OPEN-FILE REPORT 02-3

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FOREWORD

The Colorado Department of Natural Resources is pleased to present the Colorado Geological Survey Open File Report 02-3, *Geologic Map of the Keystone Quadrangle, Summit County, Colorado.* Its purpose is to describe the geologic setting and mineral resource potential of this 7.5-minute quadrangle located in eastern Summit County. Beth Widmann, Matthew Morgan, Paul Bartos, Kenneth Shaver, Francisco Gutierrez, and Andrew Lockman completed the field work on this project in the summer of 2001.

This mapping project was funded jointly by the U.S. Geological Survey (USGS) and the Colorado Geological Survey (CGS). USGS funds are competively awarded through the STATEMAP component of the National Cooperative Geologic Mapping Program (Agreement No. 00HQAG0119). The program is authorized by the National Mapping Act of 1997. The CGS matching funds come from the Severance Tax Operational Account that is funded by taxes paid on the production of natural gas, oil, coal, and metals.

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This mapping project was funded jointly by the Colorado Geological Survey and U.S. Geological Survey through the STATEMAP program of the National Cooperative Geologic Mapping Program under Agreement 01HQAG0094. Mining companies that worked in the Breckenridge district part of the Keystone quadrangle are thanked for generously releasing their exploration data. These include Asarco, Incorporated, the Anaconda Minerals Company, and the FMC Gold Company. Company geologists whose detailed maps were modified and included in this report include Mark D. Cocker (Anaconda Minerals Company), Kurt C. Friehauf (Asarco, Incorporated), and Elliot M. Crist, Peter C. Dwelley, and J. Bruce Harlan (FMC Gold Company). Anaconda was a division of Atlantic Richfield Company and has now ceased to exist as a company. Asarco is now a division of Grupo Mexico. FMC Gold Company is now part of Meridian Gold Company.

Access to closed or limited-use areas was graciously provided by Boyd Mitchell (Keystone Ski Area), Jill Butrick (Keystone Stables), and Paul Semmer (U.S. Forest Service). Bill Cobban (USGS) spent a full day in the field discussing the stratigraphy of the Pierre Shale and looking for fossils. Bill was instrumental in helping map the various sandstones within the Pierre Shale. We appreciate the knowledge shared and guidance provided to the Quaternary mappers by Jim McCalpin (GeoHaz Consulting) and Rich Madole (consulting geologist). Karl Kellogg (USGS) and Bob Kirkham (CGS) are thanked for time spent in engaging discussions and debates and for their thorough reviews. Jane Ciener was the technical editor.

INTRODUCTION

Geologic mapping of the Keystone 7.5-minute quadrangle was undertaken by the Colorado Geological Survey (CGS) as part of the STATEMAP component of the National Cooperative Geologic Mapping Act, which is administered by the U.S. Geological Survey. Partial funding for this project came from Colorado Severance Tax, which is derived from the production of oil, gas, coal, and minerals. Geologic maps produced by the CGS through the STATEMAP program are intended as multi-purpose maps useful for land-use planning, geotechnical engineering, geologic-hazards assessment, mineral-resource development, and ground-water exploration.

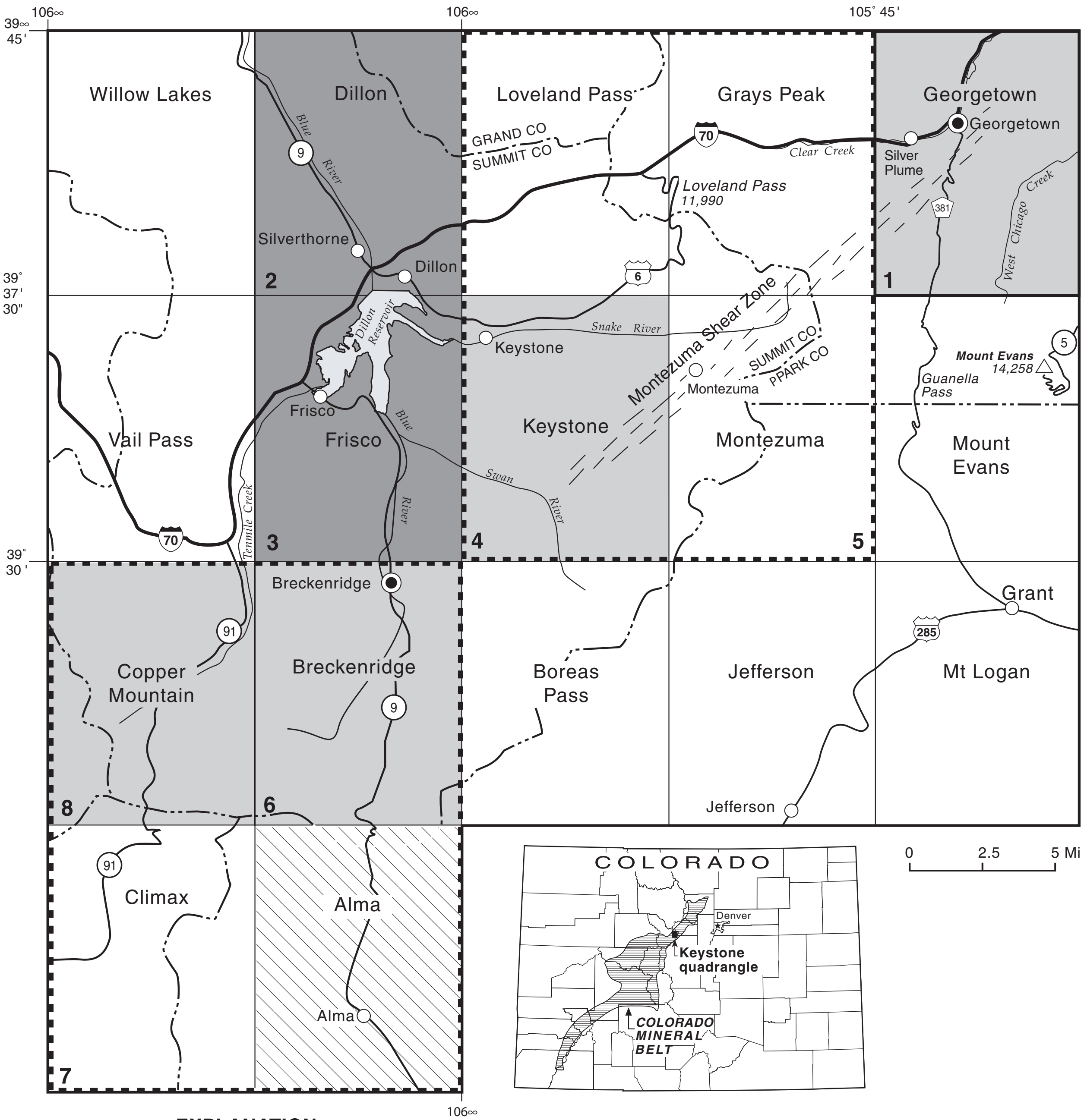
The Keystone quadrangle is located in Summit County on the western margin of the Colorado Front Range. The town of Keystone and the Keystone Ski Area lie at the northern end of the quadrangle and are accessed via U.S. Highway 6, which wraps around Dillon Reservoir before connecting with the Interstate-70 Highway transportation corridor (I-70) about 5 mi west of the quadrangle (Figure 1). Keystone Ski Area has a 6,000 acre permit area with 1,850 acres of trails on Keystone Mountain, which ranges in elevation from about 9,300 ft to 11,661 ft. The Snake River flows westward through the town of Keystone and drains into Dillon Reservoir. The Swan River and its tributaries, the North and Middle Fork, flow generally westward through the southern part of the quadrangle. The highest peaks are Independence Mountain (12,614 ft), Bear Mountain (12,585 ft), and Glacier Mountain (12,443 ft), all of which are located in the eastern part of the quadrangle. Historic metal mining production is from the Brewery Hill area (part of the Breckenridge mining district), the Saints John area (part of the Montezuma mining district), and the Swan River, or Swandyke, mining district located near Wise Mountain.

Figure 1 shows the current status of geologic mapping in the Keystone area. The Montezuma 15-minute quadrangle, which includes the Keystone 7.5-minute quadrangle, was previously mapped by Lovering (1935). The Breckenridge 7.5-minute quadrangle to the southwest was mapped concurrently with the Keystone quadrangle by Wallace and others (2003). The Frisco and Dillon quadrangles, which lie to the west and northwest of the Keystone quadrangle, were mapped by Kellogg and others (2000) and Kellogg (1997), respectively.

Field mapping for the Keystone quadrangle was undertaken during the summer of 2001. Quaternary deposits were mapped primarily by Matt Morgan (CGS) and Francho Gutierrez (University of Zaragoza, Spain). Paul Bartos (Colorado School of Mines) mapped the Brewery Hill region, southwest of the Swan River, and wrote the metallic mineral resources section. The area north of Independence Mountain and east of Camp Creek was mapped by Ken Shaver (consulting geologist). The remainder of the quadrangle was mapped by Beth Widmann (CGS) and field assistant Drew Lockman (Western State College, Colorado).

Proterozoic metamorphic and igneous rocks crop out in much of the quadrangle. The oldest are Early Proterozoic metasedimentary and metavolcanic rocks that were originally deposited more than 1,800 Ma (Tweto, 1987) and later metamorphosed during a period of intense deformation about 1,726 Ma (Selverstone and others, 1997). This metamorphic complex was subsequently intruded by granitic rocks of the Berthoud plutonic suite (Tweto, 1987) between about 1,448 and 1,420 Ma (Aleinikoff and others, 1993; Peterman and others, 1968).

During the Late Cretaceous to early Tertiary Laramide orogeny, the Proterozoic rocks were thrust over Cretaceous sedimentary rocks along the western margin of the quadrangle by the Williams Range thrust. A strong pulse of magmatism between 35 to 45 Ma (Bookstrom and others, 1987; Marvin and others, 1989) resulted in the locally forceful intrusion of numerous dikes and small stocks and the generally concordant intrusion of the Montezuma stock. Associated with the Tertiary intrusives are numerous precious and base metal veins. The youngest deposits in the quadrangle include glacial till of probable Pinedale and Bull Lake age, periglacial deposits, and other Quaternary surficial deposits.



EXPLANATION

- Current CGS 1:24,000 scale map
- CGS 1:24,000-scale map
- USGS 1:24,000-scale map
- USGS 1:62,500-scale map

Index Map No.	Map Area and Reference
1	Georgetown quadrangle (Widmann and Miersemann, 2001)
2	Dillon quadrangle (Kellogg, 1997)
3	Frisco quadrangle (Kellogg and others, 2000)
4	Keystone quadrangle (this publication)
5	Montezuma 15-minute quadrangle (Lovering, 1935)
6	Breckenridge quadrangle (Wallace and others, 2003)
7	Mount Lincoln 15-minute quadrangle (Tweto, 1974)
8	Copper Mountain quadrangle (Widmann and others, 2003)

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

DESCRIPTION OF MAP UNITS

SURFICIAL DEPOSITS

Surficial deposits shown on the map are generally more than 5 ft thick but may be thinner locally. Residuum and artificial fills of limited extent were not mapped. Contacts between surficial units may be gradational, and mapped units locally include deposits of another type. Divisions of the Pleistocene correspond to those of Richmond and Fullerton (1986). Age assignments for surficial deposits are based primarily upon the degree of erosional modification of original surface morphology, height above modern streams, and relative degree of clast weathering and soil development. Clast size is based on the modified Wentworth scale.

