Shale, which underlies the Minturn Formation west and south of the map area, was not recognized in the Breckenridge quadrangle. In the Breckenridge quadrangle the Minturn Formation is composed of interbedded conglomerate, and green, black and gray, arkose, micaceous shale, micaceous siltstone, limestone, and dolomite. Calcite cement is common in most of these clastic rocks. The minimum thickness estimated for this unit is about 460 m, but nowhere in the map area is a complete sequence exposed.

Conglomerate is light grayish pink, olive drab, grayish green, and greenish black. Framework-supported and matrix-supported conglomerate is composed of rounded to subangular clasts of granite, gneiss, schist, quartzite, and vein quartz. Pebble conglomerate is most common, but some beds contain cobble-sized clasts. Conglomerate beds are arkose. Although conglomerate beds are prominent in the poorly exposed Minturn, conglomerate and conglomeratic sandstone form only about 20 percent of the unit, based on a measured stratigraphic section (Taranik, 1974, p.63, and Section 4). Conglomerate beds contain prominent trough and planar crossbeds and channeled contacts. Carbonaceous matter occurs in some conglomerate beds.

Sandstone beds in the Minturn are light-grayish-tan, grayish-pink, light-gray, moderate gray, reddish-gray, grayish-red, and grayish-purple, micaceous, coarse-, medium-, and fine-grained arkose. Individual sandstone beds may be lenticular or laterally continuous across an outcrop, and beds are 10 cm to 1 m thick. Sandstone beds form composite sets that are about 12 m thick. Most individual sedimentation units are normally graded, although reverse and central grading occurs in some beds. Primary bedding structures are planar and trough crossbeds, ripple cross-laminations, and shallow channels. Carbonaceous material, which represents plant debris, occurs locally in sandstone beds.

Siltstone and shale are prominently micaceous, and are dark gray, black, olive drab, greenish black, and grayish tan. Siltstone and shale commonly occur in zones 2 cm to 4 m thick. Compositionally, siltstones are arkose, and many siltstone beds have a clay matrix. Shale beds are dominantly argillaceous, but most shale contains silt- and sand-sized grains of quartz, feldspar, and rock fragments as contaminants. Siltstone and shale are laminated and microlaminated, and siltstone contains ripple cross-lamination. Micaceous black shale is a prominent component of the lower part of the Minturn Formation north of Hoosier Pass.

Thin limestone and dolomite beds occur at some places in the Minturn Formation. Carbonate beds in the lower part of the Minturn Formation are poorly exposed in the Breckenridge quadrangle, but limestone and dolomite are exposed in road cuts between Monte Cristo Gulch and McCullough Gulch. Most carbonate beds appear to be laterally discontinuous. Limestone and dolomite are moderate-gray, dark-gray, and grayish-black, fine-grained, micritic beds that range from a few centimeters thick to 3 m thick. Carbonate beds are locally mottled in moderate-gray and dark-gray colors, and these beds are commonly associated with black shale and dark-colored siltstone. Limestone and dolomite are indistinguishable without using dilute HCl. According to Taranik (1974, p 75) fossils in an upper limestone bed, which he correlated with the Robinson Limestone Member as described in detail by Tillman (1971), are stromatoporids, several types of foraminifera (*Komia* sp., *Bradyina* sp., *Tetrataxia* sp., *Fusulina* sp., and *Apterrinella* sp.), phylloid and dasyclad algae, and oncolites that encrusted echnoid spines and gastropod fragments. Primary bedding structures are not obvious in carbonate rocks of the Minturn Formation. Taranik (1974) emphasized that correlation of carbonate members from the type area at Minturn (Tweto and Lovering, 1977) to the Breckenridge quadrangle is fraught with considerable uncertainty because (1) the limestone members change lithofacies vertically and laterally over short distances; (2) the limestone zones are lenticular and disappear into clastic and evaporitic rocks laterally; and (3) carbonate lithofacies are diachronous and limestone beds are time transgressive in the stratigraphic sequence. On the basis of these substantial uncertainties, we did not extend the Robinson and Jacque Mountain Limestone Members into the Breckenridge quadrangle.

MAROON FORMATION

The Maroon Formation (PIPm) probably spans the period from Late Pennsylvanian to Early Permian (Missourian-Virgilian) according to De Voto (1980). In the southeastern part of the Breckenridge quadrangle the Maroon Formation overlies the Minturn Formation on an apparent intertonguing contact according to Taranik (1974). However, in the northeastern quadrant of the map area the Maroon Formation directly overlies Middle Proterozoic rocks. The Maroon Formation is a redbed sequence of calcareous, coarse conglomerate, arkose, micaceous siltstone and shale, and limestone that has been traced southward to the area of Trout Creek, southeast of Buena Vista, Colorado, and is widely exposed in South Park and the central part of the Mosquito Range. The Maroon Formation is about 180 m thick in the northeastern part of the Breckenridge quadrangle at Gibson Hill, where the Maroon may contain a few tens of meters of Chinle Formation at the top. The Maroon Formation thickens greatly to the south in the Breckenridge quadrangle to about 1,200 m thick. The apparent thickness of the Maroon Formation has been inflated about 180 m by intrusion of hornblende-biotite monzonite porphyry (Tmp) sills.

In the Breckenridge quadrangle conglomerate is a common component of the Maroon Formation. Conglomerate is light reddish gray, reddish tan, moderate reddish gray, dark red, and grayish purple. Most conglomerate beds are dispersed-clast, polymict rocks that contain well-rounded to subangular cobbles and pebbles in a matrix of granules and coarse-grained arkose. Channels are common at the base of the conglomerate beds and within conglomerate beds, and some channels cut 1 to 2 m into underlying beds. Commonly channel bases are defined by a zone of cobbles or large pebbles. Large clasts and enclosing matrix are commonly normally graded, although reverse and central grading occur in some conglomerate beds. Equigranular and porphyritic granitic clasts are common, as are biotite schist, biotite and hornblende gneiss, vein quartz, and large feldspar crystals. Feldspar composes as much as 40 percent of coarse-grained arkose. Primary bedding structures are planar and trough crossbeds, ripple cross-laminations, cuspate and linguoid ripple marks, and parting lineations. Secondary bedding structures are deformed cross beds and load-casts. Individual conglomerate beds are generally fining-upward sequences, and conglomerate passes upward into coarse-grained, medium-grained, and fine-grained arkose; ultimately arkose grades into siltstone and shale.

Sandstone beds in the Maroon Formation are light reddish gray, reddish tan, moderate reddish gray, moderate red, grayish red, dark red, and grayish purple. Channeled basal contacts occur most commonly in coarse-grained arkose, although coarse-grained arkose can have basal contacts that appear flat on outcrop scale. Arkose is commonly normally graded. Single crystals of feldspar are granule size, and feldspar can reach about 40 percent of the rock. Planar and trough crossbeds, ripple cross-lamination, ripple marks, and parting lineation are the most common primary bedding structures, and secondary bedding structures are mainly deformed crossbeds and load casts of sand beds into argillaceous siltstone and shale.

Siltstone and shale beds of the Maroon Formation are richly micaceous, and these fine-grained rocks are darker in color than coarse-grained rocks. Dark-reddish-gray, dark-grayish-red, dark-red, moderate-red, and reddish-tan colors predominate in fine-grained rocks. The dark red colors of these fine-grained rocks results from a larger percentage of interstitial clay that is stained with iron oxide. Siltstone is feldspathic and much of the siltstone is classed as arkose. Shale beds are rare in the Maroon Formation, and most of the beds that are not resistant to weathering are argillaceous siltstone and argillaceous fine- and very fine-grained sandstone. Argillaceous siltstone and sandstone beds are calcareous. In these fine-grained rocks primary bedding structures are ripple cross-laminations, cuspate and linguoid ripple marks, rill marks, and flute casts. Secondary sedimentary structures are small load casts and convolute bedding.

Limestone beds in the Maroon Formation are lenticular, and limestone beds consist of calcareous siltstone and shale, and moderate-gray and blackish-gray fossiliferous, fine-grained limestone. Limestone beds consist of (1) nodules of moderate-gray and grayish-red, fine-grained limestone in shale and siltstone; (2) nodular moderate-gray and dark-gray limestone beds; (3) grayish-red and moderate-gray limestone-pebble conglomerate; (4) moderate-gray and dark-gray limestone edgewise conglomerate; (5) moderate-gray and dark-gray oölitic limestone; and (6) gray sandy and silty limestone. Limestone can form from aggregates of laterally adjacent nodules that form beds as thin as 3 to 5 cm thick, or limestone beds can be massive-weathering units as thick as 5 m. Thick limestone beds consist of numerous, thinly bedded, commonly argillaceous limestone sedimentation units. Taranik (1974) described the limestone beds as prominently lenticular, and most could not be traced for more than 600 m. In the Breckenridge quadrangle, a discontinuous limestone, 10 to 50 cm thick, in the Red Mountain area was tentatively correlated by Taranik (1974) with the Jacque Mountain Limestone Member of the Maroon Formation mainly on the basis of stratigraphic position 1,500 ft above the tentatively identified Robinson Limestone Member and on occurrence of poorly preserved oolites and straight cephalopods. Taranik (1974) recognized that the occurrence of oolites and straight cephalopods in a limestone on Red Mountain do not provide unique identification criteria for the Jacque Mountain Limestone Member and that equating a single, lenticular, thin limestone bed of many limestone beds that occur in that area introduces much uncertainty regarding the correlation.

STRATIGRAPHIC NOMENCLATURE AND CORRELATION OF THE MINTURN AND MAROON FORMATIONS

Stratigraphic nomenclature and correlation of Pennsylvanian and Permian rock units that have complex stratigraphic relations in the Central Colorado Trough have been controversial subjects among geologists for the last fifty years (Tweto, 1949; De Voto, 1971, 1972; Tweto and Lovering, 1977; De Voto and Peel, 1972; De Voto, 1980; Taylor and others, 1975; Lindsey and others, 1985). Rapidly subsiding, fault-bounded sedimentary basins commonly have rock units that thicken and thin drastically, show rapid lateral changes of lithofacies, and exhibit strongly diachronous formation contacts. Stratigraphic nomenclature in these Pennsylvanian and Permian rocks in the Central Colorado Trough is confusing because the current system is a mixture of time-stratigraphic units and rock-stratigraphic units; concurrence among geologists regarding formation boundaries and correlation is elusive.

Tweto (1949) defined the stratigraphic and nomenclature relations of the Minturn and Maroon Formations in the upper drainage of the Eagle River near Pando, Colorado; his stratigraphic revisions abandoned many previously used and conflicting names, such as "Weber Grit," "Weber shale," "Weber formation," "Wyoming formation," "McCoy formation," and "Battle Mountain Formation," and replaced those names with Belden Shale, and the Minturn and Maroon Formations. The Belden Shale was used as Brill (1944) defined this unit, Minturn Formation was a new name taken from exposures near the town of Minturn on the Eagle River, and Maroon Formation was redefined in Tweto's (1949) report, the name having been imported from the Maroon Bells area near Aspen, Colorado.

Tweto (1949) proposed the name "Minturn Formation" for the dominant clastic sequence above the Belden Shale as defined by Brill (1944). Tweto (1949) placed the boundary between the Minturn Formation and the Maroon Formation at the top of the Jacque Mountain Limestone in the Vail and Minturn area; the Jacque Mountain Limestone of Tweto (1949) was oölitic and contained scattered large straight and coiled cephalopods and some large gastropods. Tweto's 1949 definition of the Minturn and Maroon Formations placed a local time line in the northern part of the Central Colorado Trough, and the location of the top of the Minturn Formation became a de facto time-stratigraphic boundary. Tweto's time-stratigraphic definition of the Minturn and Maroon Formations met the standards of the stratigraphic code at the time (Ashley and others, 1933). Tweto and Lovering (1977) designated a type section for the Minturn Formation and provided a composite measured section assembled from exposures near Gilman along the Eagle River Valley and in the Game Creek area. The type section of the Minturn retained the Jacque Mountain Limestone as the upper limit of this unit (Tweto and Lovering, 1977).

Subsequent mapping in the Central Colorado Trough has shown that the limestone beds that formed his markers are local units that can be mapped and correlated reliably only in the northern part of the Central Colorado Trough near Vail, Minturn, and Kokomo (De Voto, 1971, 1972; De Voto and Peel, 1972; Tillman, 1971). The Jacque Mountain Limestone, if it exists south of the town of Breckenridge, is 10 to 50 cm thick and lenticular (Taranik, 1974), and south of Hoosier Pass and across South Park, limestone beds cannot be correlated with the marker beds described and mapped by Tweto and Lovering (1977) according to Navas (1966), De Voto (1972, 1980), and Taranik (1974). The Jacque Mountain Limestone, which is the marker between the Minturn and Maroon Formations, can be identified over an area of about 1,900 sq km which leaves no effective marker between the Minturn and Maroon Formations over about 22,700 sq km of the Central Colorado Trough where the Minturn and Maroon Formations have been mapped in South Park in the Antero quadrangle (De Voto, 1971). Moreover, limestone beds in the Minturn exhibit abrupt changes in lithofacies, thickness, and stratigraphic position (Tillman, 1971), so correlation based on lithologic character of limestone in the Minturn and Maroon Formations is uncertain outside the region of the Eagle River, Vail Pass, and the Continental Divide.

The current time-stratigraphic subdivision applied to the Minturn and Maroon Formations by Tweto (1949) and Tweto and Lovering (1977) clearly requires modification to bring nomenclature into conformance with the current North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983). Lithologic criteria define rock units under the current code, so identification of suitable lithologic criteria is needed to separate these units beyond the small area of the Central Colorado Trough to which Tweto's original definition applied. In the past, the hindrance to using lithologic criteria has been the diachronous nature of similar lithologies in the quickly subsiding Central Colorado Trough. Although revision to the stratigraphic nomenclature of the Minturn and Maroon Formations is beyond the scope of this report, two criteria have been proposed to separate these two units where marker limestone beds are absent.

De Voto (1972, p. 161) proposed that name "Minturn" be assigned to the interval of "dominantly gray, green, to tan sandstones, siltstones, conglomerates, shales, and several interbedded limestones which occur stratigraphically above the black shales of the Belden and below an overlying dominantly red bed sequence of Pennsylvanian and Permian age." The definition proposed by De Voto (1972) is principally one of a color difference inasmuch as "both units contain sandstones, siltstones, shales, and several interbedded limestones," but color is regarded as a supplementary feature rather than a distinctive lithic feature of a formation (North American Commission on Stratigraphic Nomenclature, 1983, p. 858). In addition, De Voto's (1972) definition of the Minturn is not applicable to the entire Central Colorado Trough because the Belden Shale is absent between the Kerber and Minturn Formations southeast of Buena Vista, Colorado. Although De Voto's new definition of the Minturn and Maroon Formations solved part of the problem created by using a locally occurring, time-stratigraphic boundary (Tweto, 1949), his definition was not applicable to the entire Central Colorado Trough and the solution did not focus on the distinctive lithic features that characterize each formation.

Taranik (1974, p. 96) suggested that a significant change in grain size occurred at the boundary between the Minturn and Maroon Formations in the Breckenridge area, and this lithologic distinction is compatible with the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983) and lithologic distinctions that were applied two decades later in the central and southern part of the Central Colorado Trough. In the Breckenridge quadrangle, Taranik (1974) showed that the Minturn Formation is a finer grained unit than the Maroon Formation, and he showed that the change in grain size is commonly accompanied by a color change from gray and black colors of the Minturn Formation to red colors of the Maroon Formation. The color change may not be a material feature for regional separation of these two rock units in the Eagle River and Vail Valley areas, because the color change from dark-gray to red rocks is not coincident with the change from pebble conglomerate to cobble-bearing conglomerate at approximately 1,600 m above the base of the measured section of Tweto and Lovering (1977). Taranik (1974) clearly demonstrated that the contact between the Minturn Formation and the Maroon Formation is diachronous where he traced thin, discontinuous limestone beds across the change in grain size.

The difference in grain size between the Minturn Formation and the Maroon Formation might be a regionally consistent difference that is worth evaluating. Taranik's (1974) data show that in the Breckenridge area, conglomerate accounts for about 20 percent of the sequence in the Minturn, and most of that conglomerate is in the lower part of the unit. Similarly, his data show that the Maroon Formation contains about 50 percent conglomerate, and in the Breckenridge quadrangle we have determined that, in general, clasts are larger in diameter in the Maroon Formation than in the underlying Minturn Formation. In the map area the Minturn Formation contains more siltstone and shale than does the overlying Maroon Formation, and the Maroon Formation contains more sandstone and conglomerate than does the Minturn Formation. In South Park, much of the Maroon Formation is reddish-gray shale, siltstone, and sandstone (De Voto, 1971), but the grain-size contrast is still valid because the Minturn Formation contains thick zones of shale and siltstone, some limestone, and lesser amounts of coarse-grained arkose. Coarse-grained arkose beds are rare in the Minturn Formation near Buena Vista, Colorado (Wallace and Keller, 2001), but in adjacent South Park, sandstone and conglomerate are common components of the Maroon Formation (De Voto, 1971).

MESOZOIC ROCKS

The Mesozoic sequence in the region of the Breckenridge quadrangle is represented by the Chinle Formation (Upper Triassic), Entrada Formation (Middle Jurassic), Morrison Formation (Upper Jurassic), Dakota Sandstone (Lower Cretaceous), Benton Shale (Upper Cretaceous), Niobrara Formation (Upper Cretaceous), and Pierre Formation (Upper Cretaceous). Tweto (1974) grouped the Benton Shale, Niobrara Formation, and Pierre Formation, and he grouped the Dakota Sandstone and the Morrison Formation on his reconnaissance geologic map of the Lincoln quadrangle (scale 1:62,500), which includes the Breckenridge quadrangle (scale 1:24,000). Tweto (1974) did not show the Chinle or Entrada Formation on the

Mount Lincoln map. Taranik (1974) included the Chinle Formation with uppermost the Maroon Formation, and he mapped the Garo Formation where we show the Entrada Formation. In the northeastern part of the map area, the stratigraphic interval that should represent the Chinle Formation is covered with slope wash or residuum, so in the area of Gibson Hill we add the Chinle Formation to the uppermost part of the Maroon Formation. In exposures east of Rocky Point where the Entrada and Morrison Formations overlie the Maroon Formation, the Chinle Formation appears to be absent. Taranik (1974) showed Cretaceous rocks as one undifferentiated unit, but we subdivided Cretaceous rock units. The thickness of the Mesozoic sequence is about 865 m.

CHINLE FORMATION

The Chinle Formation (ŦPcm), of Late Triassic age, is problematic in the map area because it is not exposed at the surface, but the Chinle Formation is exposed north of the Breckenridge quadrangle in the southern part of the Frisco quadrangle (Kellogg and others, 2002). Most authors have grouped the Chinle Formation with the Maroon Formation as a single map unit because exposures are generally poor and both are redbed sequences (Taranik, 1974, Kellogg and others, 2002).

Where the Chinle Formation is exposed at the surface in the Frisco quadrangle it is a bright grayish-orange and reddish-orange, calcareous shale, siltstone, and fine-grained sandstone. The Chinle Formation apparently thickens to the north; at Dillon dam in the adjacent Frisco quadrangle, the Chinle is about 61 m thick (Kellogg and others, 2002). Coarse-grained beds, such as medium- to coarse-grained arkose, and pebbly sandstone that is common in finer grained sections of the Maroon Formation are absent in the Chinle Formation. The Chinle Formation is combined with the uppermost Maroon Formation in the vicinity of Gibson Hill, but exposures are poor and this identification is not certain. About 1 mi east of Rocky Point, which is north of Indiana Creek, the Entrada Formation overlies a thin sequence of Maroon Formation and the intervening Chinle Formation appears to be absent. Again, exposures are poor in this area, but the distinctive reddish-orange soil color, and reddish-orange chips of siltstone and fine-grained sandstone are absent below the Entrada, which suggests that the Chinle Formation is absent. The Chinle Formation is not present south of Indiana Creek in the Breckenridge quadrangle.

ENTRADA SANDSTONE

The Entrada Sandstone (Je) is Middle Jurassic in age, and it is composed of light-gray to pale-yellowish-gray, well-sorted, fine- to medium-grained, crossbedded, calcite- and dolomite-cemented orthoquartzite. Sand grains are frosted and most are subrounded to rounded. Small, brown spots are common in this sandstone and they probably result from weathering of iron-rich carbonate cement. The Entrada Sandstone ranges between 5 and 11m in the Breckenridge quadrangle.

Assignment of this sandstone to the Entrada Sandstone is controversial. De Voto (1965) indicated that the sandstone intertongued with red shale inferred to be in the upper part of the Maroon Formation in South Park, and he concluded that the sandstone was correlative with the Garo Sandstone of Permian age. Taranik (1974) followed De Voto’s (1965) correlation and showed the Garo Sandstone on his map. Brennan (1969), working in the northern Vail area, identified a sandstone as Entrada Sandstone that unconformably overlies the Chinle Formation (Upper Triassic) and underlies the Morrison Formation (Upper Jurassic). The sandstone is 12 to 30 m thick and is prominently crossbedded. Kellogg and others (2002) mapped the Entrada Sandstone between the Chinle Formation and the Morrison Formation in the Frisco quadrangle that adjoins the Breckenridge quadrangle on the north. Where the Chinle Formation is identified in the Frisco quadrangle, assignment of the sandstone to the Entrada is unequivocal, and we follow the assignment of Kellogg and others (2002) in this map area.

MORRISON FORMATION

The Morrison Formation (Jm) is Upper Jurassic in age and is mostly light-gray and light-greenish-gray, locally calcareous claystone and siltstone. In the lower half of this unit, light-grayish-yellow and light-grayish-white, medium-grained sandstone beds are interbedded with claystone and siltstone, and the sandstone beds may be as thick as 5 m. Sandstone beds contain iron-rich bands parallel to joint surfaces and limonitic spots are common. A prominent moderate-gray limestone and dolomitic limestone bed occurs about 10 m above the base of the Morrison Formation. This limestone bed is micritic and is mottled in light- and dark-gray colors. Limestone is nodular, and bedding is poorly defined. Regionally, the Morrison Formation is about 55 to 79 m thick in the Blue River Valley north of Silverthorne, Colorado (Holt, 1961), and at Dillon Dam this unit is about 70 m thick (Wahlstrom and Hornback, 1962). In the map area, the thickness of the Morrison Formation is estimated to be about 65 m, but the basal contact of the Morrison Formation is intruded by porphyry sills and the base is not exposed.

DAKOTA SANDSTONE

The Dakota Sandstone (Kd), of Early Cretaceous age, consists of three informal members: an upper sandstone unit, a middle shale zone, and a lower sandstone unit (Ransome, 1911; Lovering, 1934). In the Breckenridge quadrangle the sandstone beds are completely lithified by silica cement, and commonly sandstone beds are metamorphosed by porphyry sills and dikes which led some authors to refer to sandstone beds as quartzite (Singewald, 1951).

The Dakota Sandstone is 52 to 69 m thick in the Breckenridge quadrangle (Lovering, 1934), and the best exposure of this unit is at Rocky Point, in the central part of the map area, where Lovering (1934) and Taranik (1974) measured sections. Taranik (1974) measured the upper sandstone at 10 m thick. Lovering measured the middle shale as 18 m thick; but an estimate of the thickness of the middle member based on Taranik's data is 33 m. The lower quartzite member is 12 m thick. To the north of this map area in the Frisco quadrangle (Kellogg and others, 2002) indicates that the upper sandstone unit is 6 to 20 m thick, the middle shale unit is 6 to 28 m thick, and the lower sandstone is 20 to 26 m thick. South of the map area at Boreas Pass the Dakota Sandstone is 62 m thick (Taranik, 1974).

The upper sandstone unit is composed of light-gray and yellowish-gray, fine- to medium-grained, feldspathic, silica-cemented sandstone. Thin, black shale interbeds occur at the top of fining-upward sand, silt, and shale sequences. Black shale interbeds are commonly carbonaceous. At the base of the upper unit is a massive-weathering, silica-cemented sandstone bed. Primary bedding structures are mainly ripple marks and trough and planar crossbeds. Worm tubes and casts of leaves and branches are common on some bedding surfaces.

The middle shale member is composed of interbedded moderate-gray to black, locally carbonaceous, micaceous shale, moderate-gray, black, light-gray, and tan-weathering micaceous siltstone, and gray to light-gray, fine- and medium-grained, silica-cemented sandstone. Ripple mark and planar lamination are common sedimentary structures, and carbonaceous material occurs in some shale beds.

The lower quartzite member of the Dakota Sandstone is composed of resistant-weathering, moderate-gray to light-gray, fine- to medium-grained quartzite that contains interbeds of thinly bedded, dark-gray shale and siltstone. Shale and siltstone are micaceous. Chert-pebble conglomerate, which is common in the lower member of the Dakota Sandstone elsewhere, is not present in the Breckenridge quadrangle. Crossbed sets are as thick as 30 cm, and trough and planar sets occur in the lower quartzite member.

The upper and lower quartzite units in the Dakota Sandstone are severely fractured in the northeastern part of the map area, and the quartzite beds of this unit are preferred zones for sulfide occurrences. Commonly, fractures and joints are coated with iron-oxide minerals. Quartzite beds in the Dakota Sandstone are lenticular and abrupt lateral facies change characterizes these members.

BENTON SHALE

The Benton Shale (Kb) is of Late Cretaceous age, and it consists of interbedded dark-gray to black shale, rusty-weathering siltstone, and dark-gray limestone. The Benton Shale occurs mainly in the northeastern part of the Breckenridge quadrangle where this unit is 95 to 110 m thick. This unit is generally poorly exposed, except at Rocky Point where the upper part of the unit is exposed in a faulted sequence.

The name "Benton Shale" is applied by Kellogg and others (2002) in the Frisco quadrangle to the black-shale dominated sequence that occurs between the Dakota Sandstone and limestone beds of the Niobrara Formation. Kellogg and others (2002) retained the term Benton Shale in the Frisco quadrangle because of historical use, even though parts of the Benton Shale can be correlated regionally with other units.

The Benton Shale consists of moderate-gray, dark-gray, and black, laminated and microlaminated shale that is locally wavy-bedded, and interbedded light-gray, tan-weathering siltstone. Limestone beds occur at the top of the Benton Shale, and thin, gray, quartzitic sandstone beds occur at the base of the unit. The uppermost limestone beds consist of 1.5 m of thin-bedded, black and dark-gray, fetid, resistant-weathering finely crystalline limestone that exhibits pinch-and-swell structures and contain interbeds of dark-gray, siliceous siltstone. Kellogg and others (2002) correlated this uppermost limestone zone with the Juana Lopez Member of the Carlile Shale of Berman and others (1980). Below the uppermost limestone is 5 m of dark-gray, fetid limestone and dark-brown and moderate-gray, calcareous, rusty-weathering siltstone and shale above 3 m of resistant-weathering, brownish-gray, fine-grained, rusty colored arkose. This arkose is bioturbated at the base, and it contains chert pebbles locally. Kellogg and others (2002) correlated this sequence of limestone, siltstone, shale, and arkose with the Codell Sandstone Member of the Carlile Shale of Berman and others (1980). The lower 25 m of the Benton Shale, equivalent to the Mowry Shale in Wyoming (oral commun. from W.A. Cobban, 1998, cited in Kellogg and others (2002), consists of wavy-bedded black shale that contains fish-scales; the lower 3 m consists of thinly bedded, fine-grained, gray quartzite. The Benton Shale appears to be conformable above the Dakota Sandstone in the map area.