HUMAN-MADE DEPOSITS

lf — **Landfill (latest Holocene)—**Municipal trash deposited in a landfill along the northwestern border of the quadrangle. Maximum thickness is about 50 ft. The site may be subject to severe settlement. Materials placed in landfills may generate biogenic methane gas as organic materials decay, which can create explosive hazards and may pose environmental risk to local groundwater and streams.

af — **Artificial fill (latest Holocene)—**Unsorted silt, sand, and rock fragments deposited by humans during construction of U.S. Highway 6 and Tiger Road (along the Swan River) and during development projects in the Keystone area. This unit may also include areas of construction and/or quarrying operations where original deposits have been removed, replaced, or reworked. The average thickness of the unit is less than 30 ft. Artificial fill may be subject to settlement when loaded if not adequately compacted.

tw — **Tunnel waste (latest Holocene)—**Pebble- to cobble-size angular fragments of waste rock removed from an access shaft during excavation of the Harold D. Roberts water diversion tunnel in the late 1950s and early 1960s. Clasts include Tertiary quartz monzonite of the Montezuma stock (Tqm) and hornfelsed Cretaceous shale (Kbp) that were encountered in parts of the tunnel west of the shaft (Robinson and others, 1974). May be underlain by mine waste originating from the Hunkidori mine at the head of Grizzly Gulch.

dt — **Dredge tailings (latest Holocene)—**Waste material consisting primarily of rounded clasts of river gravel removed from the Swan and Snake River beds during dredging operations that started in the late 1800s and continued until 1959. The tailings are characterized by well-rounded, pebble- to small boulder-size clasts of Precambrian gneiss and granite, Paleozoic sandstone, Tertiary intrusive rocks, and less commonly, Mesozoic sedimentary rocks. Dredge tailings may form linear ridges up to about 20 ft high adjacent to modern stream channels. In many areas the ridges have been re-graded or mined for gravel. The deposits are an excellent source of clean, well-sorted gravel.

mw — **Mine and mill waste (latest Holocene)—**Waste rock excavated from mines and prospecting pits, and mill tailings resulting from milling operations. Mine waste typically consists of pebble- to cobble-size angular fragments of altered Precambrian granite and gneiss, Cretaceous sedimentary rocks, and/or intrusive Tertiary porphyry. The deposits may be as much as 30 ft thick. Mill tailings are composed of smaller fragments and are usually only a few feet to tens of feet thick. Environmental problems, such as contamination of ground and surface water due to acid runoff and influx of heavy metals, may be associated with these deposits.

ALLUVIAL DEPOSITS—Silt, sand, and gravel in stream channels, flood plains, terraces, small debris fans, and sheetwash areas.

Qal — **Stream-channel, flood-plain, and low-terrace alluvium (Holocene)—**Deposits are mostly clast-supported, pebble, cobble, and locally boulder gravel in a sandy silt matrix. The deposits are locally interbedded with and commonly overlain by sandy silt and silty sand. Clasts are subangular to well rounded, and their varied lithology reflects the diverse types of bedrock within their provenance. This unit includes modern stream-channel deposits of the Snake River, North Fork of the Snake River, Swan River, North Fork and Middle Fork of the Swan River, adjacent flood-plain deposits, and low-terrace alluvium that lie a maximum of 10 ft above modern stream level. Deposits may be interbedded with colluvium or debris-fan deposits where the distal ends of fans extend into modern river channels and flood plains. Maximum thickness of the unit may exceed 30 ft. Areas mapped as alluvium may be prone to flooding and sediment deposition. The unit is typically a good source of sand and gravel.

Qty **Younger terrace alluvium (late Pleistocene)—** Consists of poorly sorted, clast-supported, cobble, pebble, and locally boulder gravel in a silty, sandy matrix underlying terraces 10–20 ft above modern stream channels. Fine-grained overbank deposits may be present locally. Clasts are generally unweathered and abundant on the surface. Soil development on terrace surfaces is weak. Terrace alluvium may be up to about 25 ft thick and was probably deposited as glacial outwash along the Snake, Swan, and North Fork of the Swan rivers. The unit may be a good source of sand and gravel.

Qto **Older terrace alluvium (early to middle Pleistocene)—**Chiefly stream deposits that underlie small terraces up to 160 ft above the Swan River in the southwest corner of the quadrangle. The deposits are texturally and depositionally similar to younger terrace alluvium (Qty), but clasts are moderately to highly weathered and not as abundant on terrace surfaces. Soil horizons are moderately well developed. Average thickness of the deposit is about 40 ft but locally may exceed 100 ft. The unit may be a potential source of sand and gravel.

SINTER DEPOSITS—Gravel cemented by metal-rich precipitates.

Qfe **Ferricrete deposits (Holocene)—**Poorly sorted, coarse-grained, matrix-supported sand and pebble gravel in a sandy silt matrix that is cemented by the chemical precipitation of iron oxides. Clast lithology is predominantly Precambrian granite and gneiss and Tertiary intrusive rock. A single ferricrete deposit is mapped north of the historic mining camp of Swandyke. The mapped unit presumably marks the area below a former iron-rich spring. Fragments of ferricrete were found in talus slopes west of Wise Mountain; however in-situ deposits were not located in this area.

COLLUVIAL DEPOSITS—Silt, sand, and gravel on valley sides and floors. Material mobilized, transported, and deposited primarily by gravity, but commonly assisted by sheetwash, freeze-thaw action, and water-saturated conditions that affect pore pressure.

Qc **Colluvium (Holocene and late Pleistocene)—** Includes weathered bedrock fragments that have been transported downslope primarily by gravity. Colluvium ranges from unsorted, clast-supported, pebble to boulder gravel in a sandy silt matrix to matrix-supported gravelly, clayey, sandy silt. It is generally unsorted to poorly sorted and contains angular to subangular clasts. Colluvial deposits derived from glacial or alluvial deposits contain rounded to subrounded clasts. Clast lithology is variable and dependent upon types of rocks occurring within the provenance area. Locally, this unit may include debris-fan deposits that are too small or too indistinct on aerial photography to be mapped separately. Colluvium commonly grades into and interfingers with alluvial, debris-fan, landslide, talus, glacial, and sheetwash deposits. Maximum thickness of this unit is probably about 30 ft; however, thickness may vary. Areas mapped as colluvium are susceptible to future colluvial deposition and locally are subject to debris flows, rockfall, and sheetwash. Colluvial deposits may be a potential source of aggregate.

Qta **Talus deposits (Holocene and late Pleistocene)—**Angular, cobbly and bouldery rubble derived from bedrock that was transported downslope by gravity principally as rockfalls, rock avalanches, rock topples, and rockslides. Downslope movement may have been locally aided by water and freeze-thaw action. This unit typically lacks matrix material near the surface, but dissected talus reveal significant matrix at depth. Talus deposition is active and widespread over the eastern half of the quadrangle, especially below the steep walls of glacial cirques. Significant talus deposits are located on the north face of Sheep and Glacier mountains, the area north of the Swandyke, and near the junction of the North Fork of the Snake River and the Snake River. Thickness of the deposits may exceed 20 ft in thickness. Talus areas are subject to severe rockfall, rock-topple, and rockslide hazards.

Qlsy **Younger landslide deposits (Holocene and late Pleistocene)—**Heterogeneous deposits consisting of unsorted and unstratified deposits of clay, silt, sand, and angular, boulder-size rock fragments. Unit includes rotational and translational slides and complex slide-flow mass movements. They show obvious geomorphic expression that disrupts the original profile of the slopes. Generally, head scars are readily recognizable and common diagnostic features include hummocky topography, closed depressions hosting paludal environments, and pressure ridges at the toe of the mobilized mass. Some of the young landslides in the high areas in the eastern half of the quadrangle have rectilinear limits, strongly suggesting a structural control. The upper parts of the landslides mapped near Bear Mountain, Garibaldi Gulch, and on the southern slope of Keystone Mountain display a distinct series of gravitational scarps. Generally, these landslides are late- to post-glacial and some of them are very recent and have clear signs of active movement. In glaciated areas, a large proportion of these landslides may have been triggered by unloading (release of lateral confining pressure) subsequent to the melting and retreat of the ice masses.

Landslide areas may be subject to future movement during periods of excessive rain or snowfall or may be reactivated by human-made disturbances such as cutting of slopes for road construction, housing developments, irrigation, and septic systems. Landslide deposits may be prone to settlement when loaded or wetted. Large rock fragments within this deposit are a potential source of riprap and aggregate.

Qlsp

Pre-glacial landslide deposits (early to middle Pleistocene)—Includes large toreva blocks and unsorted, unstratified rock fragments ranging in size from boulders to sandy silt. Erosional processes have dissected and obliterated most of their original morphological expression, but poorly preserved undulating surfaces and closed depressions filled with paludal sediments (Qps) may be present locally. In outcrop scale, large transported rock masses may be strongly deformed by brittle deformation or may show no evidence of internal disruption. On the southeast and northwest flanks of Glacier Mountain, these large landslides may have been structurally controlled by the Montezuma shear zone and Saints John and Jones Gulch faults. These landslides appear to have developed previous to glacial advance and were subsequently smoothed and reworked by glacial erosion. Intense fracturing of the bedrock in these areas may have facilitated development of the landslides. Thickness of the landslides is unknown but may be as much as a few hundred feet.

These landslides may be in a state of quasi-equilibrium, but anthropogenic disturbances such as cutting of slopes for roads or development may affect the stability of the landslides and instigate renewed activity.

Qls

Landslide deposits, undifferentiated (early to late Pleistocene)—Mapped in areas where the relative age of a landslide is difficult to ascertain because many of the more common diagnostic features used to establish relative age have been altered either by human activities or glacial scouring. May also include large blocks of intact bedrock.

The landslide complexes on the west margin of Jones Gulch and the north slope of Keystone Mountain cover approximately 1.4 and 3.6 sq mi, respectively, and locally have obvious geomorphic expression and fresh signs of instability (such as head scars, closed depressions, and reversed slope gradients) suggesting recent localized movement.

ALLUVIAL AND COLLUVIAL DEPOSITS—Gravel, sand, and silt in debris fans, stream channels, flood plains, and lower reaches of adjacent hillslopes. Depositional processes in stream channels and on flood plains are primarily alluvial, whereas colluvial and sheetwash processes are predominant on debris fans and along the hillslope-valley floor boundary.