NIOBRARA FORMATION

The Niobrara Formation (Kn) is Late Cretaceous in age, and it consists mainly of shale and shaly limestone. Regionally the Niobrara Formation consists of the Smoky Hill Shale Member at the top and the Fort Hays Limestone Member at the base, but these units were not separated in the map area. In the Frisco quadrangle, to the north of this map area, the thickness of the Niobrara Formation is 148 m. In the map area, the Niobrara Formation is estimated to be about 150 m thick.

The Smoky Hill Shale Member consists of moderate-gray and light-gray, calcareous shale and interbedded shaly limestone. Limestone is fine grained and fetid and becomes more shaly upward. The limestone is platy weathering and has a characteristic very pale-gray patina. In the Frisco quadrangle to the north, this member is 138 m thick. The Fort Hays Limestone Member is composed of blocky weathering, moderate-gray and light-gray, micritic limestone that is resistant to weathering. Limestone beds are 5 to 15 cm thick, and limestone weathers light gray. Inoceramid bivalves (rudistid oysters) occur in some limestone beds. The Fort Hays Limestone Member is 6 to 10 m thick in the map area, and this member appears to be conformable above the Benton Shale.

PIERRE SHALE

The Pierre Shale (Kp) is Late Cretaceous in age, and this unit consists mainly of black and grayish-brown shale and brownish-gray sandstone. In the Frisco quadrangle to the north, the Pierre Shale is subdivided into three informal members (Kellogg and others, 2002), with a combined thickness of about 1,000 m. Only the lowest member occurs in the Breckenridge quadrangle. The lower shale member is about 400 m thick in the map area, and the top is not exposed.

The lower shale member consists of dark-gray, brownish-gray, and black shale and mudstone. The base of this member is calcareous, and calcite veins are common within about 10 m of the Niobrara contact. Weathered outcrops show bedding fissility. In the Breckenridge quadrangle the lower contact of the Pierre Shale is apparently conformable with the underlying Niobrara Formation.

CENOZOIC ROCKS AND DEPOSITS

Cenozoic rock units are represented by Tertiary intrusives including sills, dikes, and stocks that intrude Paleozoic and Mesozoic sedimentary rocks in the eastern part of the quadrangle, and intrude Proterozoic basement rocks in the western part of the quadrangle. These intrusives are middle to late Eocene in age. Cenozoic surficial deposits are mainly Quaternary units that form residual and alluvial deposits east of the Blue

River, and glacial deposits in the Blue River Valley and in the Tenmile Range. Gold-dredge tailings left over from the early 1900s cover large portions of the Blue River and French Gulch valley floors in the northeast part of the quadrangle in and near the town of Breckenridge.

TERTIARY INTRUSIVE ROCKS

Six types of Tertiary intrusive rocks were identified in the Breckenridge quadrangle. Intrusive bodies occur as dikes, sills, stocks, plugs, and laccoliths. They are mostly intermediate calc-alkalic in composition, predominantly quartz monzonite. Sills and a possible laccolith are most common in the eastern half of the quadrangle where they intrude Pennsylvanian through Cretaceous sedimentary rocks. In the Tenmile Range of the western half of the quadrangle, where Proterozoic rocks predominate, Tertiary intrusives mainly form dikes and small stocks or plugs. In the Breckenridge mining district in the northeastern part of the quadrangle, Ransome (1911) thoroughly described the petrography of three igneous rock types — two varieties of quartz monzonite porphyry (our Tqp and Tqpm) and hornblende-biotite monzonite porphyry (our Tmp) — and concluded that they all were emplaced close together in time. Lovering (1934) also described the intrusives and reached the same conclusion.

The map area contains three additional Tertiary intrusive types not described by Lovering or Ransome because these intrusives are present only outside the main mining district. A quartz monzonite stock (Tqm) with phaneritic texture mapped as the Humbug stock by Tweto (1974) and described by Bergendahl (1963) intrudes the Proterozoic basement rocks in the Tenmile Range around Peak 9. Quartz monzonite intrusion breccia (Tqmb) related to the Humbug stock is present in a few places. A very light-colored, very fine-grained quartz latite (Tql) unit occurs as sparse, narrow dikes cutting the Proterozoic basement in the Quandary Peak area. Singewald (1951) also noted this unit in his study of the Upper Blue River area.

HORNBLENDE-BIOTITE MONZONITE PORPHYRY

The hornblende-biotite monzonite porphyry (Tmp), of Eocene age, was described and referred to as monzonite porphyry by Ransome (1911) and Lovering (1934). This porphyry is distinguishable from other intrusives in the area by its lack of quartz phenocrysts and darker color. This rock unit is medium to dark gray to greenish gray, with 5 percent plagioclase phenocrysts 1 to 3 mm long, 5 percent orthoclase phenocrysts 1 to 3 mm long, 3 percent hornblende as subhedral blades 1 to 6 mm long, and 3 percent biotite as pseudo-hexagonal phenocrysts 1 to 2 mm wide in an aphanitic groundmass. The hornblende and biotite are often altered to chlorite (penninite), epidote, quartz, and calcite to varying degrees. Feldspar is commonly altered to varying degrees to calcite, sericite, and epidote. The groundmass consists of abundant orthoclase and plagioclase, and minor quartz, biotite, augite, hypersthene, hornblende, magnetite, apatite, allanite, and zircon (Lovering, 1934).

The hornblende-biotite monzonite porphyry occurs mainly as thin dikes and sills and as a large intrusive mass (laccolith?) in the northeastern corner of the quadrangle. The monzonite porphyry is intruded by, and thus is older than, megacrystic quartz-monzonite porphyry (Tqpm), although both phases are considered close in age (Ransome, 1911; Lovering, 1934).

QUARTZ MONZONITE OF THE HUMBUG STOCK

The Humbug stock, of middle Eocene age, is a quartz monzonite (Tqm) and quartz monzonite intrusion breccia (Tqmb) that is 8.7 sq km in area centered around Peak 9 in the west-central map area. Several smaller plugs occur adjacent to the main Humbug stock. Another small stock of fine- to medium-grained quartz monzonite in Monte Cristo Gulch was shown as “Silver Plume” granite of Precambrian-age by Singewald (1951), but this stock is petrographicallly more similar to the quartz monzonite of the Humbug stock than to Proterozoic “Silver Plume” quartz monzonite. A definitive isotopic age is lacking for the quartz monzonite in Monte Cristo Gulch, but field relations suggest that it is Tertiary in age. We have tentatively correlated it with quartz monzonite of the Humbug stock.

Rocks of the Humbug stock are very light gray, sparsely mottled with black mafic minerals, mostly medium to course grained, and phaneritic. They have an hypidiomorphic-granular crystalline texture. Bergendahl (1963) examined thin sections of quartz monzonite from the Humbug stock and found the principle minerals to be quartz, oligoclase-andesine, and microcline microperthite. Biotite, hornblende, and magnetite form less than ten percent of the rock, although biotite commonly gives the rock a black-mottled appearance. Apatite and sphene are common accessory minerals. Phenocrysts of euhedral plagioclase and potassium feldspar are commonly present, but these minerals are not always conspicuous due to the overall phaneritic texture of the rock. The rock is sometimes weathered to a light-tan-orange color from oxidation of small amounts of disseminated and fracture-fill pyrite. On the northeast margin of the Humbug stock, small exposures of Lower Paleozoic sedimentary rocks (xenoliths?) display strong contact metamorphism. Quartzitic sandstone has been recrystallized to quartzite, and dolomite is now whitish-gray, coarse-grained marble.

The Humbug stock was previously mapped by Tweto (1974) as Tertiary-Cretaceous in age. Bergendahl (1963) showed a younger dike of quartz monzonite porphyry (Tqpm in this study) that intruded the Humbug stock. A new $^{40}Ar/^{39}Ar$ age of 42.05 ± 0.23 Ma on biotite was made from sample K01-059 collected from the Humbug stock on the south flank of Peak 9 during this mapping project [analysis by Richard Esser, New Mexico Geochronological Research Laboratory, Socorro]. This analysis indicates that the quartz monzonite is middle Eocene in age. Four potassium-argon dates reported by Marvin and others (1974) for biotite in the Humbug stock yielded an average age of 40.1 Ma.

Intrusion contact breccia (Tqmb) was mapped in two areas along faulted contacts between quartz monzonite and Proterozoic rocks. The intrusion breccia consists of angular to sub-angular clasts of country rock (mostly migmatite) up to 60 cm in diameter in a matrix of fine- to medium-grained quartz monzonite. The matrix material is finer grained than the typical quartz monzonite and indicates more rapid cooling than the main body of the Humbug stock. This breccia occurs only on, or adjacent to, northwest-trending faults, which suggests that intrusion was contemporaneous with tectonic movement. The breccia does not occur along igneous contacts away from faults. Slickensided fault surfaces that cut through the breccia clasts and matrix at one exposure on Peak 8 also show that post-intrusive movement has occurred on northwest-trending faults in the quadrangle. Clasts of Cambrian-age Sawatch Quartzite were enclosed in the breccia in Monte Cristo Gulch. The Sawatch is exposed only a short distance to the north of the breccia, and prior to erosion the Sawatch was only a short distance vertically above the breccia exposure.

Biotite-Hornblende Quartz Monzonite Porphyry

Two varieties of buff- or light-brown-weathering, porphyritic quartz-plagioclase-orthoclase-biotite-hornblende quartz monzonite porphyry (Tqp and Tqpm), of probable Eocene age, are widely distributed in the map area. Distinction between the two varieties is based on the presence of large phenocrysts (megacrysts) of orthoclase, quartz, and plagioclase in Tqpm, or the lack of such megacrysts in Tqp. Compositionally, the two varieties of quartz monzonite appear identical, although field relations suggest that megacrystic quartz monzonite (Tqpm) crosscuts quartz monzonite porphyry without megacrysts (Tqp). Quartz monzonite porphyry without megacrysts is present in the Rocky Point area as well as in numerous dikes and less common sills in the Tenmile Range; at most places east of the Blue River the quartz monzonite porphyry is the megacryst-bearing variety, and it forms mainly sills and possibly laccoliths. Lovering (1934) referred to the quartz monzonite variety that lacks megacrysts as "quartz monzonite porphyry (intermediate type)." Both authors referred to the megacryst-bearing unit as "quartz monzonite porphyry." Singewald (1951) referred to the megacryst-bearing variety as "Lincoln Porphyry," and correlated these rocks with Lincoln Porphyry in the Leadville area. However, the Lincoln Porphyry in Leadville is considerably older than the quartz monzonite porphyry in the Breckenridge area (Pearson and others, 1962; Marvin and others, 1989).

In the megacrystic variety of quartz monzonite porphyry, prominent orthoclase phenocrysts comprise as much as 20 percent of the rock, and quartz phenocrysts (commonly partly resorbed and embayed) comprise 2 to 10 percent of the rock. Megacrysts are typically 1 to 4 cm in length; Lovering (1934) reported orthoclase phenocrysts as long as 8 cm. Euhedral biotite forms 1 to 3 percent of the rock and is usually much more abundant than hornblende. Grayish-white, chalky plagioclase phenocrysts are also common and can be up to 1 cm in length. Typical phenocryst size exclusive of the megacrysts is 1 to 5 mm. The groundmass is fine grained (less than 0.5 mm). Similar quartz monzonite porphyry from a large intrusive mass in the Frisco quadrangle to the north of Breckenridge yielded a potassium-argon date from biotite of 44.1 (1.6 Ma (Marvin and others, 1989) and a rubidium-strontium whole-rock age of 44 Ma (Simmons and Hedge, 1978).

Quartz monzonite porphyry without megacrysts contains 10 to 30 percent phenocrysts of feldspar, quartz, and biotite in a fine-grained matrix. Phenocrysts of feldspar (mostly plagioclase, less orthoclase) comprise 10 to 25 percent of the rock, are usually chalky and altered, and are 1 to 6 mm in length. Quartz phenocrysts comprise 2 to 8 percent of the rock, are often rounded and partially resorbed, and can be as large as 8 mm in diameter. Biotite phenocrysts up to 3 mm in length are commonly altered to chlorite (penninite) and comprise 2 to 10 percent of the rock. Hornblende is rare or absent in most samples. At most places the rock is partially altered. Where alteration is most intense, it is difficult to distinguish the phenocrysts from the groundmass without the aid of a petrographic microscope. On freshly broken surfaces, the fine-grained groundmass is often a medium to dark bluish- to greenish-gray color from alteration of mafic minerals to chlorite. The feldspar phenocrysts are commonly partly altered to sericite or clays and minor carbonate.

Quartz Latite

Intrusives of quartz latite (Tql), locally as felsic as rhyolite, were mapped only as a few narrow, north-south-trending dikes in the Tenmile Range on and near Quandary Peak. Quartz latite is the youngest and least common of the Tertiary igneous rocks in the quadrangle and is late-Eocene in age. Singewald (1951) correlated this unit to rocks he had previously mapped in 1941 as "later white porphyry" in the vicinity of the Lincoln Amphitheater and Wheeler Lake about 1 mi south of the Breckenridge quadrangle. He showed that this unit was younger than intrusive units he labeled "gray porphyry group", which are the quartz monzonite and monzonite porphyries of the present study. Quartz latite dikes with a similar description (Mach and Thompson, 1998) on Tucker Mountain, which is two miles west of the Breckenridge quadrangle, yielded a fission track date from zircon of 38.3 Ma (Naeser, C.W., in written commun. referenced in Mach and Thompson, 1998).

The quartz latite is very light gray or tan to nearly white, very fine grained, and contains small phenocrysts (1 to 2 mm) of quartz, plagioclase, and potassic feldspar (sanidine?). Sparse biotite phenocrysts are usually altered to fine-grained muscovite, chlorite, and iron oxide. The small, equant phenocrysts comprise 5 to 20 percent of the rock. Quartz phenocrysts are rounded and partially resorbed. The groundmass is dense and locally porcelain-like. K-feldspar stain on thin sections shows that potassic feldspar is a large component of the groundmass, except where sericitic alteration has destroyed most feldspar, including phenocrysts. Intrusives of this type are easily distinguishable in the field because of their light color and dense, fine-grained groundmass.

QUATERNARY DEPOSITS

Quaternary units are mainly glacial tills and their associated outwash terraces, preglacial terrace deposits, landslides, and a suite of periglacial deposits above treeline in the Tenmile Range. In general, the oldest Quaternary geomorphic surfaces, and corresponding deposits, are found at the highest elevations above the modern valley floor. Landslide deposits are found throughout the quadrangle, at all elevations, and range from small slumps in Quaternary deposits to large, quasi-intact masses of bedrock that slid off walls of the glacial valleys. Alluvial deposits are present in most large drainages, and colluvium mantles many of the hillslopes below treeline. Age estimates for most Quaternary deposits are based mainly on correlation of the youngest, massive moraines with the Pinedale glacial advance in the Rocky Mountains (dated at 16–23 ka), and correlation of adjacent subdued moraines to the Bull

Lake glacial advance (dated at 130-150 ka). This correlation is based on the similarity of moraine morphology, weathering characteristics, surface-boulder frequency, and amount of stream dissection, compared to Pinedale and Bull Lake type deposits (Chadwick and others, 1997).

Glacial and Periglacial Deposits

The oldest glacial deposits (Qto) exist on the piedmont west of Breckenridge, on which the ski area is developed. This map unit probably includes both Bull Lake and pre-Bull Lake till deposits that cannot be subdivided. The unit was also mapped at high levels on a ridge between Spruce Creek and McCullough Gulch. This high-level deposit is highly eroded and is possibly non-glacial in origin. Directly north of downtown Breckenridge, the westernmost part of older (pre-Bull Lake) gravels (Qgo) contains boulders up to 2 m in diameter in a poorly sorted matrix. This part of the older gravel deposit may be till rather than alluvium, and the original morainal morphology may simply have been flattened by erosion.

Moraines of the Bull Lake glaciation (Qtb), which range in age from 130 ka to 150 ka, occur directly downstream of, or adjacent to but upslope of, Pinedale moraines in the Blue River, Sawmill Gulch, Cucumber Creek, South Barton Creek, Indiana Creek, and Pennsylvania Creek. The Bull Lake terminal moraine of the Blue River glacier was severely eroded by later Pinedale outwash and now exists as two disconnected ridges. The eastern ridge is in the southernmost part of downtown Breckenridge between lower Illinois Gulch and Edwin G. Carter Memorial Park; the ridge is separated from the Pinedale terminal moraine by the alluviated valley of Illinois Gulch. Illinois Gulch was not glaciated in the Pleistocene but adopted an ice-marginal position during the Pinedale glaciation. The western Bull Lake moraine ridge forms the interfluve between the Blue River and Lehman Gulch (Warrior's Mark area). The proximity of Bull Lake and Pinedale terminal moraines suggests that the Bull Lake glaciers were only slightly more extensive than the Pinedale glaciers, which is typical in the Rocky Mountains (Porter and others, 1983).

Pinedale moraines cover the largest area of all Quaternary deposits in the quadrangle, covering the floor and sides of the Blue River Valley from Breckenridge to the southern map boundary, a linear distance of about 10 km. Pinedale moraines also cover much of the piedmont northwest of Breckenridge and the lower parts of deep glacial valleys in the Tenmile Range. The Blue River glacier at its maximum Pinedale extent was 18 km long (measured from the head of the Monte Cristo valley) and up to 250 m thick. The glacier advanced to within 0.5 km of downtown Breckenridge at the maximum Pinedale advance at about 23 ka, and the glacier deposited a massive terminal moraine (Qtp_1). This Blue River glacier was fed by four large tributary glaciers in the Tenmile Range - the Monte Cristo Creek, McCullough Gulch, Spruce Creek, and Crystal Creek glaciers, as well as by a small amount of ice that spilled over Hoosier Pass, directly south of the quadrangle, from the Platte River glacier. Although the tributary glaciers in the southern three drainages merged with main Blue River ice in the normal fashion, the Crystal Creek glacier was forced to turn abruptly north by the combined Blue River and Spruce Creek ice mass, and ice spilled out of Crystal Creek valley onto the interfluve between Crystal Creek and Carter Gulch. At that location the ice mass merged with a smaller glacier flowing down Carter Gulch, and together they built a terminal moraine just south of the confluence of Carter and Lehman Gulches. This moraine complex is separated from the Blue River terminal complex by a ridge composed of Bull Lake till (Qtb). A separate, 4.5 km-long glacier in Sawmill Gulch terminated in the Blue River valley about 1 km west of the terminus of the Blue River glacier, where it built a moraine complex that contains Old Town Lake and the Breckenridge Outdoor Education Center.

Pinedale glaciers east of the Blue River, in Pennsylvania and Indiana Creeks, did not advance far enough to merge with the Blue River glacier. The Pinedale terminal moraine of the Pennsylvania Creek glacier (Qtp) nearly merges with a bulging lateral moraine of the Blue River glacier that pushed eastward into the mouth of Pennsylvania Creek. The Pinedale moraine of the Indiana Creek glacier occurs 2 km upstream from the eastern Pinedale lateral moraine of the Blue River glacier, which blocked Indiana Creek and formed a short-lived ice-marginal lake. Early Pinedale moraines are composed of bouldery till deposits, with subround to round boulders up to 4 m in diameter embedded in a massive, unstratified matrix of sand, silt, and clay.

After the early Pinedale ice advance, glaciers retreated and then readvanced, forming a younger belt of moraines (Qtp_2) that can be differentiated in terminal moraine complexes of the Blue River glacier, the Crystal Creek and Carter Gulch glaciers, and the Sawmill Gulch glacier. In the smaller glacial deposits of Indiana Gulch, Pennsylvania Creek, Lehman Gulch, Cucumber Gulch, Cucumber Creek, and South Barton Gulch, moraines of early Pinedale age cannot be distinguished. The last major Pinedale readvance, which occurred at about 16 ka, is represented by the younger Pinedale till (Qtp_3). In the Blue River valley, glacial ice retreated south of Goose Pasture Tarn, forming a lake behind the Qtp_1 or Qtp_2 moraine, but then ice readvanced over the lake bed, plowing up silt and sand to form the boulder-poor moraine that presently impounds the tarn (Qtp_3). In the Crystal Creek valley, younger Pinedale ice spread as a thin body onto the Crystal Creek and Carter Gulch interfluve and then stagnated, creating an extremely complex topography of small ridges, hummocks, and closed depressions. Young Pinedale till is also mapped in Cucumber Creek and South Barton Creek.

The youngest till in the quadrangle (Qtn) forms very stony, unvegetated moraines in the cirques of McCullough Gulch, Spruce Creek, and Crystal Creek. These sharp-crested, steep moraines occur within 0.5 km of cirque headwalls, and the moraines are assigned to the early Neoglacial stade of the Holocene, at about 3 to 5 ka.

Lacustrine deposits (Ql) of sand, silt, and clay were mainly deposited during and shortly after the Pinedale glaciation, when moraines dammed the Blue River and its tributaries to create temporary lakes. The largest area of lacustrine deposits underlies Goose Pasture Tarn and the Goose Pasture in the Blue River Valley, where a lake was dammed by the younger Pinedale terminal moraine (Qtp_3). Another small lake existed at the mouth of Indiana Creek, where the eastern Pinedale lateral moraine of the Blue River glacier blocked the drainage.

The glaciated valleys of the Tenmile Range are rimmed with a variety of periglacial and mass-movement deposits, including rock glaciers, protalus ramparts, talus cones, colluvium, and several ages of landslides. The typical pattern is for active and inactive talus (Qta and Qti), respectively, to cover the oversteepened valley sideslopes below the Pinedale glacial trimline. If these talus deposits clearly emanate from a single gully, are distinctly cone-shaped, and contain an axial channel flanked by debris-flow levees, they were mapped as talus fan deposits (Qtf). At most locations where talus deposits are shaded by high valley or cirque walls, the talus has been transformed into active or inactive rock glaciers (Qra or Qr). The most common rock glaciers, such as occur against the southern valley walls of upper Spruce and Crystal Creeks, are lobate rock glaciers composed of talus boulders and interstitial ice. In contrast, the tongue-shaped rock glaciers occupying the cirques of McCullough Gulch, Spruce Creek, and Crystal Creek were probably formed when talus buried wasting Neoglacial cirque glaciers, so they probably contain a solid ice core beneath a veneer of rubble. Other periglacial deposits include solifluction deposits (Qs) that are commonly above treeline; these are defined by stone stripes and terraces that show the surficial frost-shattered rubble is (or was) moving downslope. In contrast, where bedrock is covered by a thin veneer of frost-shattered rubble (felsenmeer) that shows no signs of downslope movement, the area is mapped as the underlying bedrock.

Landslide Deposits

Landslide deposits are widespread above and below treeline and have been subdivided by age but not by type. Most larger landslides (Qls) are rotational slumps derived from bedrock and range in size from the 1 km-diameter slump on the eastern flank of Peak 8 to slumps less than 50 m wide (about the limit of mapping at this scale). The deposits are composed of angular rock rubble from sand to boulder size embedded in a finer matrix of crushed rock material. The larger bedrock slumps consistently occur near treeline on the eastern end of the major ridges of the Tenmile Range. Each landslide has created an east-facing amphitheater that contains landslides of mid-late Holocene age (Qlsy), early Holocene to latest Pleistocene age (Qlsi), or pre-Pinedale age (Qlso). The two former deposits are composed of rock rubble, whereas the latter is generally large blocks of quasi-intact bedrock that slid off the headscarp and were subsequently overrun and smoothed by Pinedale-age cirque ice. Thus, it appears that the landslide amphitheaters on the north side of McCullough Gulch and at the heads of Carter Gulch, Sawmill Gulch, and Cucumber Creek were formed by pre-Pinedale slumping and were later occupied by Pinedale cirque ice.

Landslides derived from Quaternary deposits are typically smaller than the bedrock slumps and are most commonly derived from till on steep valley sidewalls. The largest such slides occur on the west valley wall of the Blue River between McCullough Gulch and Spruce Creek. Only a single historic landslide deposit (Qlsh) was mapped in the quadrangle. This 30 m-wide by 100 m-long slump in Pinedale till formed shortly before 1999 and buried Aqueduct Road near the southern boundary of the map area. However, that slide is only the latest manifestation of slumping that has continued since Pinedale deglaciation.

Colluvial and Alluvial Deposits

Colluvial deposits and mixed alluvial-colluvial deposits are common in the nonglaciated northeastern part of the quadrangle. Colluvial deposits (Qc of Holocene age and Qco of Pleistocene age) are composed mainly of silt and sand and are typically mapped at the foot of hillslopes and in broad swales that may extend nearly to hilltops. Mixed alluvial-colluvial deposits (Qac of Holocene age and Qaco of Pleistocene age) are also sandy but are better sorted and stratified than colluvium and occur in deeper swales or on piedmont erosion surfaces (such as the southern Breckenridge ski area) that occasionally carry running water.

Because glacial deposits are so widespread in this quadrangle, alluvial deposits are somewhat underrepresented. The largest areas of alluvial deposits are the aggraded valleys of French Gulch and the Blue River north of its terminal moraine. The Blue River Valley downstream from the terminal moraines is dominated by five fluvial terraces, the younger three of which (Qob, Qop_1, Qop_2) can be traced directly back to the terminal moraines. For example, downtown Breckenridge is built mainly on the proximal outwash terraces derived from the Pinedale and Bull Lake terminal moraines. East of Ridge Street, downtown Breckenridge is on the Bull Lake outwash terrace (Qob), which lies 12 to 14 m above the modern Blue River. Between Ridge Street and Main Street, the city is built on the narrow older Pinedale outwash terrace (Qop_1), which is 5 m above stream level, whereas west of Main Street and west of the Blue River the developed parts of downtown are on a younger Pinedale outwash terrace (Qop_2), which is 2 to 3 m above stream level. This latter terrace was severely disturbed by placer mining. Holocene alluvium (Qal) is mapped along the courses of most tributary valleys, as well as in the Blue River valley south of the Goose Pasture.