Qac

Alluvium and colluvium, undivided (Holocene and late Pleistocene)—Unit primarily consists of stream channel, low-terrace, and flood-plain deposits along valley floors of ephemeral, intermittent, and small perennial streams and colluvium deposits along valley sides. Probably interfingers with stream alluvium (Qal), debris-fan deposits (Qf), and colluvium (Qc) deposited along valley margins. Alluvium is typically composed of poorly to well sorted, stratified, interbedded, pebbly sand, sandy silt, and sandy gravel. Colluvium may range from unsorted, clast-supported, pebble to boulder gravel in a sandy silt matrix to matrix-supported, gravelly, clayey, sandy silt. Clast lithologies vary and are dependent upon the bedrock or surficial unit from which the deposit was derived. Maximum thickness of the unit is approximately 20 ft.

Qcs

Colluvium and slopewash deposits, undivided (Holocene and late Pleistocene)— Colluvium and sheetwash deposits are found on gentler slopes along Soda Creek and west of Muggins Gulch. These deposits consist primarily of weathered pebble- to clay-size particles of Cretaceous Pierre Shale and lesser cobble- to sand-size fragments of Proterozoic basement rock and Tertiary quartz monzonite. Maximum thickness is probably less than 10 ft.

Qf

Debris-fan deposits (Holocene and late Pleistocene)—Poorly sorted to moderately sorted, matrix-supported, gravelly, sandy silt to clast-supported, pebble and cobble gravel in a sandy silt or silty sand matrix. Clasts are mostly angular to subround with varied lithologies dependent upon local source rock. Sediments are deposited by debris flows, hyperconcentrated flows, streams, and sheetwash. Fan-shaped deposits form where tributary drainages with steep gradients join lower gradient streams. Debris-fan deposits commonly grade from boulder- and cobble-size fragments at the head of the fan to silty sand near the fan terminus. The maximum estimated thickness for debris fans along the Snake River may exceed 60 ft. Elsewhere, the deposit is typically less than 30 ft. Extraordinary precipitation events may trigger future deposition in areas mapped as debris-fan deposits. Debris-fan deposits may be prone to collapse when wetted or loaded.

PALUSTRINE DEPOSITS—Peat, clay, silt and sand deposited primarily by water in shallow basinal areas.

Qps

Paludal sediments (Holocene to late Pleistocene)—Organic-rich, fine-grained sediments formed in swampy closed depressions where the water table is near or slightly above the ground surface. The reducing conditions in these stagnant environments slow the rate of decay of the organic matter, which favors accumulation of organic material. These types of sediments are found in and adjacent to tarns and in closed depressions generated by landslide activity. Paludal sediments are highly compactible. Basins in which these sediments are deposited have elevated water tables and may be prone to flooding.

PERIGLACIAL DEPOSITS—Deposits formed in cold environments by freeze-thaw action, solifluction, and nivation.

Qpr

Protalus-rampart deposits (Holocene and late Pleistocene)—Unsorted, unstratified deposits of angular rock fragments that form arcuate ridges at the downslope edge of existing or perennial snow fields. Rock fragments are moved downslope across snowfields by freeze-thaw action, melt-water percolation, and gravity and are deposited at the distal ends of the snow fields. This unit typically lacks matrix material near the surface, but has considerable silty, sandy matrix at depth. A single 0.6 mi long protalus rampart with a 10 ft high ridge crest lies at the base of the northwest flank of Glacier Mountain.

Qs

Solifluction deposits (Holocene and late Pleistocene)—Angular to subrounded pebbles, cobbles, and large boulders in a chiefly sandy matrix deposited in alpine and subalpine basins. Solifluction deposits result from the slow downslope flowage of surficial deposits that are water saturated and subject to seasonal freezing. Frost creep and meltwater transport are also important factors in the formation of these deposits. This type of slope movement, involving a slow, downslope plastic deformation of the soil and surficial deposits, primarily affects the upper slopes in the eastern half of the quadrangle. Solifluction areas are characterized by hummocky terrain, ground cracks and fissures up to several inches wide, and numerous seeps and springs. On open hillslopes solifluction may also produce lobes or terracettes, with small ledges or benches up to about 5 ft high, through differential movement of surficial material. Solifluction also affects tree- covered slopes as indicated by downslope leaning of tree trunks. Average thickness of these deposits is typically less than about 15 ft. These deposits may be susceptible to future downslope movement and shallow groundwater.

Qrg

Rock glaciers (Holocene or late Pleistocene) —Poorly sorted angular to sub-angular boulders, cobbles, gravel, and sandy silt in a matrix of firn or glacier ice. The outer part of the rock glacier is typically clast-supported, matrix-free, and composed of angular to subangular, predominantly boulder-sized rock fragments. Downslope movement is the result of internal deformation of the firn or ice core. Rock glaciers commonly have a lobate or tongue-like morphology and form in cirque basins where sediment supply is abundant. There are three rock glaciers with well-developed, lobate morphology emanating from a cirque to the north of Sheep Mountain at the base of a large, active talus slope. Another smaller, less well-developed rock glacier is at the base of the north flank of Bear Mountain.

GLACIAL DEPOSITS—Gravel, sand, silt, and clay deposited by ice along the Snake River, North and Middle Forks of the Swan River, and Grizzly and Saints John Creeks.

Qtn **Neoglacial till (Holocene)—**Heterogeneous deposits of gravel, sand, silt, and clay deposited by ice on the floor of some of the highest north-facing cirques in the east part of the quadrangle, such as at the head of Grizzly Gulch. These deposits are chiefly poorly sorted, unstratified or poorly stratified, matrix-supported, boulder, pebble, and cobble gravel in a silty-sand matrix. Clasts are typically angular to subrounded. Deposition of this young till is the result of retreat and/or advance of ice masses during the Holocene, and may be temporally related to ground moraine or lateral and terminal moraine ridges. These deposits have an irregular topography with abundant boulders exposed at the surface, very little evidence of clast weathering, and almost no soil development. Estimated thickness is about 25 ft.

Qti **Glacial till, undivided (late and middle? Pleistocene)—**Heterogeneous deposits of gravel, sand, silt, and clay deposited by ice in ground, lateral, and end moraines. May also include localized lenses of material transported by melt-water adjacent to ice. These deposits are chiefly poorly sorted, unstratified or poorly stratified, matrix-supported, boulder, pebble, and cobble gravel in a silty-sand matrix. Clasts are typically angular to rounded. Surface topography and soil development in till throughout the quadrangle are highly variable.

Clasts are abundant at the ground surface in till deposited along the margins of the North Fork and Middle Fork of the Swan River, Saints John Creek, and parts of the Snake River. The clasts are generally unweathered to slightly weathered. Locally, however, some clasts are very weathered. Pedogenic soils in these locations have a moderately well-developed A-horizon and weakly developed C-horizon. Small kettle holes and hummocky topography, which are typical of late Pleistocene glacial till are locally developed. Degree of clast weathering, lack of soil development, and surface morphology suggest a late Pleistocene (Pinedale) age for these deposits.

Till deposited on the high slopes surrounding Porcupine Peak and on the margins of the Swan River contain clasts that are unweathered to highly weathered. Soils developed on these till surfaces have well-developed A-, B-, and C-horizons, with local variability. Clast weathering characteristics, well-developed soils, and erosional modification of surface morphology suggest these deposits may be late middle Pleistocene (Bull Lake) in age.

Qm **Moraine deposits, undifferentiated (late and middle? Pleistocene)—**Includes glacial deposits located near the northwestern corner of the quadrangle. The deposits are generally similar in texture and lithology to glacial till (Qti) and are exposed in a steep-sided, well-preserved, arcuate landform that has the appearance of an end or terminal moraine. Locally, however, the unit is stratified and well sorted, which suggests a possible fluvial component. Two foundation excavations into the deposit exposed subrounded to well-rounded clasts of gneiss, granite, and porphyry in a gravely sand to sandy silt matrix. Clasts range from unweathered to very highly weathered. Weakly developed A- and C-horizons were observed, along with a moderately developed B-horizon.

Weak to moderate soil development, the presence of numerous unweathered clasts, and a well-preserved landform suggests this deposit is young, possibly late Pleistocene (Pinedale) in age. However, the surface of the landform lacks the mounds and depressions characteristic of most other Pinedale moraines in the area, and the presence of some highly weathered clasts indicates the deposit may be older. Furthermore, it appears as though the sediments were not solely deposited by ice but also by fluvial transport, as indicated by pockets of well stratified and well sorted material. The deposit is inferred to be a moraine deposit with a possible fluvial component based on its landform and sedimentological character. The age of the deposit is considered late or middle Pleistocene.

BEDROCK UNITS

TERTIARY INTRUSIVE ROCKS—Tertiary intrusive rocks in the northeastern part of quadrangle are genetically related to the 35 to 40 Ma Montezuma stock (Cunningham and others, 1994). Lithologically similar intrusive rocks in the southwestern part of the quadrangle are associated with the slightly older Swan Mountain intrusive complex (43 to 44 Ma) centered near Breckenridge (Bryant and others, 1975). Herein, Tertiary rocks younger than 38 Ma are considered Oligocene in age on the basis of the geologic time scale by Palmer and Geissman (1999). Intrusive rocks were named using the classification system of Streckeisen (1976).

Tqm **Quartz monzonite porphyry of the Montezuma stock (early Oligocene to Eocene)—**Buff to light gray porphyritic quartz monzonite. Phenocysts of orthoclase, quartz, and plagioclase are poorly to randomly oriented in a coarse- to medium-grained matrix of plagioclase, orthoclase, quartz, and biotite. Lesser constituents include hornblende, magnetite, and sphene. Pink orthoclase phenocrysts are blocky to tabular and range up to a few inches in length. Phenocrysts of quartz are smaller, typically less than about 0.3 in., and commonly have a resorbed texture. Coarse, euhedral biotite may locally exceed 0.2 in. in diameter. Orthoclase and plagioclase occur in roughly equal proportions and together comprise about 60 percent of the rock; about 25 percent of the rock is quartz, and 2.5 to 8 percent is biotite (Robinson and others, 1974). Light pink aplite dikes and veinlets with a fine-grained sugary texture formed by quartz and feldspar crystals are locally associated with the stock.

Bookstrom and others (1987) reported a zircon fission-track age of 39.8 ± 4.2 Ma for the Montezuma stock east of the quadrangle and 37.4 ± 3.0 Ma for a sericitized sample collected from the southeast margin of the stock, also east of the quadrangle. The younger age is suspected to reflect hydrothermal alteration and partial resetting associated with intrusions stemming from a slightly younger, much larger, hidden stock south of the Montezuma stock (Bookstrom and others, 1987). Marvin and others (1989) reported a potassium-argon age of 37.9 ± 1.4 Ma on biotite in the Montezuma stock, and Cunningham and others (1994) reported a zircon fission-track age of 35.0 ± 3.2 Ma for stock. Although the error margins of these dates overlap, the younger date may represent a slightly younger pulse of intrusion, as suggested by Bookstrom and others (1987).