The two older fluvial terraces of the Blue River cannot be traced to moraines, so their age is estimated based on height above modern streams and on degree of clast weathering and soil-profile development. The younger of these terrace deposits (Qgo) is 36 m above the modern Blue River and forms the interfluve between the Blue River and French Gulch (Weisshorn subdivision); a correlative terrace lies north of French Gulch (Highlands subdivision). This terrace is nearly three times as high above the Blue River as is the Bull Lake outwash terrace (36 m versus 12 to 14 m), but its weathering is not significantly greater than that of Bull Lake deposits. Thus, we assign a middle-to-lower Pleistocene age to this deposit.

The oldest terrace deposits (QTgg) underlie an extensive surface that is best preserved west of the Blue River. The top surface of these terrace deposits is 115 m above stream level at the northern map boundary but slowly converges to a height of only 60 m above stream level in southern Breckenridge. Thus, the top of this deposit forms a nearly horizontal surface, in strong contrast to all younger terraces, which slope northward at 15 m/km. This terrace deposit includes two facies, an older Blue River alluvium and a younger (or coeval) alluvium and colluvium from tributaries. Blue River alluvium is well stratified sand and round-subround cobble gravels derived from Proterozoic crystalline rocks. The alluvium underlies terraces west of Blue River between Sawmill Gulch and the northern map boundary. Tributary alluvium and colluvium underlie the southern slopes of French Gulch north of Barney Ford Hill between elevations of 9700 and

9880 ft (up to 55 m above French Gulch) and the slopes northeast of Gibson Hill. Tributary alluvium is generally massive to poorly stratified gravelly sand that contains angular cobbles and pebbles floating in sandy clay matrix. The deposit is capped by a strong red soil with textural B horizons greater than 2 m thick, which compares favorably to the type Rocky Flats paleosol of the Colorado Front Range (Birkeland and others, 1996), which is estimated to be about 1 Ma. The Blue River gravels were mapped as "older terrace gravels" by Ransome (1911), whereas he mapped the tributary facies as "older hillside wash." Kellogg and others (2002) mapped both facies in the adjacent Frisco quadrangle as "Boulder gravel of Gold Run," from which we adopted their terminology and age estimate of lower Pleistocene to late Tertiary.

Alluvial fan deposits (Qf), although small, are widespread throughout the quadrangle. Fans typically form where large tributary streams enter the Blue River valley or where smaller tributaries enter the large tributaries. The oldest fan deposits (Qfp) accumulated during the Pinedale glaciation from glacial outwash and ice-marginal streams, but their source streams have been captured or incised so they no longer receive significant deposits. Postglacial alluvial fans are divided into an older group of incised fan surfaces (Qfi) and a younger group of active fan surfaces (Qfy).

STRUCTURAL GEOLOGY

STRUCTURAL SETTING

The Breckenridge quadrangle is within a structurally complex part of the Southern Rocky Mountains. The quadrangle straddles the crest of the Tenmile Range, the upper Blue River valley, and the western-most slopes of the Front Range. Elements of five large-scale tectonic and tectono-stratigraphic features are recognized within the quadrangle: Early Proterozoic regional metamorphism of crystalline rocks (Reed and others, 1987), Middle Proterozoic east-northeast trending shear zones (Tweto and Sims, 1963; Shaw and others, 2001), the Central Colorado Trough of Pennsylvanian-Permian time (DeVoto, 1980), the Laramide-age Colorado mineral belt (Tweto and Sims, 1963), and the northern part of the Neogene-age Rio Grande rift system (Tweto, 1979; Kellogg, 1999).

Regional metamorphism during Early Proterozoic time resulted in the formation of amphibolite-grade gneisses derived from sedimentary protoliths on the Breckenridge quadrangle. The metamorphism that produced the foliated rocks probably occurred simultaneously with the emplacement of large plutons during the Early Proterozoic (Reed and others, 1987). During the Middle Proterozoic, a series of east-northeast-trending shear zones developed that deformed the older Proterozoic rocks (Shaw and others, 2001).

The Central Colorado Trough (DeVoto, 1980) is a complex graben system into which thick deposits of clastic sediments were deposited during the uplift of Ancestral Rockies in Pennsylvanian and Permian time. The faults and folds of the trough were recurrently active from Proterozoic time until possibly Quaternary time (Fig. 4; DeVoto, 1980). The ancestral Front Range uplift bounds the trough to the northeast of the quadrangle.

The Colorado mineral belt is a 400 km long northeast-trending zone characterized by numerous Laramide (Late Cretaceous-Early Tertiary) igneous intrusions, associated ore deposits, and faults. The Colorado mineral belt follows a zone of structural weakness defined by major northeast-trending shear zones that originated during Precambrian time (Tweto and Sims, 1963).

The Rio Grande rift system is a regional extensional tectonic feature expressed as a series of north to north-northwest-trending normal faults and grabens that extend from New Mexico to the Wyoming border through the heart of the southern Rocky Mountains in Colorado. The Blue River graben north of the Breckenridge quadrangle is the largest of the northernmost structures of the Rio Grande rift system (Kellogg, 1999).

FAULTS

In the Tenmile Range, northwest-trending high-angle faults are the most obvious tectonic features. At least two faults of large separation are present in the map area. Both are northwest-trending, steeply east-dipping normal faults. The fault exposed near the Briar Rose Mine and Peak 9 in the Tenmile Range juxtaposes Pennsylvanian-age sedimentary rocks with Proterozoic gneisses and also cuts the 42 Ma Humbug stock. The other large fault is buried beneath Quaternary glacial deposits in the north-central part of the quadrangle near Breckenridge and probably juxtaposes Cretaceous sedimentary rocks with Proterozoic basement. This fault projects into a fault mapped in the Frisco quadrangle (Kellogg and others, 2002) and may have moved as recently as the Quaternary. Most northwest-trending fault planes measured in the field have dips greater than 70 degrees. Co-genetic, generally north-trending faults and tension fractures with small separation that run between the larger northwest-trending faults in the Tenmile Range provided zones of weakness and open spaces that were filled by intrusive dikes and mineralized veins in mid-Tertiary time. These north-trending faults, dikes, and veins are prominent in the southern part of the map area in the Tenmile Range but not in the northern part. The northwest-trending major faults have been active from before Eocene time, and some have been active possibly into the Holocene. Eocene-age intrusive breccia bodies aligned along the faults indicate that the faults were probably active during Eocene time. Post-intrusive faulting was also noted on these faults. Northwest-trending faults have possibly

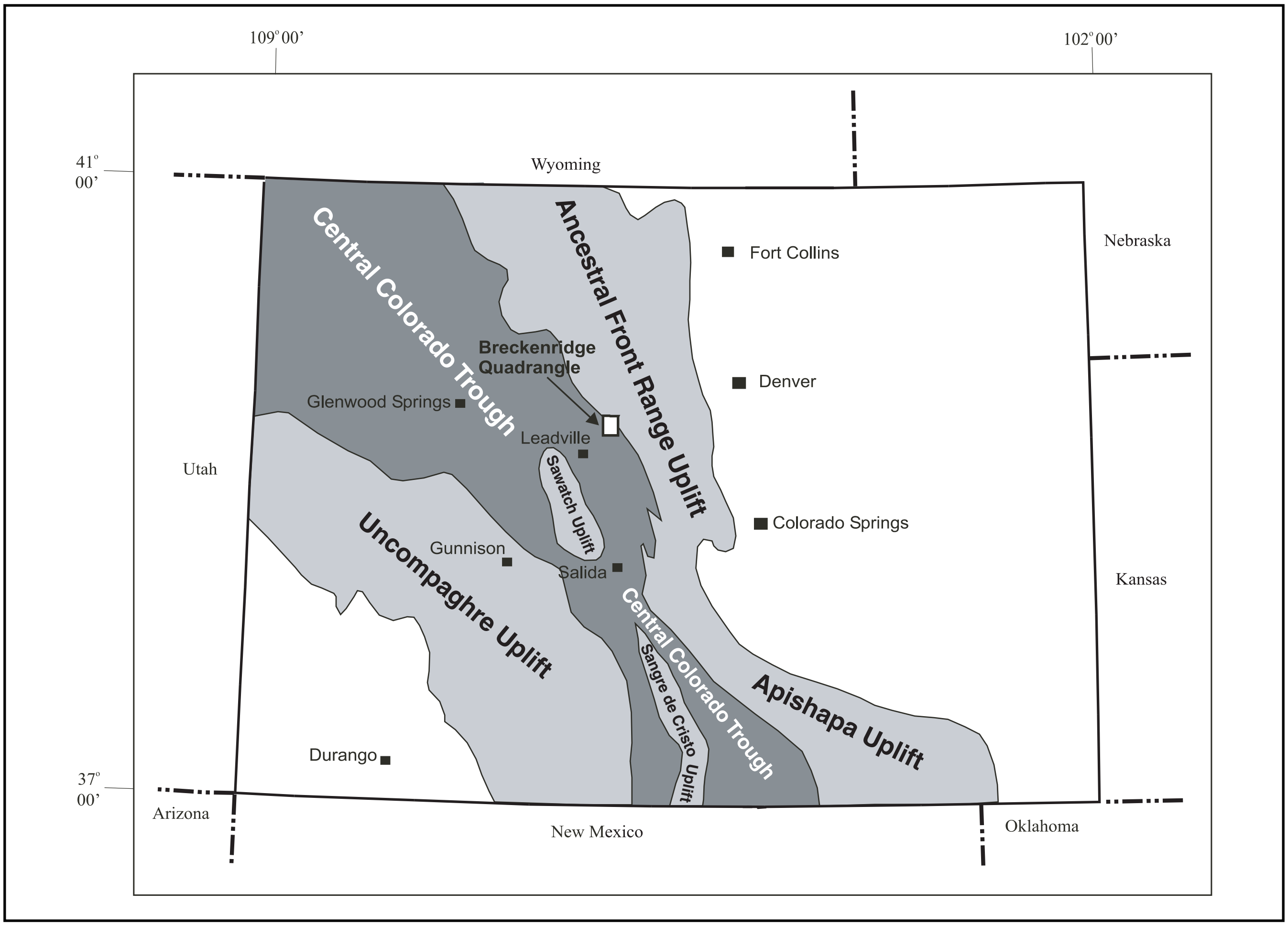

Figure 4. Sketch map showing tectonic uplifts (dark gray) in relation to the Central Colorado Trough of De Voto (1980) during Pennsylvanian time. Modified from De Voto, 1980, Fig. 3.

displaced Pinedale-age (late Quaternary) glacial deposits on the eastern flank of the Tenmile Range. This is indicated by linear features and possible scarps in the glacial deposits. Some of the linear features (identified from aerial photographs) in Quaternary glacial deposits extend from mapped brittle faults in adjacent bedrock. Kellogg and others (2002) also noted northwest- to north-trending faults of Quaternary age in the Frisco quadrangle. There is some evidence for pre-Tertiary movement on these northwest- and north-trending faults. The presence of Tertiary-age mineralization and silicification on the faults show that some of the faults existed prior to the Eocene intrusive and mineralization event. On Mt. Helen, between Crystal Creek and Spruce Creek in the Tenmile Range, a northwest-trending shear zone that is probably contiguous with the fault at the Bryn Mawr Mine exhibits shear fabric, chloritic alteration, and cataclastic texture indicative of ductile or brittle-ductile deformation indicating that the shear zone was active during Middle Proterozoic time, concurrent with the Middle Proterozoic deformational event of the Homestake Shear trend (Shaw and others, 2001). Movement on north-northwest-trending faults may be related to movement on the very large Mosquito Fault, which lies about 2.5 km west of the Breckenridge quadrangle boundary. The latest movement on the Mosquito Fault is probably late-Pleistocene (Widmann and others, 1998). The younger movement on these north and northwest-striking faults, including Quaternary-age faulting, may be tectonically related to the Rio Grande rift system (Kellogg, 1999).

An east-northeast-trending set of faults, fractures, Tertiary intrusive dikes, and low-grade hydrothermal alteration transects the Tenmile Range in the vicinity of the Humbug stock. This structural zone is interpreted to be originally Proterozoic in age but has been reactivated during late Paleozoic, Laramide, and possibly mid-Tertiary time. The intersection of this east-northeast structural zone with the younger northwest-trending faults may have provided a significant zone of weakness that was exploited by magma that formed the Humbug stock. This east-northeast structural zone is interpreted to be an expression of the Colorado mineral belt (Tweto and Sims, 1963) and the Middle Proterozoic Homestake Shear trend (Shaw and others, 2001). The zone appears to be a structural link between the Breckenridge mining district to the northeast and the Kokomo-Tenmile district to the southwest. This fault zone may also continue beyond Breckenridge northeast to the Keystone quadrangle, where Widmann and others (2003) mapped the southwestward continuation of the Montezuma Shear Zone. Figure 5 is a rose diagram of the strike attitudes of faults as measured at the outcrop in the Tenmile Range of the Breckenridge quadrangle.

In the eastern part of the Breckenridge quadrangle a mosaic of closely spaced faults have small separations, and these faults show five directions of preferred strikes. From oldest to youngest, the strikes of faults are (1) northwest, (2) east, (3) north-northeast, (4) northeast, and (5) north. Northwest-striking faults are relatively rare east of the Blue River in comparison to the Tenmile Range west of the Blue River where the northwest-trending faults may be Proterozoic in age. In the northeastern part of the Breckenridge quadrangle the dominant structural grain is north-northeast and south-southeast, but faults of this orientation are rare in the southeastern part of the map area. East of the Blue River, the northeast-striking faults appear to be ladder or crossover faults between north-northeast-trending faults. North- and northwest-striking faults appear to have the largest separation and the longest strike length.