Tql **Quartz latite (Eocene)—**White to light gray, fine-grained felsic intrusive rock with alkalic feldspar and quartz phenocrysts. Compositionally, the rock is chiefly a quartz latite, but it varies locally towards rhyolite. Weathered fragments are commonly similar in appearance to shards of white pottery, and dendrites of manganese oxide are found locally along fracture surfaces. Quartz-latite porphyries intruded as narrow dikes on Wise Mountain and as a small plug in the cirque north of Swandyke. A rhyolite body at the Wirepatch mine just south of the quadrangle that is correlated with quartz latite of the Keystone quadrangle has a potassium-argon date of 41.4 Ma (Pride and Robinson, 1978).

Tqpm **Quartz monzonite porphyry, megacrystic variety (Eocene)—**Buff or light brown weathering, porphyritic, quartz-plagioclase-orthoclase-biotite-hornblende monzonite. Megacrysts of orthoclase, quartz, and plagioclase are typically 0.5 to 1.5 in. in length; Lovering (1934) reported orthoclase phenocrysts as long as 3 in. The groundmass is medium to coarse grained. Orthoclase phenocrysts comprise as much as 20 percent of the rock, and quartz phenocrysts (commonly partially resorbed and embayed) comprise 2 to 10 percent of the rock. Euhedral biotite comprises 1 to 3 percent of the rock and is much more abundant than sparse hornblende. White, chalky plagioclase phenocrysts are also common. A greenish colored variety of the monzonite porphyry is similar in texture and composition but contains a higher percentage of hornblende phenocrysts.

Quartz monzonite porphyry crops out as large stocks, sills, and narrow dikes and is most prevalent in the southwest part of the quadrangle. Quartz monzonite porphyry at Brewery Hill yielded a potassium-argon age on biotite of 43.8 ± 1.5 Ma (Bryant and others, 1975), and a whole-rock, rubidium-strontium age of about 44 Ma (Simmons and Hedge, 1978). Analogous porphyry underlying Swan Mountain, which is located southwest of the quadrangle, was similarly dated at 44.1 ± 1.6 Ma (Marvin and others, 1989).

Tbx

Breccia (Eocene)—Highly variable unit ranging from igneous breccia (sedimentary rock clasts in an igneous matrix), to hydro-thermal breccia (sedimentary and igneous clasts in a communated rock matrix), typically with hydrothermal mineral deposition in void spaces. Clasts are angular and range in size from less than 0.5 in. up to 5 ft and are predominantly composed of Pierre Shale; only a small percentage of clasts are composed of Dakota Sandstone, quartz monzonite porphyry, or gneiss. Includes only two deposits near Brewery Hill.

Tmp

Hornblende-biotite monzonite porphyry (Eocene)—Dark gray monzonite porphyry composed of plagioclase, orthoclase, hornblende, and biotite phenocrysts in an aphanitic groundmass. Plagioclase and orthoclase phenocrysts are present in roughly equal proportions and make up about 10 percent of the rock. Hornblende and biotite each comprise about 3 percent of the rock. Plagioclase and orthoclase phenocrysts are typically less than 0.15 in. long, whereas subhedral blades of hornblende range up to about 0.3 in. long. Biotite phenocrysts are pseudohexagonal and generally only 0.1 in. long.

Thin dikes of hornblende-biotite porphyry crop out near the southwestern corner of the quadrangle in the Brewery Hill region. This porphyry and the mega-crystic quartz-monzonite porphyry (Tqpm) are considered close in age (Ransome, 1911; Lovering, 1934).

CRETACEOUS SEDIMENTARY ROCKS—Thick sequences of shale, minor limestone, and sandstone deposited in a marine or beach environment.

Pierre Shale (Upper Cretaceous)—The Pierre Shale, which consists of a lower, middle, and upper part, is described in detail by Izett and others (1971). The lower and upper parts consist of massive, light to dark gray marine shale, whereas the middle part is characterized by silty shale interbedded with sandstone. Only the lower and middle parts of the Pierre Shale are exposed in the Keystone quadrangle. The upper part has been eroded or is truncated by the Williams Range thrust and is not exposed in the quadrangle. The contact between the lower and middle parts is placed roughly 250 ft below the lowest sandstone unit in the middle part on the basis of stratigraphy reported by Izett and others (1971). Adjacent to the Tertiary Montezuma stock (Tqm) in the northeastern corner of the quadrangle, the Pierre Shale has been altered to a dark gray to black, fine-grained hornfels through contact metamorphism.

Kpm

Middle Part—The middle part of the Pierre Shale consists of alternating sequences of black shale and silty sandstone. Six sandstone members were described in the middle part of the Pierre Shale by Izett and others (1971), but only the lower three members crop out in the Keystone quadrangle. They include, in descending order, the Hygiene Sandstone, Muddy Buttes Sandstone, and Kremmling Sandstone Members. Correlation of these members is based primarily on grain size, bedding patterns, and trace fossils in the sandstone.

Kpmh

Hygiene Sandstone Member—Composed of massive, locally calcareous, buff to light gray, fine-grained sandstone that grades upwards into thinly bedded sandstone. Trace fossils and shell fragments are present but are not abundant. This ridge-forming sandstone is separated from the underlining Muddy Buttes Member by several hundred feet of dark gray to black marine shale. The Hygiene Sandstone Member crops out only in the northwestern corner of the quadrangle, where it forms a cliff about 15 ft high. Total thickness of the unit is estimated at about 50 to 60 ft. The age of this unit is about 75.8 Ma (W.A. Cobban, 2001; written communication).

Kpmm

Muddy Buttes Sandstone Member—Consists of thinly bedded, locally flaggy, fine-grained sandstone and shaly siltstone. Trace fossils and ripple marks are abundant throughout, but shell fragments are scarce. The unit is locally carbonaceous. It weathers yellowish brown and forms discontinuous ledges along Soda Creek and the north side of the Snake River. The lower part of the member is gradational with underlying shale, but thickness of the sandstone member is probably about 40 ft. The member overlies about 100 ft of marine shale and silty shale above the Kremmling Sandstone Member.

Kpmk

Kremmling Sandstone Member—Texturally and lithologicaly similar to the Muddy Buttes Sandstone Member. The lower part of the member is shaly siltstone and sandstone, and the upper part is flaggy to blocky, fine-grained sandstone. Trace fossils and ripple marks are abundant throughout, but shell fragments are scarce. The member is about 40 ft thick and is well exposed in the northwestern part of the quadrangle.

Kpms

Sandstone members, undivided— Fine-grained sandstone and shaly siltstone that weathers yellowish brown to medium gray. Typically, this unit does not crop out and is mapped on the basis of small sandstone fragments in the surface float. Trace fossils were observed in some fragments, and the unit is locally calcareous. The sandstone beds may be equivalent to the Muddy Buttes or Kremmling Sandstone Members, but could not be mapped decisively in Soda Creek due to poor outcrop exposure and limited fossil control.

Kpl

Lower Part—The lower part of the Pierre Shale is composed almost entirely of dark gray, non-sandy, clayey marine shale, with rare, thin, silty or sandy beds and bentonite layers. Conchoidal fracture on broken surfaces is very common. Izett and others (1971) reported numerous limestone and ironstone concretions and an abundance of plant and fish fossils, although in the Keystone quadrangle these lithologies and fossils are scarce. The lowest 30 to 60 ft is calcareous, and calcite veins are common near the conformable basal contact with the Niobrara Formation. This basal contact crops out in the southwest corner of the quadrangle west of Muggins Gulch and the rocks at the contact are considered to be about 80 Ma (W.A. Cobban, 2001; written communication). The lower part of the Pierre Shale in the Keystone quadrangle is at least 800 ft thick.

Kn

Niobrara Formation (Upper Cretaceous)— Includes the upper Smoky Hill Shale Member and the lower Fort Hays Limestone Member, not mapped separately in this quadrangle. The Smoky Hill Shale Member consists of light to medium gray, platy-weathering, calcareous shale and shaly limestone. This member crops out on the west side of Soda Creek and in the southwestern part of the quadrangle. Only a 30 ft thick section of the member is exposed beneath the Pierre Shale on the north side of the Swan River. South of the Swan River, the Smoky Hill Shale is intensely intruded by Tertiary porphyry, making it difficult to determine the total thickness of the unit. The member is estimated to be at least a few hundred feet in thickness in the southern part of quadrangle, but it probably does not attain the 450 ft thickness described by Robinson and others (1974) in the Roberts Tunnel to the north.

The Fort Hays Limestone Member is characterized by light gray, micritic limestone beds ranging in thickness from only a few inches to a few feet that crop out in and near Muggins Gulch. Kellogg and others (2000) reported inoceramid bivalves (large oysters) in the Fort Hays Member in the Frisco quadrangle to the west. None of these bivalve fossils were observed in the limited exposures of this member in the Keystone quadrangle. The Fort Hays Member is about 25 ft thick. It conformably overlies the Benton Shale, although in upper Muggins Gulch the sequence appears to be overturned in a thrust wedge.

Kb

Benton Shale (Upper Cretaceous)— Thick sequence of dark gray to black, carbonaceous shale interbedded with sandy or silty shale and minor limestone. Benton Shale is poorly exposed near the mouth of Soda Creek, south of the Swan River, and in the thrust wedge near Muggins Gulch. Where better exposed west of the quadrangle, the formation is about 325 ft thick (Kellogg and others, 2000). The base of the shale is faulted out along Soda Creek, and it is intruded and deformed by Tertiary porphyry south of the Swan River. These factors make it difficult to determine formation thickness. Benton Shale is presumably less than 250 ft thick in the quadrangle. It conformably overlies Dakota Sandstone. The Benton Shale is susceptible to mass movement and has moderate shrink-swell potential.

Kpb

Pierre Shale, Niobrara Formation, and Benton Shale, undivided (Upper Cretaceous) —These three formations are mapped as a single unit in the northeastern part of the quadrangle. In this area, the Montezuma stock has metamorphosed these rocks, which makes it difficult to differentiate between the three formations. Fine-grained, dark gray to black hornfels is the predominant lithology. Minor and laterally discontinuous layers of fine-grained sandstone and limestone are present locally but were not mapped separately.

Kd

Dakota Sandstone (Lower Cretaceous)— Light gray to white, fine- to medium-grained, well-sorted, massive sandstone and quartzite. Dakota sandstone is poorly exposed within the quadrangle. A small fault block of Dakota Sandstone, intruded by Tertiary porphyry (Tqpm), crops out in the Brewery Hill region in the southwestern part of the quadrangle. Dakota Sandstone crops out in a thrust wedge rooted to the main Williams Range thrust, and numerous small fragments of Dakota Sandstone are present along much of the fault trace. Total thickness of the Dakota Sandstone west of the quadrangle is 180 ft (Taranik, 1974).

J₸u

Jurassic and Triassic rocks, undivided— Shown only in cross section

PROTEROZOIC INTRUSIVE ROCKS—Proterozoic intrusive rocks of the Colorado Front Range belong to three different suites (Tweto, 1987). The oldest igneous rocks belong to the Routt plutonic suite, which was emplaced about 1,700 Ma. The Berthoud plutonic suite was emplaced about 1,400 Ma. Rocks that intruded around 1,000 Ma include mafic and intermediate dikes and rocks of the Pikes Peak batholith. Igneous rocks in the Keystone quadrangle are correlated to the Berthoud plutonic suite.

Ysp

Silver Plume Granite (Middle Proterozoic)— Pink to pinkish gray, massive to moderately foliated, medium- to coarse-grained granite consisting primarily of microcline, plagioclase, and quartz, with minor to moderate amounts of biotite and/or muscovite. The granite is typified by a seriate porphyritic texture defined by alignment of feldspar phenocrysts, many of which exhibit Carlsbad twinning. Tabular phenocrysts of orthoclase and microcline may exceed one inch in length. Locally, the granite is finer grained and contains a higher percentage of biotite than the coarser variety. This unit also includes smaller concentrations of equigranular granite, pegmatitic granite, and a foliated variety with thin anastomizing biotite-rich seams. Near the type locality at Silver Plume, about 25 mi east of the quadrangle, this granite yielded a uranium-lead zircon age of 1,422 ± 2 Ma (Graubard and Mattison, 1990). The Silver Plume Granite is a good source of building stone, riprap, and aggregate.

Ybx

Intrusion breccia (Middle Proterozoic)— Fragments of felsic gneiss (Xf) and hornblende gneiss (Xh) partially assimilated in the northwest margin of the granite on Sheep Mountain (Yg). Granitic material in the intrusion breccia is finer grained than in the main intrusive body, but is similar in composition. It is light pink in color and contains microcline, quartz, and minor biotite. Many of the smaller (generally less than 2 ft in any dimension) fragments of host rock tend to be angular and have a sharp contact with the enclosing granite. Larger inclusions (up to several tens of feet in length) are stretched and partially assimilated by the intrusion. The intrusion breccia is presumably very close in age to the granite of Sheep Mountain.

Yg

Granite of Sheep Mountain (Middle Proterozoic)—A small body of pinkish gray, massive to slightly gneissic, coarse-grained to pegmatitic microcline-quartz-biotite granite that crops out on Sheep Mountain in the southeast corner of the quadrangle. The groundmass consists of microcline, quartz, orthoclase, oligoclase, biotite, and minor hornblende. Abundant pink, Carlsbad-twinned, microcline phenocrysts, locally as much as 2 in. long, are responsible for the pinkish color of the rock. An associated intrusion breccia (Ybx) is present on the northwest margin of the stock.

This unit was correlated to the Rosalie Granite by Lovering (1935). Rosalie Granite about 20 mi northeast of Sheep Mountain was dated at 1,448 ± 9 Ma (U-Pb zircon age; Aleinikoff and others, 1993).

Yd

Proterozoic intrusives, undifferentiated (Middle Proterozoic?)—Medium- to dark gray, fine- to medium-grained, slightly porphyritic rocks composed primarily of plagioclase and hornblende. A small plug and a short dike on Porcupine Peak are of the dark gray variety. Both are medium-grained with a ground mass of plagioclase, pyroxene, and minor magnetite. Pheno-crysts include laths of plagioclase and subhedral crystals of pyroxene that are less than 0.1 in. in diameter. Sericite alteration is moderate. A few fragments of this rock type are also present on Glacier Mountain, but the associated intrusive body could not be found.

Robinson and others (1974) mapped the plug on the northwest flank of Porcupine Peak as a Tertiary augite diorite. However, on the basis of composition, Ulrich (1963) correlated it with Middle Proterozoic diabase and andesite dikes in the northern Front Range (Tweto, 1987). Although the rock has not been dated it is herein considered a Precambrian intrusive due to its compositional and textural dissimilarity with other Tertiary intrusives in the area.

A medium gray, dark brown weathering, fine-grained dike is well exposed on the eastern peak of Bear Mountain and can easily be seen from the town of Saints John as a dark band cross-cutting the somewhat lighter colored Early Proterozoic rocks. The chief mineral constituent of this dike is potassium feldspar. The rock contains less than 8 percent amorphous opaque minerals and minor epidote alteration.

YXp

Pegmatite, aplite, and related rocks (Middle and Early Proterozoic)—Includes pegmatite, coarse-grained granite, and fine-grained aplite, all of which are composed of feldspar and quartz with accessory biotite, muscovite, magnetite, and hornblende. Pegmatite dikes consist of light pink orthoclase or microcline, slightly smoky quartz, and small amounts of mica. Granitic bodies have a similar composition, but has greater amounts of mica and magnetite, tends to be medium to coarse grained, and is locally weakly foliated. Biotite is more abundant than muscovite, and the two types of mica usually, but not always, occur in different pegmatite bodies. Aplite dikes and veinlets are light pink and have a fine-grained sugary texture formed predominantly by quartz and feldspar crystals.

PROTEROZOIC METAMORPHIC ROCKS— Metasedimentary and metavolcanic rocks in the Keystone quadrangle historically were included in the Idaho Springs and Swandyke Formations (Spurr and others, 1908; Lovering, 1935). Lovering (1935) considered the Swandyke Formation to be slightly younger than the Idaho Springs Formation. This stratigraphic relationship was not substantiated in this study, nor has it been determined on a more regional scale. More recently, the rock units have simply been named on the basis of their mineralogy. These rocks were originally deposited or erupted about 1,780 to 1,800 Ma (Premo and Fanning, 1997). Similar rocks in the northern Front Range experienced peak metamorphism about 1,726 ± 15 Ma (U-Pb age on zircon, Selverstone and others, 1997), and the Proterozoic rocks in the Keystone quadrangle are thought to have been strongly metamorphosed during roughly this same time.

Xm

Migmatite (Early Proterozoic)—High-grade metamorphic rocks that have been heavily intruded by granitic material, commonly in a layer-parallel manner, and/or have been intensely deformed and heated to the point of partial melting. Migmatite is most prevalent in the eastern part of the quadrangle, where the country rock is composed chiefly of hornblende gneiss and minor felsic and amphibolite gneiss. Hornblende and felsic gneiss layers range up to a few feet in thickness, whereas amphibolite and the intrusive granitic/pegmatitic layers are typically less than about 6 in. thick. The rock commonly has boudinage, sigmoidal structures, and numerous small, tight folds giving it a "swirled-chocolate-and-vanilla-pudding" appearance.

This unit is a very good source of riprap and crushed aggregate. It may be prone to rockfall in areas where it is exposed in cliffs.

Xh

Hornblende gneiss (Early Proterozoic)— Medium to dark gray, medium-grained gneiss consisting chiefly of hornblende and plagioclase with lesser amounts of quartz, biotite, and pyroxene. Garnet is locally abundant but not widespread. The rock is either massive or layered. Massive hornblende gneiss has a salt-and-pepper appearance due to dark hornblende crystals in a light gray matrix of plagioclase. Layered hornblende gneiss is moderately foliated and the segregation of light minerals (plagioclase and quartz) and dark minerals (hornblende and pyroxene) gives the rock a banded appearance. The layered variety of hornblende gneiss typically has a green tint due to chlorite alteration. Thin (generally less than 6 in.) bands of amphibolite are common within the hornblende gneiss.

Felsic gneiss (Xf) is frequently interlayered with hornblende gneiss. Where hornblende gneiss is predominant, the rock is mapped as unit Xh; where proportions of the two are roughly equal the rock is mapped as Xhf. Lovering (1935, p. 11) suggested hornblende gneiss originated as an "igneous rock intermediate between gabbro and diorite in composition". Hornblende gneiss is a potential source of riprap and aggregate. It may be prone to rockfall where exposed in cliffs.

Xhf

Interlayered felsic and hornblende gneiss (Early Proterozoic)—Unit is composed of roughly equal proportions of hornblende gneiss and felsic gneiss. Thin layers of dark gray to black amphibolite greater than 50 percent hornblende) are also locally interlayered. Thickness of individual layers is commonly a few inches to a few feet but locally may exceed several tens of feet.

Xf **Felsic gneiss (Early Proterozoic)—**White to light gray, medium- to coarse-grained and slightly porphyroblastic, massive to moderately well-foliated microcline gneiss. Where massive, the rock is composed primarily of microcline, plagioclase, and quartz, with locally abundant euhedral magnetite crystals as long as 0.3 in. Foliated felsic gneiss contains thin, discontinuous, biotite-rich layers but little or no magnetite. Small amounts of hornblende and garnet may be present locally in either variety. Felsic gneiss is commonly interlayered with hornblende gneiss.

Regionally, felsic gneiss is considered to have originated either as an arkosic sandstone (Sims and Gable, 1967; Robinson and others, 1974) or as a volcanic tuff (Tweto, 1987). Felsic gniess believed to have originated as a sandstone is typically found within metasedimentary sequences composed chiefly of biotite gneiss. Conversely, felsic gneiss originating as a tuff is more commonly found as a stratigraphic unit in layered sequences of meta-volcanic rocks primarily represented by hornblende gneiss. In the Keystone quadrangle, felsic gneiss is closely associated with hornblende gneiss, thus suggesting a probable volcanic protolith. Felsic gneiss is a very good source of riprap and crushed aggregate.

Xfa **Interlayered felsic and amphibolite gneiss (Early Proterozoic)—**Felsic gneiss (Xf) and amphibolite gneiss (Xa) are closely interlayered on Wise Mountain. Felsic layers tend to be thicker than amphibolite layers and are as much as several tens of feet thick. Amphibolite layers are generally less than one foot thick.

Xa **Amphibolite gneiss (Early Proterozoic)—** Dark gray to black, fine-grained, hornblende-plagioclase gneiss. This rock differs from hornblende gneiss in that it has a higher concentration of hornblende (greater than 50 percent), has almost no quartz, biotite, or pyroxene, and is darker in color. Amphibolite gneiss is commonly interbedded with thin (a few inches) layers of hornblende gneiss. Individual amphibolite gneiss layers are discontinuous and typically less than about 2 ft thick. The rock weathers dark green due to alteration of hornblende to chlorite. Locally, as on the east flank of Sheep Mountain, hornblende gneiss is composed almost entirely of hornblende and is highly schistose. Amphibolite gneiss layers probably represent Proterozoic andesitic lava flows (Lovering, 1935).

Xb **Biotite gneiss (Early Proterozoic)—** Fine-grained, light to medium gray gneiss composed primarily of quartz, plagioclase, and biotite, with accessory magnetite, sillimanite, garnet, and/or cordierite. The rock commonly weathers to a rusty brown color. Its texture is typically equigranular, which gives it a salt-and-pepper appearance in outcrop, although in places it is schistose or migmatitic. Foliation is generally parallel to compositional layering and is defined by the orientations of coarse-grained lepidoblastic biotite flakes. Thin layers are commonly deformed into small, isoclinal folds. Locally, the unit contains laterally extensive layers of hornblende gneiss and discontinuous layers of sillimanitic biotite gneiss. The protolith of the biotite gneiss is considered a sandy shale or graywacke (Sheridan and Marsh, 1976). This unit is a potential source of good quality riprap and crushed aggregate, especially where it is equigranular and not schistose.