Taranik (1974) showed the Blue Valley fault trending north along the Blue River Valley from Hoosier Pass. The Blue Valley fault was shown as being covered by Quaternary deposits along most of the trace. At Hoosier Pass he showed Minturn Formation on both sides of the fault, with beds dipping toward the fault on opposite blocks. Taranik's cross section B-B′ showed nearly 275 m of separation on a reverse fault that was down on the west block. Our structural solution using folds shown on our cross-section B-B′ does not require separation along a fault to explain the distribution of rock units and dip directions of rocks, so we do not show the Blue Valley fault on our map.

FOLDS

Large-scale folds dominate in Paleozoic rocks in the eastern part of the map area, but small-scale ductile folds related to Early Proterozoic deformation are common in metamorphic rocks of the

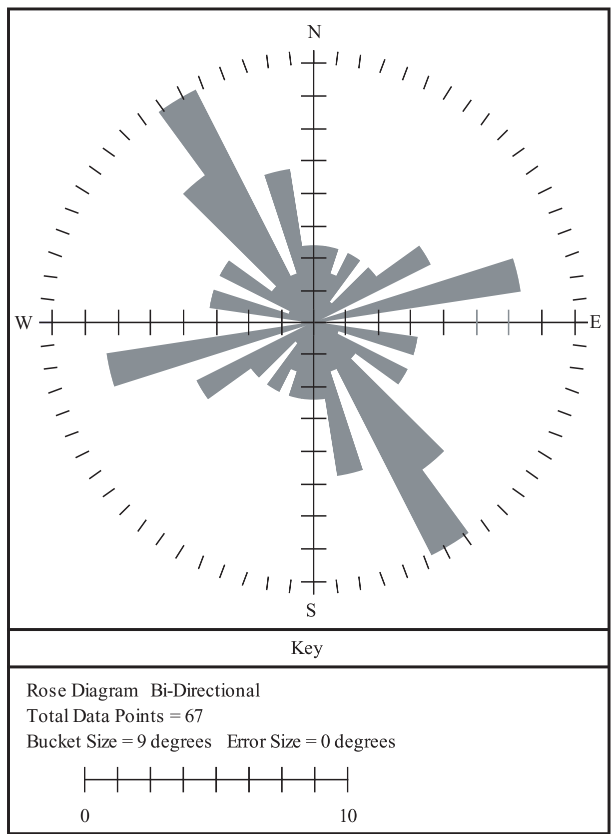

Figure 5. Rose diagram of strike direction of fault planes measured on the outcrop in the Precambrian area of the Tenmile Range, Breckenridge quadrangle. The strong structural trends of N30W to N45W, and N50E to N80E is evident.

Tenmile Range and in small exposures in the northeastern part of the Breckenridge quadrangle.

Several large-scale folds were mapped in the eastern part of the Breckenridge quadrangle. North of French Gulch and east of the Blue River, a large-scale anticline was mapped by Bartos east of Gibson Hill (see cross-section A-A′). This anticline trends northwest into the southern part of the Frisco quadrangle (Kellogg and others, 2002) where the east flank of the anticline is exposed east of the Blue River. Taranik (1974) showed the Monte Cristo syncline trending northward from Hoosier Pass down the Blue River Valley, and he showed the Hoosier anticline trending northward along the east side of the Blue River Valley. Both folds are depicted on our map at similar locations to those shown by Taranik (1974). The Monte Cristo syncline and Hoosier anticline are broad, open, north-plunging structures (cross-section B-B′) that are covered by Quaternary deposits over most of their traces.

Small-scale folds related to Early Proterozoic regional metamorphism are common in the gneisses of the Tenmile Range. Ptygmatic folding of felsic layers and quartz segregations is common in the migmatitic gneiss. The attitudes of folds in the migmatite were not recorded because they usually appeared chaotically oriented on the outcrop scale.

METAMORPHIC FOLIATION

Numerous attitudes of metamorphic foliation were measured in the Proterozoic rocks of the Tenmile Range. The rose diagrams in Figure 6 show that the foliation has a remarkably consistent north-northeast strike and southeast dip. This contrasts with metamorphic foliations in the

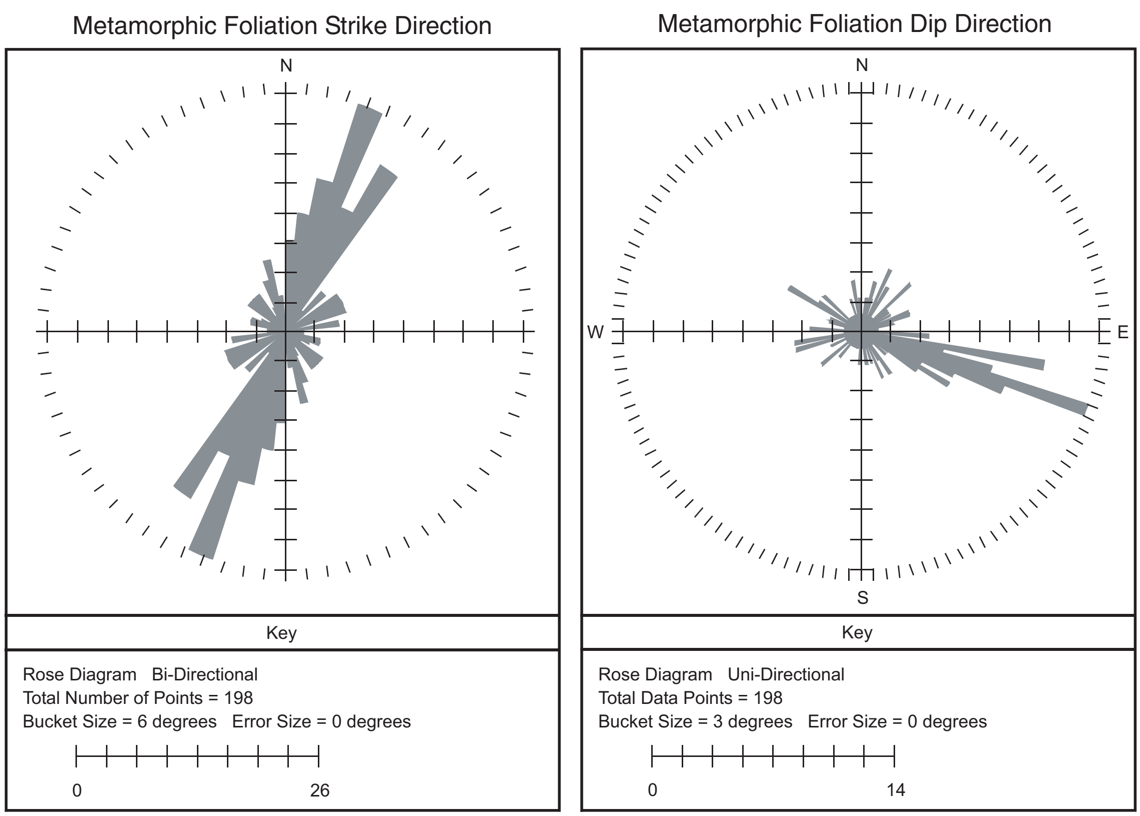

Figure 6. Rose diagrams of metamorphic foliation strike and dip directions in the Tenmile Range, Breckenridge quadrangle. A dominant foliation strike direction of N10E to N35E is evident. East-southeast dips are also indicated. Most dips are steep.

Keystone quadrangle (Widmann and others, 2003), which show a much wider variation in strike and dip. The rose diagrams (Fig. 6) also suggests that foliation in the Breckenridge quadrangle has locally been either rotated parallel with east-northeast- and north-northwest-trending faults or shear zones, or possibly has developed as primary foliation in localized shear zones that were active in the Middle Proterozoic (Shaw and others, 2001). In the northern part of the Tenmile Range, within and north of the northeast-trending structural zone centered near the Humbug stock, foliations are less consistently oriented than they are in the higher and better exposed area to the south of the Humbug stock.

STRUCTURAL EVOLUTION

The oldest structures on the quadrangle are observed in the early Proterozoic gneisses of the Tenmile Range. Primary metamorphic foliation and folding in the gneisses trends dominantly north-northeast. This foliation is thought to have developed contemporaneously with the emplacement of large intrusive masses between 1,790 and 1,660 Ma (Reed and others, 1987). The east-northeast faults and dikes that transect the northern part of the Breckenridge quadrangle are an expression of the Middle Proterozoic (1.4 Ga) Homestake Shear trend (Shaw and others, 2001) and the Colorado mineral belt (Tweto and Sims, 1963). Faults of this structural trend were rejuvenated during Laramide time, and possibly Quaternary time, and intrusives exploited these structurally weak zones during early Tertiary time. North-northwest-trending faults show evidence of slip as early as Proterozoic time and were rejuvenated during and after Eocene time. Post-Eocene slip on north-northwest-trending faults was also observed in the Tenmile Range. Some north-northwest-trending faults have possibly been active as recently as the late Pleistocene.

In the eastern part of the map area, the location of range-front growth faults that governed erosion and deposition of the thick Pennsylvanian and Permian sequences remains a mystery; the thickness of the Maroon Formation increases drastically east of Rocky Point, but specific faults responsible for the thickness change were not located. After lithification and later uplift of the Paleozoic and Mesozoic sequence, large-scale folds formed in the eastern part of the map area, possibly during Laramide deformation; the anticlinal structure east of Gibson Hill, the Hoosier anticline, and the Monte Cristo syncline pre-date most faults of the five different orientations described above. This folding event post-dated deposition of the Late Cretaceous Pierre Shale and pre-dated late Eocene plutonic activity. In the eastern part of the map area, as in the Tenmile Range, faults were active during Eocene igneous activity. Clearly, faults controlled the emplacement of dikes, and dikes and sills are also cut by faults of all orientations. Prominent north-south trending faults may be related to extensional tectonics of the Rio Grande rift (Erslev and others, 1999; Kellogg, 1999), which is generally considered to have begun around 29 Ma (Tweto, 1979).

ECONOMIC GEOLOGY

The Breckenridge area has a long and productive history as a mining center. The principal focus of mining was gold, and extremely rich placers, and to a lesser extent lode deposits, were mined from 1859 to 1959. Most of the mines were located in the northeastern part of the Breckenridge quadrangle, and these mines are the main subject of this section on economic geology. Other mines and adits are scattered through the southeastern and western part of the map area. Mines in the Breckenridge quadrangle have had extensive production, and significant mineral resources likely remain in the ground. However, conversion of the local economy from resource based to recreation based, with accompanying widespread high-cost residential development, will likely preclude any future development of metallic resources in the Breckenridge area.

The dominant mining operation in the quadrangle was placer dredging, focused in the Blue River and French Gulch drainages. More than $15.5 million worth of gold (at historical prices of $17.50 to $35 per oz) was recovered from these placers (Parker, 1974). Placer dredging in the quadrangle lasted for one hundred years (from 1859 to 1959), with most production occurring between 1906 and 1924 (Parker, 1974).

Lode mining commenced in 1869 and during the main phase of lode mining twenty-five to thirty veins were exploited over a period of about 60 years. Although the initial exploration interest in the Breckenridge district was gold, arrival of the railroad in the Blue River Valley allowed transport of base-metal ores to smelters in Denver, and production of silver, lead, and zinc became economically feasible. The Wellington Mine was the largest lode mine in the Breckenridge district. Limited mining activity also occurred on scattered locales throughout the Tenmile Range (Upper Blue River District) from sulfide veins that cut Paleozoic and Proterozoic rocks (Singewald, 1951).

The northeastern part of the Breckenridge quadrangle, specifically Gibson Hill, was explored by Asarco, Incorporated, in 1990 under the supervision of Paul J. Bartos; descriptions of mine geology, alteration, and geochemistry are derived from this work.

BRECKENRIDGE MINING DISTRICT

The main part of the Breckenridge mining district is located in the northeastern part of the Breckenridge quadrangle. Ransome (1911) and Lovering (1934) provide detailed descriptions of the geologic setting of the mining district and of the mines that were in operation at the time they completed their studies. Placer mining operations and lode mines were active in the northeastern part of the Breckenridge quadrangle from 1859 to 1959.

The dominant mining operation in the quadrangle was placer dredging in the Blue River and French Gulch drainages. Initial mining efforts produced substantial rewards. The Denver Rocky Mountain News issue of July 24, 1861 (referenced in Parker, 1974) stated that placers at the mouth of what is now known as Barney Ford Gulch yielded $3.64 to the pan or more than 0.1 oz per pan. Development of the district was rapid; by 1870, French Gulch had 27 km of ditches, 2,000 m of flumes, and 5 hydraulic monitors mining the stream gravels (Parker, 1974).

More than $7 million in gold was generated in the district's first twenty years, most from simple sluice box and hydraulic washing methods on gulch and bench gravels (Lovering and Goddard, 1950). Attention then turned to the deep gravels beneath the stream level in broad valleys such as French Gulch and the Blue River. Starting in 1898 several hydraulic elevator plants were operated near the mouths of French and Indiana Gulch. The largest hydraulic operation was the Gold Pan mine in the town of Breckenridge. By 1901, the Gold Pan Mining Company had constructed a 4.8-km ditch and a 2,400 m pipeline, which delivered water that had a 107-m head to the monitors and four hydraulic elevators (Parker, 1974). A gravel thickness of more than 22 m was mined. This operation lasted until 1905 when it closed because grades were lower than expected and the very large boulders presented an insurmountable mining problem (Parker, 1974).