Xsb **Sillimanitic biotite gneiss (Early Proterozoic)—**Medium to dark gray, well-foliated gneiss consisting primarily of quartz, plagioclase, biotite, sillimanite, and locally, garnet. Microcline, muscovite, tourmaline, and cordierite are lesser constituents. Sillimanite is present as cloudy white rods and bundles or small, flattened elongate pods up to about 2 in. long that parallel foliation. The pods of sillimanite are slightly more resistant to weathering than the surrounding biotite and form knobby surfaces in outcrops. The rock is locally migmatitic. The high concentration of sillimanite suggests that the protolith of this rock is an alumina-rich mud or shale (Sheridan and Marsh, 1976). It is a potential source of riprap and crushed aggregate.

STRUCTURAL GEOLOGY

The Keystone quadrangle is marked by a complex pattern of folds, faults, and shear and fracture zones that range in age from early Proterozoic to Oligocene and possibly younger time (Figure 2). Throughout most of the quadrangle, bedding in Cretaceous sediments and foliation in Precambrian rocks strike north to northwest. In contrast, bedding south of the Swan River strikes east–west, and foliation on Bear and Independence mountains strikes northeast. Fault orientations have a strong northwest strike and a subordinate northeast to east strike.

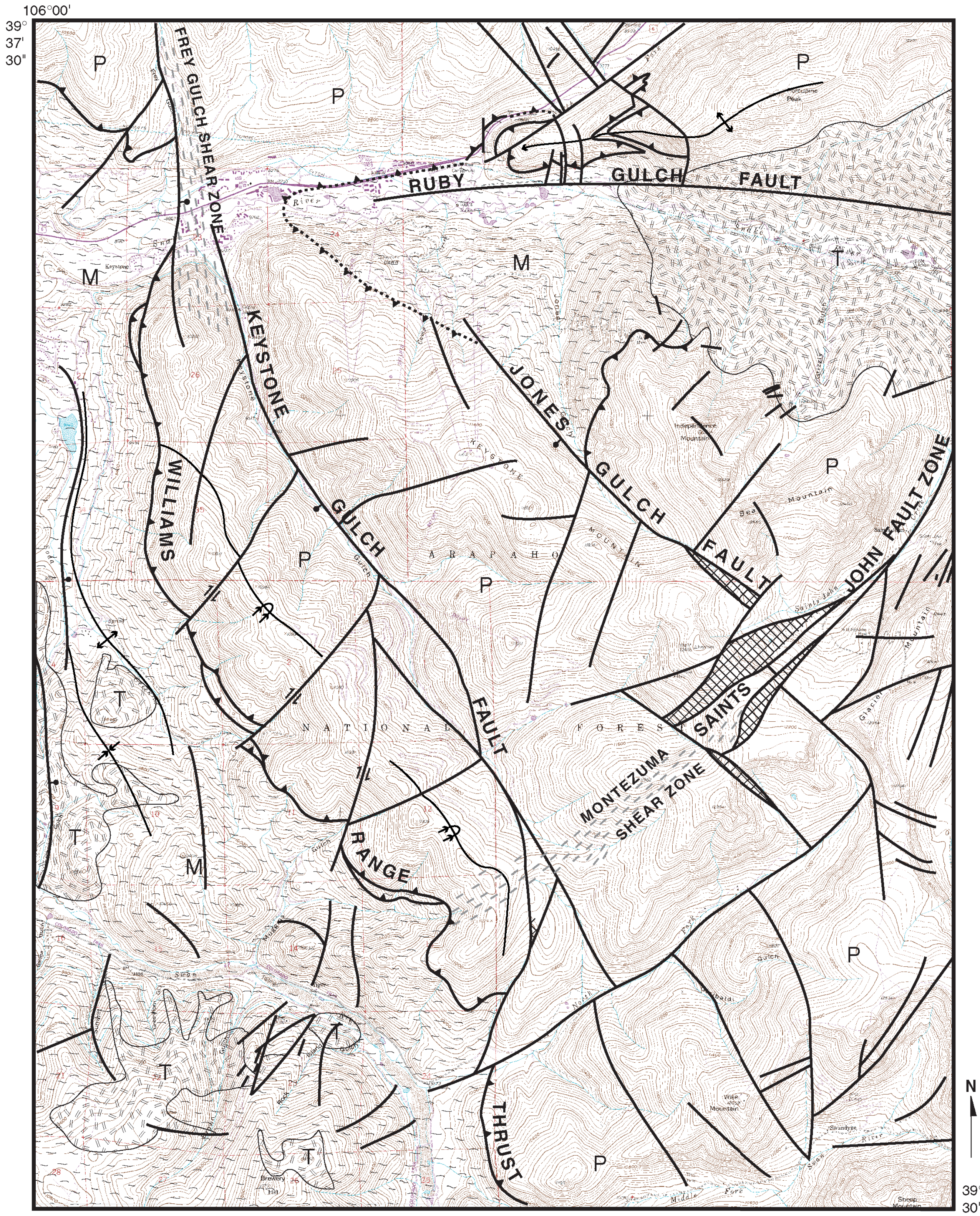
The first known deformation event affecting the quadrangle was probably synchronous with peak metamorphism in the northern Front Range during the early Proterozoic about 1,726 ± 15 Ma (Selverstone and others, 1997). This event, featuring deep-seated, plastic deformation in the form of nearly isoclinal, overturned folds, accompanied regional peak metamorphism and is characterized by folds with northwest-striking axial planes that dip 40° or more to the northeast.

The northeast trending Montezuma shear zone probably originated shortly after peak metamorphism. The Montezuma shear zone is part of the more regional Homestake shear zone first described by Tweto and Sims (1963). Shaw and others (2001) reported two periods of movement along the Homestake shear zone on the basis of monazite-dating techniques: 1.71 to 1.63 Ma and 1.45 to 1.38 Ma. Similarly, Graubard (1991) indicated that the Idaho Springs-Ralston Creek shear zone, which is northeast of and parallel to the Montezuma shear zone and is also part of the more regional Homestake shear zone, was active by at least 1.7 Ma. The Montezuma shear zone extends as far as the Georgetown area about 20 mi northeast of Keystone. It is coincident with the Colorado Mineral Belt (Figure 1) and forms the south- eastern boundary of the Montezuma mining district (Bookstrom, 1993). The southwestern end of the Montezuma shear zone is debatable. Neuerburg and Botinelly (1972) extended the shear zone south-southwest beyond the eastern flank of Sheep Mountain. Bookstrom (1993) described the shear zone as passing through the town of Montezuma, which is east of the quadrangle, to the historic mining town of Swandyke. However, the best alignment of the shear zone is coincident with the herein named Saints John fault zone. Field evidence supports this alignment on the basis of a structural corridor that extends southwest from Saints John to the north flank of Brewery Hill (Figure 2).

There are numerous northeast-striking faults southeast of Saints John, and the rocks at the head of Saints John Creek are intensely fractured, sheared, and recrystallized. A northeast-oriented fault underlying the North Fork of the Swan River, and other similarly oriented faults and zones of fractured rock to the north, are all part of this structural corridor. It is likely that the Tertiary-age (or younger) faults on the north flank of Brewery Hill developed along this ancestral grain generated during formation of the Montezuma shear zone.

Precambrian deformation was followed by a period of major uplift in Pennsylvanian-Permian time which formed the Ancestral Front Range. This mountain range was first eroded and later partially buried by sediments during late Permian to Jurassic time when inland seaways encroached from the east and west. Thousands of feet of Cretaceous marine sediments were deposited before Laramide orogenesis once again elevated the Front Range above sea level. The north to northwest trending, west-verging Williams Range thrust developed during the Laramide in latest Cretaceous or early Paleocene time (Howard, 1966).

The Williams Range thrust forms the western structural boundary of the Colorado Front Range in the Keystone quadrangle. It is a low-angle, concave-downward structure that steepens with depth. Where the thrust daylights, it dips to the east an average of 30° to 35°, although the dip angle may vary from nearly horizontal to as much 45° east (Howard, 1966). Proterozoic basement rocks were thrust westward as much as 5.6 mi (9 km) over predominantly Cretaceous sediments (Erslev and others, 1999). A northwest trending bulge, or low anticline, was formed in the Cretaceous sedimentary rocks immediately in front of the leading edge of the thrust plate along Soda Creek (cross section B– B'). Slices of Mesozoic sedimentary rock and



EXPLANATION

P — Proterozoic metamorphic rocks

M — Mesozoic sedimentary rocks

T — Tertiary intrusive rocks

Figure 2. Generalized map of the Keystone quadrangle showing geology and structural features. See accompanying geologic map for explanation of symbols.

Proterozoic basement rock are commonly caught up in thrust wedges rooted to the main thrust.

Movement along the thrust produced a wide zone of cataclasis and localized mylonitization in the basement rocks immediately above the thrust. Aerially extensive zones of intensely shattered rock east of the thrust, like the zone at the head of Saints John Creek, were produced by movement of the hanging wall rocks over the concave-downward flexure of the thrust plane (Kellogg, 2001). The rocks at the head of Saints John Creek were sheared by the Precambrian Montezuma shear zone and subsequently overprinted by intense brittle deformation associated with the Laramide Williams Range thrust. The shattered bedrock in the area appears to be the source of material for the numerous recurrent landslide complexes found within the basin. Major landslide complexes derived from similarly shattered Proterozoic rocks in the hanging wall were mapped along the Williams Range thrust to the northwest of the quadrangle (Kellogg, 1997; Kellogg, 2001). The Williams Range thrust is locally offset by northeast trending, right-lateral, strike-slip or tear faults that may have developed syntectonically with the thrust.

Many of the faults in southeastern corner and central part of the quadrangle appear to have been initiated or reactivated during the Laramide orogeny. Suspected Laramide faults are nearly vertical and are commonly marked by soft gouge and/or slickensides. The Keystone Gulch fault appears to have developed in the upper plate of the Williams Range thrust syntectonically with, or shortly after thrusting. Near-vertical faults in the southwestern and northeastern corners of the quadrangle are related to emplacement of the Montezuma stock and the stock in the Brewery Hill region during the Eocene. The northwest-trending fault along Frey Gulch and the Jones Gulch fault cut, and therefore post-date, the Williams Range thrust (Figure 2) and may be related to Neogene extension associated with the Rio Grande Rift (written communication, K. Kellogg, 2002). Neogene movement on the Keystone Gulch fault is also quite possible.

In the northeast part of the quadrangle, contact metamorphism associated with the intrusion of Tertiary quartz monzonite and related rocks of the Montezuma stock has preserved the Williams Range thrust in a magnificent cliff exposure on the north side of the western flank of Porcupine Peak (Figure 3). Hornfelsed Pierre Shale crops out at the base of this exposure. The Williams Range thrust plane dips 40° to the north and is immediately overlain by approximately 10 ft of Proterozoic hornfels. The hornfels grades upwards to a wide zone of cataclasite that in turn grades into relatively unaltered biotite gneiss (Erslev and others, 1999). The unusual outcrop pattern of the thrust fault on this ridge is a result of the thrust plane being bowed upward by intrusion of the Montezuma stock (cross section A–A' on map). South of the Snake River, at an elevation of 11,400 ft, the thrust dips in a southerly direction, and it is cut by the Ida Belle vein. The mineralization in this vein clearly post-dates thrusting. North of the Snake River, on the west ridge of Porcupine Peak, the thrust fault crops out at elevations ranging from 9,600 ft to approximately 10,800 ft. The thrust plane is bowed upward and forms an antiformal surface that plunges to the west. Outcrops of baked Cretaceous shale are exposed in fensters on both sides of the ridge of Porcupine Peak.

The Blue River Valley lies immediately west of the Williams Range thrust. Structurally, it is a west-tilted half graben in the northern extension of the late Cenozoic Rio Grande Rift (Tweto, 1978; Kellogg, 1999). Kellogg (1997) and Kellogg and others (2000) noted numerous north-striking, east-facing faults in the Blue River graben east of the Keystone quadrangle. These faults were presumed to have been active as recently as middle Pleistocene (Kellogg and others, 2000). High-angle, down-to-the-east, normal faults on the west side of Soda Creek cut Cretaceous sediments and Tertiary intrusive rocks and are assumed to be of similar age and origin to those mapped by Kellogg (1997) and Kellogg and others (2000).

Numerous linear topographic troughs (sackungen) are present along the ridge crests of Bear, Keystone, and Sheep Mountains. Sackungen indicate deep-seated rock creep, ridge spreading movements, and slope failure. These features are generally parallel to ridge lines and develop in response to gradual gravitational movement of rock masses into adjacent valleys. This movement may have been propagated by extensive fracturing of the rock in association with the Williams Range thrust and by scouring and over-steepening of valley walls by glacial ice.

Figure 3. Geologists Beth Widmann and Bob Kirkham examine the well preserved exposure of the Williams Range thrust on the north flank of Porcupine Peak. The surface they are standing on is Cretaceous Pierre Shale hornfels in the footwall of the thrust. The rock face in front of them is Precambrian biotite gneiss hornfels in the cataclastic zone above the thrust. Tertiary intrusion of the Montezuma stock metamorphosed the rocks to hornfels and arched the thrust plane upward, exposing this window into the thrust. Inset photo shows the sharp contact between altered Pierre Shale and biotite gneiss. Arrows point to the thrust plane, which dips 40° to the north.

METALLIC MINERAL SOURCES

Historic metal mining production is from three areas within the quadrangle: the southwestern corner of the quadrangle in the northeastern part of the Breckenridge district (Ransome, 1911); the Saints John area in the western edge of the Montezuma district (Patton, 1908, Lovering, 1935); and the Swan River, or Swandyke, district located near Wise Mountain (Lovering and Goddard, 1950).

The predominant economic metal mining operation in the Keystone quadrangle was placer dredging, which was focused in the Swan River drainage of the Breckenridge district. Lovering (1935) estimated that several million dollars of gold (at historical prices of $17.50–$35 per oz.) were recovered from the Swan River by dredging, hydraulic mining, and sluicing. Placer activities started in 1859 and continued until 1959 (Parker, 1974). The remains of one of the last dredges can still be seen in a small pond next to the Swan River at the mouth of Galena Gulch.

There are three major mines in the Breckenridge district in the Keystone quadrangle: the Hamilton Mine, Cashier Mine, and I.X.L. Mine. Deposits at the three mines are similar and typically consist of a sericitically altered, intrusive quartz monzonite porphyry containing a stockwork of sulfides (pyrite, sphalerite, galena) and lesser quartz veinlets. Intrusion breccia is common. Gold, lesser quantities of silver, and negligible base metals were mined principally between 1895 and 1905. Total production from each of the mines was on the order of 50,000 to 130,000 tons. For more information on Breckenridge-type deposits, the reader is referred to Ransome (1911) and Kellogg and others (2000), who provided thorough descriptions of the comparable Jessie Mine, which is located just west of the Keystone quadrangle.

The Hamilton Mine, at the head of Summit Gulch, produced on the order of $400,000 from 1893 to 1909, with very little output since (Lovering and Goddard, 1950). The geology consists of a series of east–west trending stringer zones, spaced less than 50 ft apart, of pyrite, sphalerite, and galena in pyritized and sericitized quartz monzonite porphyry. Stopes had dimensions of up to 150 ft in length, 5–15 ft in width, and up to 150–200 ft vertically. Ore shipped from the Hamilton Mine assayed 0.67 oz/ton gold and 4.15 oz/ton silver (Ransome, 1911).

The Cashier Mine, located on the east side of Browns Gulch, operated only for a limited time (1898 to 1903). Total production was estimated between $200,000 and $500,000 by Ransome (1911). The ore consisted of a stockwork of pyrite, sphalerite, and minor galena veinlets in a sericitically altered quartz monzonite porphyry. The principal vein direction is northeast, with stopes up to 60 ft in width. Ore shipped from the Cashier Mine graded 0.55 oz/ton gold, 10 oz/ton silver, and 5 percent Zn (Ransome, 1911).

The I.X.L. Mine is 0.5 mi east of Browns Gulch, immediately south of the ghost mill town of Tiger. Production started on the property in 1881, and a mill was constructed in 1883. Production was minimal and was drawing to a close by 1898 despite considerable money spent on exploration and mill development. Like the Hamilton and Cashier Mines, mineralization at the I.X.L. Mine consists of a quartz monzonite porphyry cut by many irregular veinlets of pyrite, sphalerite, and galena. Of particular note was a large block of Dakota Sandstone found in one of the lower tunnel levels; this was cut by numerous dikelets of quartz monzonite porphyry and then later shattered and filled with veinlets of pyrite, sphalerite, galena, minor chalcopyrite, and local bismuthinite (Ransome, 1911). This mineralization is accompanied by strong sericitic alteration, local leaching of orthoclase, and local metamorphism (hornfels) and metasomatism (pyrite-pyrrhotite-garnet-pyroxene skarn) of limestone in the adjacent Niobrara Formation. A weak propylitic halo typically surrounds the zone of sericitic alteration. J.B. Harlan (1989, private FMC report) reported secondary biotite and potassium-feldspar at depth in drill holes beneath the I.X.L. Mine. Quartz-molybdenite-pyrite veins and stockworks are also reported in the I.X.L. Mine workings (Stednick and others, 1987). A breccia at the I.X.L. Mine contains up to 20 percent fragments of Dakota Sandstone, Benton Shale, and quartz monzonite porphyry in a comminuted rock matrix. Although the breccia is very poorly exposed, it appears to have an arcuate geometry. At the Wirepatch Mine just south of the quadrangle, emplacement of breccia of this type was accompanied by or shortly followed precious and base metal mineralization (Pride and Robinson, 1978). Similar timing relations are invoked for the I.X.L. Mine.

In 1983 and 1984, the Anaconda Minerals Company drilled eight core holes at the I.X.L. and Cashier Mines. These drill holes ranged in depth from 190–800 ft and totaled 4,346 ft. Two of the drill holes had scattered, thin (1–6 ft) intercepts of 0.06–0.37 oz/ton gold material; a third hole had an intercept of 81 ft averaging 0.058 oz/ton gold and numerous other short intercepts that ranged from 0.05 to 0.18 oz/ton gold. FMC Gold Company acquired the property in 1988 and drilled eleven, angled, reverse- circulation drill holes, which ranged in depth from 200–825 ft and totaled 5,120 ft. Two of the holes near the Cashier Mine had significant intercepts: one drill hole contained 80 ft averaging 0.10 oz/ton gold; the other had 375 ft that averaged 0.044 oz/ton gold. Two of the other drill holes had 5–15 ft intervals of 0.045 to 0.29 oz/ton gold. The remaining drill holes were barren, and no record of follow-up or additional drilling exists.

Within the Keystone quadrangle, the mines of the Breckenridge district form an east–west trend that Lovering (1934) attributed to a structural zone of weakness associated with the Williams Range thrust. Cocker and Pride (1979) suggested that these mines represent the top of a hypothesized porphyry molybdenum system. On the basis of field work, however, it is herein postulated that these mineral occurrences represent telescoped porphyry gold deposits, and existence of an underlying Climax-type molybdenum deposit is not viewed as particularly likely. Drilling by FMC Gold Company to depths of up to 800 ft has not yielded reported molybdenite mineralization; the very minor molybdenite at the Cashier Mine occurs in conjunction with the gold deposit. Furthermore, the presence of local potassic alteration at a shallow depth in the I.X.L. Mine and in the breccia body at Brewery Hill suggests a telescoped hydrothermal system occurring at relatively shallow depths. A closer variant to these deposits is the zoned base metal lodes such as at Central City, Colorado (Lovering and Goddard, 1950; Sims and others, 1963), which have a similar metal suite (including minor molybdenite in the central portion), as well as a strong association with early Tertiary silicic porphyries.

Another prospect of significance within the Breckenridge district part of the quadrangle is a 1,000 ft long by 500 ft wide breccia body located on the east side of Brewery Hill. This body was exploited through several adits and prospect pits, but recorded production is unknown. The breccia was emplaced between quartz monzonite porphyry and Pierre Shale, and is clast supported with approximately 5 percent open voids. The open voids are filled with variable amounts of iron oxides, sericite, quartz, occasional barite, rhodochrosite, and rare pyrite, chalcopyrite, and galena. Clast lithology is predominantly Pierre Shale, with rare quartz monzonite porphyry, Dakota Sandstone, or gneiss. Geochemical sampling by FMC Gold Company suggested spotty, but locally high-grade gold-silver values. The breccia is dominated by sericitic alteration, although there does appear to be rare local potassic alteration as well. In 1986, FMC installed two reverse-circulation drill holes totaling 1,155 ft on Brewery Hill. One of these holes had good results (35 ft averaging 0.047 oz/ton gold). A follow-up campaign of seven reverse-circulation drill holes totaling 2,210 ft was made the next year. The results from these holes were much less favorable, with only a few thin intercepts containing greater than 0.02 oz/ton gold material. Four of the holes had no significant values. The drilling suggested that the volume of breccia at depth is less than appears on the surface.

The Montezuma district encroaches onto the eastern part of the Keystone quadrangle near the town of Saints John. In contrast to the Breckenridge district, the focus here was on silver found in pyrite-sphalerite-galena veins. Gangue minerals include quartz, ankerite, barite, and/or rhodochrosite accompanied by a thin sericitic alteration selvage (Lovering and Goddard, 1950). Production from any given mine in the area was small; typically only a few hundred to several thousands tons were generated.

The Saints John Mine, discovered in 1865, is one of the oldest silver mines in the state. There was extensive development of high-grade ruby silver ore at Saints John from 1865 to 1890, but production records from this period have been lost.