The technical answer to the presence of large boulders was the use of dredges to mine placer gold, and dredges were successfully employed in the district beginning in 1906. The initial dredge was constructed by the Reliance Gold Company at a cost of $35,000 and was soon yielding $1,000 a day in gold (Parker, 1974). Dredging continued until 1959; the remains of the last dredge can still be seen in French Gulch about 300 m west of the Country Boy Mine.

Lode mining in the Breckenridge mining district commenced in 1869. Twenty-five to thirty veins in the Breckenridge mining district each produced at least a thousand tons of ore (Lovering, 1934). At first, the interest was principally in gold; significant production of lead and zinc did not occur until a railroad to Denver was completed in 1880, which allowed access to smelters and markets (Lovering and Goddard, 1950). The Wellington Mine, on the north side of French Gulch approximately 2.5 km east of Breckenridge, was by far the largest lode mine in the district. From 1887, when production started, to 1929, over 737,000 tons of ore were produced, and the ore yielded 6,500 oz of gold, 750,000 oz of silver, 41 million lbs of lead, and nearly 165 million lbs of zinc (Lovering and Goddard, 1950). At the Wellington Mine there were over 20,000 m of tunnels and shafts through a vertical range of 238 m. The Wellington mine was inactive from 1929 to 1948. Between 1948 and 1958 production occurred in the portion of the mine above the water table. According to smelter sheets from the Resurrection Mill, where the ore was shipped, over 58,000 tons of ore were mined during this period with grades of about 0.04 oz/ton gold, 3 oz/ton silver, 10 percent lead, 14.5 percent zinc, and 0.4 percent copper.

Veins at the Wellington Mine strike northeasterly and dip 60º to 65º, typically to the southeast. The main vein consisted of irregular shoots of sphalerite and galena scattered through a strike length of 900 m (Lovering, 1934). At depth, the mineralized zone became pyritic and non-commercial. Vein widths varied from a few cm to 10 m; 1.5 m was the approximate average. The largest ore shoot was on the Great Northern vein, which extended 213 m along strike and extended downdip from the surface to 15 m below the fifth level. According to Lovering (1934), major ore deposits occurred where brittle rocks of the monzonite porphyry or the Dakota Formation formed one wall, which was favorable for formation of open space, as opposed to soft, easily deformed shale. In addition, ore shoots tended to occur where veins steepened or made a strike change (Lovering and Goddard, 1950). The general geology of the Wellington Mine consisted of a vein complex within the hornblende biotite monzonite stock; sections drawn by Lovering (1934) through the workings show considerable structural complexity.

Veins in the district are typically sulfide rich and consist of aggregates of pyrite, sphalerite, and galena in varying abundances, plus common gangue minerals of ankerite, quartz, sericite, and calcite (Lovering, 1934, p. 27). Gangue composed of siderite and ankerite appears to be late relative to sulfide minerals, and the gangue fills cracks in early sulfide mineral deposits. Sulfides tend to be massive with no crustification or depositional banding (Lovering, 1934). Much of the sphalerite is dark brown to black and iron-rich (marmatite). Most of the rich gold ore came from the shallow oxidized zone that generally extended 30 to 90 m below the surface. Both Ransome (1911) and Lovering (1934) concluded that much of the gold in the vein ores was supergene enriched. The upper portions of many veins were also enriched in lead as well; much of the enrichment is attributed to residual enrichment from dissolution of sphalerite (Lovering and Goodard, 1950), although some hypogene zonation of galena relative to sphalerite probably occurred. Adjacent to the veins, the igneous wallrock is typically converted to an aggregate of sericite, quartz, and ankerite and minor pyrite (Ransome, 1911). Locally, the quartzitic sandstones of the Dakota Formation show evidence of leaching, and the bright-red sandstone and siltstone of the Maroon and Morrison Formations are commonly bleached to a gray-green color near veins.

Skarns occur locally in the Breckenridge mining district, and these contact metamorphic mineral deposits had some minor production. Garnet-epidote-magnetite skarn occurs in the calcareous lower portion of the Morrison Formation on Gibson Hill and on Prospect Hill west of the Wellington Mine. Accompanying the skarn are local occurrences of pyrite-chalcopyrite-(gold), which were mined on a small scale. The cluster of faults at Gibson Hill, along with the occurrence of skarns and hornfels, suggests that an intrusion occurs at depth in this area.

Mining essentially ceased in the Breckenridge mining district in 1958, although the Country Boy Mine on French Gulch operates as an historical mine park for tourists. This mine, located south of the Wellington Mine across French Gulch, produced about 20,000 tons of ore. In 1947 production was about 500 tons/month with grades approximately 0.1 oz/ton gold, 3 oz/ton silver, 1 percent lead, 0.2 percent copper, and 30 percent zinc from a 1 m wide vein (Asarco private report). Production at the Country Boy Mine ceased shortly after 1947 and the mine was idle until 1993 when it was rehabilitated and opened for the tourist trade.

Exploration continued in the Breckenridge mining district until 1990. The Gibson Hill area, in the northeastern part of the Breckenridge quadrangle, was explored by Asarco Incorporated in 1989-1990 under the supervision of Paul J. Bartos. Thirteen angled reverse-circulation drill holes, ranging in depth from 32.6 to 120.4 m, totaling 1,132 m, were drilled following geochemistry and ground magnetic surveys. The target was a large deposit of disseminated gold in the sandstone of the Dakota Formation. The Detroit Mine, on the southern end of Gibson Hill, had extensive high-grade stopes that contained veinlets, replacements, and disseminations within bedding-plane shears in fractured quartzitic sandstone of the Dakota Formation; these were known as "blanket" deposits in the district (Lovering and Goddard, 1950). Shock Hill and Little Mountain areas have similar types of "blanket" deposits. Dump samples from the Detroit Mine contained stockwork veinlets of pyrite-sphalerite-galena-quartz-calcite, which were oxidized to goethite and quartz; disseminated pyrite and quartz occurred away from the veinlets. Alteration was typically obscure, although local silica dissolution and leaching of the Dakota sandstone occurred. In general, the gold and silver were distributed among many small fractures or segregated into local pockets, which could contain high concentrations of gold and silver. Lovering (1934) described "mud" seams that consisted of altered rock selvages along bedding plane slips in the Detroit Mine, and these selvages graded from 0.5 to 2 oz/ton gold; the adjoining quartzitic sandstone contained varying amounts of disseminated gold that could be detected only by assay. Fifty-eight samples of Dakota Sandstone were collected from the dump of the Detroit Mine; these samples did not show sulfide minerals, but they assayed nearly 0.1 oz/ton Au. At the Detroit Mine, ground induced polarization and magnetic anomalies were found to correspond closely with geochemical anomalies detected from surface geochemical samples, and these anomalies outlined the area of old stopes. The drilling program showed interesting intercepts locally, the best being 27.4 m of 0.048 oz/ton Au, but a fence of holes spaced 22.9 m apart along the edge of the Detroit workings only intersected low-grade or marginal mineralization. Overall, the mineral deposits encountered were perceived to be insufficient to be mined in bulk and too low in grade to be selectively mined underground.

OTHER MINES AND PROSPECTS

Some mining activity occurred in the Tenmile Range before the close of the nineteenth century, mostly in the upper Blue River area (Fig. 2), but mining in the Tenmile Range ceased by 1940. Production of gold, silver, lead, and copper was from mixed-sulfide veins that cut Proterozoic and Paleozoic rocks (Bergendahl, 1963; Singewald, 1951). Small mines and adits are scattered widely in a band west of the Blue River that extends from the southern boundary of the map area northward to the Briar Rose mine southwest of the town of Breckenridge. Several small mines and adits are scattered along terrain east of the Blue River.

Typically, veins in the Tenmile Range consist of quartz-pyrite with subordinate to absent sphalerite, chalcopyrite, and galena. Gold is found both native and in auriferous pyrite (Singewald, 1951; Alaric, 1952). Other reported minerals include magnetite, specularite, molybdenite, tetrahedrite, hubnerite, bismuthinite, tetradymite, and argentite (Singewald, 1951; Alaric, 1952; Parker, 1974). Most veins in the Proterozoic rock of the Tenmile Range occur along north-south or north-northeast-trending faults or fractures. A few (such as at the Briar Rose Mine) are on north-northwest-trending structures. Geochemical samples K01-139, K01-179, and K01-

254 (Table 1) were taken from veins hosted by Proterozoic rocks in the Tenmile Range.

Veins centered on North Star Mountain tend to be rich in gold and commonly contain minor molybdenite (Singewald, 1951). These veins are believed by Parker (1974) to be the source of the native bismuth nuggets reported from the placers from the upper reaches of the Blue River (Engineering and Mining Journal, 1877, v. 23, p.353). These veins are typically thin (0.1 to 1 m wide on average) and widely spaced. The North Star veins were discovered in about 1875 and intermittently worked until the 1940’s. Limited sampling and returns from smelter sheets of the North Star veins suggest metal concentrations of 0.1 to 2.5 oz/ton gold and 1 to 6 oz/ton silver; these grades were almost certainly from hand-selected material. Northward from Quandary Peak, the veins are much more silver dominated, with considerably more sphalerite and galena. Barite and jasperoid are reported from the northernmost mines, which was interpreted by Singewald (1951) as distal to the main heat source centered on North Star Mountain. Production from each mine ranged from $10,000 to $80,000 at historic prices (Singewald, 1951). Total production for the upper Blue River area is estimated by Singewald (1951) to have been greater than $1 million, chiefly from gold and silver.

Several prospects, adits, and mine dumps occur along the south side of Monte Cristo Creek; these were probably related to the Vanderbilt Mine (near sample site 01080) (Singewald, 1951). Singewald (1951) reported the Vanderbilt Mine was a producer of “noteworthy quantities of gold ore”. A main adit, stopes, and drifts were developed in the upper part of Cambrian quartzite, most likely in calcareous sandstone and interbedded shale of the Peerless Shale (Singewald, 1951). Singewald (1951) described mineralized zones as ore beds and he described replacement bodies in Cambrian quartzite. Sulfide minerals, primarily pyrite, galena, and sphalerite form most of the mineral deposits, and Singewald (1951) described fractures as the main conduits for ore-forming fluids. The main adit is caved, but samples of sulfide ore were collected from mine dump for chemical analysis. The results are shown in Table 1.

On the north side of Monte Cristo Gulch excavations at the Monte Cristo Mine opened sulfide replacement zones in the Dyer Dolomite and Parting Quartzite. Singewald (1951, p. 46) reported that gold was the principal objective of the mining operation, but the grade was too low to be profitable, and there was “no substantial commercial output.” The ore body is on the southeast downthrown block of a fault that has a few meters of separation (Singewald, 1951), and the main ore channel is about 23 m wide and trends at N. 55º W. Singewald (1951) described a zonation in ore-forming minerals: (1) pyrite-rich ore occur at the western corner of the ore body in, and adjacent to, the fault; and (2) galena and sphalerite, and minor chalcopyrite and pyrite in a gangue of manganese and iron carbonate. Chalcopyrite decreases in abundance toward the southeast and sphalerite increases in abundance toward the southeast. Manganese and limonite coat rock surfaces and fill veins. An analysis of two samples in the main ore body indicated 15.9 percent and 16.0 percent manganese (Singewald, 1951, p. 47). Chemical analyses of two samples (01059A, B) collected from outcrops are reported in Table 1. Near the Monte Cristo Mine a sulfide sample (01064) from the Sawatch Quartzite contains anomalous concentrations of gold.

East of the Blue River and south of Pennsylvania Creek, several mines and prospects are sited in sedimentary rocks of the Minturn and Maroon Formations. The Fredonia Mine is located at timberline in Fredonia Gulch, and the Hunter Boy Mine is located in an unnamed gulch south of Fredonia Gulch (NE1/4 Sec. 6, T. 8 N., R. 77 W.).

The Fredonia Mine is located in the lower part of the Maroon Formation as mapped in this report and as mapped by Taranik (1974). This mine had been mined for silver, and it produced lead and zinc as well. Singewald (1951, p. 57) indicated that it produced approximately $25,000 in metals. Several limestone beds occur in the vicinity of the Fredonia Mine, one of which Taranik (1974) correlated with the Robinson Limestone Member. Singewald (1951) reported that the ore body occurred in the thickest limestone where porphyry had been fractured along a fault. Pre-ore alteration consisted of extensive silicification of limestone and alteration of limestone to dolomite. Shattered rock provided permeable areas for circulation of ore-forming fluids (Singewald, 1951). According to

Singewald, high-grade ore consists of vuggy silicified rock (jasperoid) permeated with greenish-gray silver-chlorite stain and minor amounts of limonite. The metal concentration of a dump sample of mineralized limestone (01122A) and silicified limestone (01122B) is reported in Table 1.

The Hunter Boy Mine is an adit in a sill of quartz monzonite megacrystic porphyry. According to Singewald (1951) prospecting was confined to oxidized zones along minor faults, and gold was reported to be greatly in excess of silver. Little mineralization is seen at the surface in the area of the adit, but oxidized copper minerals occur in a prospect pit near the top of the porphyry sill. The metal concentration of a grab sample taken from that prospect pit is reported in Table 1.

Table 1. Trace-element geochemistry of rock samples taken in the Breckenridge quadrangle.
[All samples were prepared and analyzed by Bondar Clegg, Inc. of Sparks, NV and Vancouver, B.C. All concentrations are in parts per million (ppm) unless otherwise noted. Gold was analyzed by fire assay (30 g charge). All other elements were analyzed by inductively coupled plasma optical emission spectrometry (ICP) with acid digestion (HCl and HNO3). <, less than; >, greater than; ppb, parts per billion]

Sample Number	Description	Au (ppb)	Ag	Cu	Pb	Zn	Mo	Ni
01122C	Fredonia Mine, ore grab sample	37	200	2224	17,900	15,000	64	14
K01-139	Mine dump sample (North Star area) - quartz-pyrite vein	1061	4.4	4	35	39	128	13
K01-179	Solitary Mine (upper Crystal Lake), quartz-pyrite vein	2640	188.2	110	926	273	277	20
K01-254	Last Dollar Mine (McCullough Gulch) quartz w/ pyrite, other sulfides	13,070	65.9	2439	2468	2741	<1	81
01007	Iron-stained sandstone, Morrison Fm.	<5	2.1	10	126	812	3	14
01059A	Monte Cristo Mine, mineralized sandstone of Parting Quartzite	1724	13.6	1728	1795	448	5	10
01059B	Monte Cristo Mine, mineralized sandstone of Parting Quartzite	3326	45.8	4781	177,100	2134	2	7
01064	Near Monte Cristo Mine, sulfide replacement in Sawatch Quartzite	874	3.2	5	101	20	<1	33
01080	Vanderbilt Mine area, sulfide replacement in Peerless Shale	4550	480.3	48,600	1980	737	<1	15
01122A	Fredonia Mine, replacement in limestone bed, Maroon Fm.	29	1344.6	1983	8230	73,800	9	26
01122B	Fredonia Mine, silicified and mineralized limestone, Maroon Fm.	19	390.5	727	9382	3521	12	12
01181	Hunter Boy area copper oxide mineralization of Tqpm	<5	3212.5	14,300	116,500	4140	13	14

Sample Number	Description	Co	Cd	Bi	As	Sb	Hg	Fe(%)
01122C	Fredonia Mine, ore grab sample	5	51.5	<5	209	298	1.088	1.15
K01-139	Mine dump sample (North Star area) - quartz-pyrite vein	28	0.3	9	<5	<5	0.071	10
K01-179	Solitary Mine (upper Crystal Lake), quartz-pyrite vein	6	1.1	<5	<5	<5	0.021	2.28
K01-254	Last Dollar Mine (McCullough Gulch) quartz w/ pyrite, other sulfides	96	13.5	95	<5	<5	0.037	7.45
01007	Iron-stained sandstone, Morrison Fm.	3	5.2	<5	13	<5	0.014	1.42
01059A	Monte Cristo Mine, mineralized sandstone of Parting Quartzite	11	1.4	12	<5	<5	0.026	>10
01059B	Monte Cristo Mine, mineralized sandstone of Parting Quartzite	7	12.1	13	<5	16	0.055	>10
01064	Near Monte Cristo Mine, sulfide replacement in Sawatch Quartzite	48	0.3	7	<5	<5	<0.01	>10
01080	Vanderbilt Mine area, sulfide replacement in Peerless Shale	165	4.9	>2000	<5	6	0.027	>10
01122A	Fredonia Mine, replacement in limestone bed, Maroon Fm.	46	220.6	20	268	259	2.246	4.46
01122B	Fredonia Mine, silicified and mineralized limestone, Maroon Fm.	4	26	<5	107	143	0.308	1.3
01181	Hunter Boy area copper oxide mineralization of Tqpm	3	50.3	38	3146	>2000	6.973	1.11

Sample Number	Description	Mn	Te	Ba	S(%)	Cr	V	Sn
01122C	Fredonia Mine, ore grab sample	340	<10	195	0.08	563	15	<20
K01-139	Mine dump sample (North Star area) - quartz-pyrite vein	45	<10	12	10	275	<1	<20
K01-179	Solitary Mine (upper Crystal Lake), quartz-pyrite vein	35	<10	54	1.78	363	5	<20
K01-254	Last Dollar Mine (McCullough Gulch) quartz w/ pyrite, other sulfides	904	<10	26	5.56	319	15	<20
01007	Iron-stained sandstone, Morrison Fm.	10861	<10	185	<0.01	583	14	<20
01059A	Monte Cristo Mine, mineralized sandstone of Parting Quartzite	>20000	<10	13	1.85	285	<1	<20
01059B	Monte Cristo Mine, mineralized sandstone of Parting Quartzite	>20000	<10	9	7.19	183	<1	<20
01064	Near Monte Cristo Mine, sulfide replacement in Sawatch Quartzite	172	<10	12	10	391	11	<20
01080	Vanderbilt Mine area, sulfide replacement in Peerless Shale	386	15	16	10	204	4	<20
01122A	Fredonia Mine, replacement in limestone bed, Maroon Fm.	3295	<10	64	0.28	362	4	<20
01122B	Fredonia Mine, silicified and mineralized limestone, Maroon Fm.	1444	<10	33	0.07	595	16	<20
01181	Hunter Boy area copper oxide mineralization of Tqpm	117	<10	33	1.85	430	6	<20

Sample Number	Description	W	La	Ti(%)	Mg(%)	Ca(%)	Na(%)	K(%)
01122C	Fredonia Mine, ore grab sample	<20	1	<0.01	0.03	0.05	<0.01	0.09
K01-139	Mine dump sample (North Star area) - quartz-pyrite vein	<20	<1	<0.01	0.04	0.02	<0.01	0.35
K01-179	Solitary Mine (upper Crystal Lake), quartz-pyrite vein	<20	7	<0.01	0.02	<0.01	<0.01	0.21
K01-254	Last Dollar Mine (McCullough Gulch) quartz w/ pyrite, other sulfides	<20	5	<0.01	0.43	0.11	<0.01	0.35
01007	Iron-stained sandstone, Morrison Fm.	<20	6	<0.01	0.04	0.09	<0.01	0.11
01059A	Monte Cristo Mine, mineralized sandstone of Parting Quartzite	32	<1	<0.01	0.28	0.18	<0.01	0.04
01059B	Monte Cristo Mine, mineralized sandstone of Parting Quartzite	<20	<1	<0.01	0.91	0.27	<0.01	0.04
01064	Near Monte Cristo Mine, sulfide replacement in Sawatch Quartzite	<20	<1	<0.01	0.02	<0.01	<0.01	0.05
01080	Vanderbilt Mine area, sulfide replacement in Peerless Shale	<20	<1	<0.01	0.36	0.22	<0.01	0.06
01122A	Fredonia Mine, replacement in limestone bed, Maroon Fm.	49	<1	<0.01	0.22	0.38	<0.01	0.05
01122B	Fredonia Mine, silicified and mineralized limestone, Maroon Fm.	<20	<1	<0.01	1.28	2.98	<0.01	0.08
01181	Hunter Boy area copper oxide mineralization of Tqpm	<20	4	<0.01	0.02	0.58	<0.01	0.04

Sample Number	Description	Sr	Y	Ga	Li	Nb	Sc	Zr
01122C	Fredonia Mine, ore grab sample	7	2	<2	<1	<1	<5	3
K01-139	Mine dump sample (North Star area) - quartz-pyrite vein	<1	<1	2	3	5	<5	5
K01-179	Solitary Mine (upper Crystal Lake), quartz-pyrite vein	25	<1	<2	<1	2	<5	2
K01-254	Last Dollar Mine (McCullough Gulch) quartz w/ pyrite, other sulfides	2	3	3	9	6	<5	3
01007	Iron-stained sandstone, Morrison Fm.	20	6	<2	<1	2	<5	4
01059A	Monte Cristo Mine, mineralized sandstone of Parting Quartzite	8	2	<2	<1	9	<5	4
01059B	Monte Cristo Mine, mineralized sandstone of Parting Quartzite	<1	2	<2	<1	7	<5	4
01064	Near Monte Cristo Mine, sulfide replacement in Sawatch Quartzite	<1	<1	4	<1	5	<5	6
01080	Vanderbilt Mine area, sulfide replacement in Peerless Shale	7	<1	4	7	<1	<5	9
01122A	Fredonia Mine, replacement in limestone bed, Maroon Fm.	13	3	<2	<1	2	<5	3
01122B	Fredonia Mine, silicified and mineralized limestone, Maroon Fm.	15	1	<2	<1	<1	<5	3
01181	Hunter Boy area copper oxide mineralization of Tqpm	75	2	<2	<1	<1	<5	1

GEOLOGIC HAZARDS

Potential geologic hazards in the Breckenridge quadrangle fall into four categories: (1) landslides, (2) floods and debris flows, (3) abandoned mined lands and placer deposits, and (4) seismicity.

LANDSLIDES AND ROCK SLIDES

Landslide deposits occur throughout the Breckenridge quadrangle. These landslides are mostly rock slumps, rock slides, and debris slides according to the terminology of Cruden and Varnes (1996). Older (pre-Pinedale glaciation) landslide deposits occur in several cirques of the Tenmile Range and consist of large, semi-intact masses of bedrock derived from the cirque walls. Younger (post-glacial) landslide deposits occur in diverse settings: (1) slumps in Pinedale till; (2) shallow debris slides in Bull Lake till; (3) slumps and deep-seated gravitational spreading in Tertiary intrusives; (4) rock slides and slumps in Paleozoic strata on the eastern flank of the Tenmile Range; and (5) slumps and rockslides in Proterozoic crystalline rocks. The latter group of landslides are restricted to a north-northwest-trending belt on the eastern flank of the Tenmile Range that coincides with a zone of faults and shear planes.

Aside from the landslide deposits mapped, there are also areas of incipient slope failure and deep-seated gravitational spreading called "sackung" structures by Varnes and others (1989). These areas are marked by upslope- and downslope-facing scarps and troughs that parallel slope contours. At some places, such as the north slope of Red Mountain, sackung landforms are adjacent to young landslide detachment areas, suggesting that future landslides will detach along the sackung scarps and troughs.

The linear belt of large bedrock landslides in the Tenmile Range is associated with two bedrock controls. North of Spruce Creek, landslides coincide with rock units weakened by faulting, shearing, or by hydrothermal activity associated with Tertiary intrusions. A landslide complex (Qlsc) occurs on the northwestern flank of Mount Argentine, where the landslide is coincident with the intrusive contact of Tertiary porphyry against rocks of the Maroon Formation. South of Spruce Creek, large landslide complexes coincide with the thin outcrop band of Paleozoic sedimentary rocks, particularly the incompetent shale within the Minturn Formation. For landslides in Quaternary deposits, such as glacial till, the main contributory causes are slope oversteepening from glacial or fluvial erosion and local saturation of slopes due to concentrated spring or seep areas. However, at the southern margin of the quadrangle along Aqueduct Road, it appears that the shallow groundwater causing slumps in Pinedale till occurs only where the till overlies shaley Paleozoic units, such as in the Minturn Formation.

FLOODS AND DEBRIS FLOWS

Intense summer rainstorms or rapid melting of deep snowpack during unusually warm spring thaws may cause localized flooding and debris-flow activity. The 100- and 500-year flood plains, as mapped in the Town of Breckenridge by the Federal Emergency Management Agency (FEMA), are restricted to Holocene alluvium (Qal) and younger Pinedale outwash (Qop_2) in the Blue River Valley. In tributary drainages these flood areas have not been defined by FEMA but should also generally coincide with the limits of Holocene alluvium.

However, a more widespread hazard is that of debris flows in ephemeral and intermittent streams and on alluvial fans. Holocene alluvial fans (map units Qf, Qfy) are potentially subject to debris-flow deposition anywhere on their surfaces. Fans with the highest hazard are those whose drainage basins contain steep tributaries affected by debris slides, such as Pennsylvania Creek.

ABANDONED MINES AND PLACER DEPOSITS

Collapse of abandoned mine shafts and tunnels, many of which may be covered by thin surficial material, pose a potential hazard, especially in the northeastern part of the quadrangle. Mine water also tends to be acidic and commonly contains toxic levels of metals, such as zinc, cadmium, lead, and arsenic. Soil contaminated by acid mine drainage may be corrosive to metal and concrete and pose a constraint to building foundations. In areas mined by dredging or hydraulic methods, surface soil may ravel or wash downward into subsurface void spaces in the underlying, coarse, matrix-free gravel. This process, known as piping, can create cylindrical cavities, holes, and small sinkholes at the surface. The vertical bluffs in unconsolidated alluvium left by hydraulic mining, some of which are up to 10 m high, can collapse if saturated.

SEISMICITY

The Breckenridge quadrangle lies near the northern terminus of the Rio Grande rift, an active zone of crustal extension. As in other parts of the rift, the level of historic seismicity is very low. A search of the USGS/NEIC catalog of earthquakes (NEIC, 1992) in the eastern, central, and mountain states of the U.S. (1534–1986 A.D.) reveals only a single earthquake within a 20 km radius of the center of the Breckenridge quadrangle. This earthquake occurred on 23 May 1964, in the Copper Mountain quadrangle west of Breckenridge, but the magnitude and depth were not recorded.

Despite the low level of historic seismicity, geologic evidence suggests that some faults may have been active as recently as the lower to middle Pleistocene. Kellogg and others (2002) mapped a series of down-to-the-east normal faults on the eastern flank of the Tenmile Range in the Frisco quadrangle, which is directly north of the Breckenridge quadrangle. These faults occur at a major break in slope between the steep, bedrock-cored slopes of the Tenmile Range, and the eroded remnants of an old erosion surface underlain by early Quaternary gravels (map unit QTgg). This break in slope continues southward into the Breckenridge quadrangle, through the Breckenridge Ski Area, and as far south as Carter Gulch, beyond which it is buried by glacial deposits. However, no young fault scarps are preserved in Quaternary deposits along this escarpment, so the fault has probably not been active since at least Pinedale time (16–23 ka). Recurrence intervals for damaging earthquakes in and near the Breckenridge quadrangle are largely unknown.

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