Incomplete records from 1889 to 1930 indicate that 3,654 tons were mined, from which 4.3 oz. of gold, 80,690 oz. of silver, 2,448,222 lbs. of lead, and minor copper were produced (Lovering and Goddard, 1950). The main ore shoot had a strike length of 1,300 ft, a depth of at least 700 ft, and a maximum vein width of 4 ft. The main vein was vertically zoned, with galena, moderate sphalerite, tetrahedrite, and rare polybasite in the upper levels; galena, sphalerite, chalcopyrite, and minor argentite and stephanite in the intermediate levels; and large amounts of proustite, poly- basite, stephanite, and tetrahedrite, with very minor sphalerite and galena at depth. This high-grade shoot occurred some 600 ft below the surface and did not show any evidence of oxidation or supergene enrichment (Lovering and Goddard, 1950).

The Ida Belle Mine, located on the north-west ridge of Independence Mountain, was established in 1880. Recorded output from 1888 to 1930 was 143 tons, yielding 25.9 oz. of gold, 2,016 oz. of silver, and 86,707 lbs. of lead (Lovering, and Goddard, 1950). This mine is of particular interest as the mineralized vein cuts the Williams Range thrust. The Ida Belle vein ranges from 2–60 in. thick, depending predominantly on rock type, with shale being a particularly unfavorable host. Mineralization is strongest where the vein cuts the thrust and consists of massive sphalerite and galena (Lovering, 1935; Lovering and Goddard, 1950).

Other mines in the area include the Hunkidori, Wild Irishman, and General Teller Mines. The Hunkidori Mine was established in 1880 and operated sporadically until 1911. Limited records suggest a production of 53 tons with hand-cobbed grades of 0.05 oz/ton gold, 33.5 oz/ton silver, and 48 percent Pb (Lovering, 1935). This vein contained quartz, ankerite, pyrite, galena, barite, and sphalerite. The Wild Irishman vein was a narrow, 8 in. wide, manganosiderite-galena vein with minor production from 1883 to 1913. As recorded by Lovering (1935), production was 375 tons, yielding trace gold, 10,347 oz. of silver, and 171,741 lbs. of lead. The ore shoot zoned upwards into quartz-barite-galena with traces of sphalerite and pyrite from the predominant manganosiderite-galena seen at depth. There is no published information on the General Teller Mine, but traverses in the area suggest small-scale quartz-pyrite-galena-barite veins are present.

Lovering and Goddard (1950, p. 125) claimed that hornfels (baked Pierre Shale) adjacent to the west side of the Montezuma stock contained widely disseminated gold with values on the order of 0.01–0.05 oz/ton. If this was true, the volume of hornfels present in the area would have been sufficient to stir interest in a possible bulk-tonnage gold deposit. However, reconnaissance traverses indicate that the hornfels contains, at best, trace values of gold (typically less than 0.01 ppm gold). Although there are small patches of garnet skarn that contain up to 1.6 ppm gold, it is extremely limited in extent and has minimal lateral continuity.

The third mining area in the quadrangle is the Swandyke, or Swan River, district near Wise Mountain. There was a limited amount of gold ore produced from this area prior to 1900. In the Carrie Mine on the summit of Wise Mountain, free gold was found associated with oxidized supergene-enriched pyrite and pyrite-quartz veins. The zone of high-grade gold only extended to a depth of about 25 ft; adits driven beneath the high-grade zones encountered pyrite veins with values of 0.1–0.2 oz/ton gold (Lovering and Goddard, 1950). Pyrite veins on the glaciated flanks of Wise Mountain also did not contain significant values in gold, strongly supporting a supergene enrichment origin for the high-grade gold. The area contains small intrusions of quartz latite and quartz monzonite porphyry; these have limited zones of associated sericitic or argillic alteration. There have been at least three holes drilled in the area, but results are unavailable.

REFERENCES CITED

Aleinikoff, J.N., Reed, J.C., Jr., and DeWitt, Ed, 1993, The Mount Evans batholith in the Colorado Front Range; revision of its age and reinterpretation of its structure: Geological Society of America Bulletin, v. 105, p. 791–806.

Benn, D.I., and Evans, D.J.A., 1998, Glaciers and glaciation: New York, Edward Arnold [co-published by John Wiley and Sons], 734 p.

Bookstrom, A.A., 1993, The Silver Plume-Georgetown district: Colorado School of Mines Quarterly Review, v. 93, no. 1, p. 25–30.

Bookstrom, A.A., Naeser, C.W., and Shannon, J.R., 1987, Isotopic age determinations, unaltered and hydrothermally altered igneous rocks, north-central Colorado mineral belt: Isochron/West, no. 49, p. 13–20.

Bryant, Bruce, Marvin, R.F., Mehnert, H.H., and Naeser, C.W., 1975, Upper Eocene porphyries in the Colorado mineral belt and the history of the west margin of the Front Range uplift: Geological Society of America Abstracts with Programs, v. 7, no. 5, p. 591.

Bryant, Bruce, McGrew, L.W., and Wobus, R.A., 1981, Geologic map of the Denver 1° x 2° quadrangle, north-central Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-1163.

Cocker, M.D., and Pride, D.E., 1979, Hydrothermal alteration-mineralization of a subvolcanic complex, Breckenridge mining district, Colorado (U.S.A.), *in* Ridge, J.D., ed., Papers on mineral deposits of western North America, International Association on the Genesis of Ore Deposits, 5th Quadrennial Symposium Proceedings, v. II: Nevada Bureau of Mines and Geology Report 33, 214 p.

Cunningham, C.G., Naeser, C.W., Marvin, R.F., Luedke, R.B., and Wallace, A.R., 1994, Ages of selected intrusive rocks and associated ore deposits in the Colorado mineral belt: U.S. Geological Survey Bulletin 2109, 31 p.

Erslev, E.A., Kellogg, K.S., Bryant, Bruce, Ehrlich, T.K., Holdaway, S.M., and Naeser, C.W., 1999, Laramide to Holocene structural development of the northern Colorado Front Range, *in* Lageson, D.R., Lester, A.P., and Trudgill, B.D., eds., Colorado and adjacent areas: Geological Society of America Field Guide 1, p. 21–40.

Graubard, C.M., 1991, Extension in a transpressional setting; Emplacement of the mid-Proterozoic Mount Evans batholith, central Front Range, Colorado: Geological Society of America Abstracts with Programs, v. 23, no. 4, p. 27.

Graubard, C.M., and Mattison, J.M., 1990, Syntectonic emplacement of the ~1440 Ma Mt. Evans pluton and history of motion along the Idaho Springs–Ralston Creek shear zone, central Front Range, Colorado: Geological Society of America Abstracts with Programs, v. 22, no. 2, p. 12.

Howard, J.H., 1966, Structural development of the Williams Range thrust, Colorado: Geological Society of America Bulletin, v. 77, no. 11, p. 1247–1264.

Izett, G.A., Cobban, W.A., and Gill, J.R., 1971, The Pierre Shale near Kremmling, Colorado, and its correlation to the east and the west: U.S. Geological Survey Professional Paper 684-A, 19 p.

Kellogg, K.S., 1997, Geologic map of the Dillon quadrangle, Summit and Grand Counties, Colorado: U.S. Geological Survey Open-File Report 97-738, scale 1:24,000.

Kellogg, K.S., 1999, Neogene basins of the northern Rio Grande rift-partitioning and asymmetry inherited from Laramide and older uplifts: Tectonophysics, v. 305, p. 141–152.

Kellogg, K.S., 2001, Tectonic controls on a large landslide complex, Williams Fork Mountains, near Dillon, Colorado: Geomorphology, v. 41, p. 355–368.

Kellogg, K.S., Bartos, P.J., Williams, C.L., and Friehauf, K.C., 2000, Geologic map of the Frisco quadrangle, Summit County, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-2340, scale 1:24,000.

Lovering, T.S., 1934, Geology and ore deposits of the Breckenridge mining district, Colorado: U.S. Geological Survey Professional Paper 176, 64 p.

Lovering, T.S., 1935, Geology and ore deposits of the Montezuma quadrangle, Colorado: U.S. Geological Survey Professional Paper 178, 119 p.

Lovering, T.S., and Goddard, E.N., 1950, Geology and ore deposits of the Front Range, Colorado: U.S. Geological Survey Professional Paper 223, 325 p.

Marvin, R.F., Mehnert, H.H., Naeser, C.W., and Zartman, R.E., 1989, U.S. Geological Survey radiometric ages—Compilation "C", part five, Colorado, Montana, Utah, and Wyoming: Isochron/West, no. 53, p. 14–19.

Neuerburg, G.J., and Botinelly, Theodore, 1972, Map showing geologic and structural control of ore deposits, Montezuma district, central Colorado: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-750, scale 1:31,680.

Palmer, A.R., and Geissman, John, 1999, 1999 Geologic time scale: Boulder, Colorado, Geological Society of America, product code CTS004.

Patton, H.C., 1908, The Montezuma mining district, Colorado: Colorado Geological Survey, 1st Annual Report.

Parker, B.H., Jr., 1974, Gold placers of Colorado (Book 1): Quarterly of the Colorado School of Mines, v. 69, no. 3, 268 p.

Peterman, Z.E., Hedge, C.E., and Braddock, W.A., 1968, Age of Precambrian events in the northeastern Front Range, Colorado: Journal of Geophysical Research, v. 73, no. 6, p. 2277–2296.

Premo, W.R., and Fanning, C.M., 1997, U-Pb zircon ages for the Big Creek Gneiss, Wyoming and the Boulder Creek batholith, Colorado; Implications for the timing of early Proterozoic accretion of the northern Colorado province: Geological Society of America Abstracts with Programs, v. 29, no. 6, p. A-407.

Pride, D.E., and Robinson, C.S., 1978, Multiple intrusion and hydrothermal activity, eastern Breckenridge mining district, Summit County, Colorado: Geological Society of America Bulletin, v. 89, p. 866–874.

Ransome, F.L., 1911, Geology and ore deposits of the Breckenridge district, Colorado: U.S. Geological Survey Professional Paper 75, 187 p

Richmond, G.M., and Fullerton, D.S., 1986, Stratigraphy and correlation of glacial deposits of the Rocky Mountains, the Colorado Plateau and the ranges of the Great Basin, *in* Sibrava, V., Bowen, D.Q., and Richmond, G.S., eds., Quaternary glaciations in the northern hemisphere: Quaternary Science Reviews, v. 5, p. 99–127.

Robinson, C.S., Warner, L.A., and Wahlstrom, E.E., 1974, General geology of the Harold D. Roberts tunnel, Colorado: U.S. Geological Survey Professional Paper 831-B, 47 p.

Selverstone, J., Hodgins, M., Shaw, C., Aleinikoff, J.N., and Fanning, C.M., 1997, Proterozoic tectonics of the northern Colorado Front Range, *in* Bolyard, D.W., and Sonnenberg, S.A., eds., Geologic history of the Colorado Front Range: Rocky Mountain Association of Geologists Guidebook, p. 9–18.

Shaw, C.A., Karlstrom, K.E., and Williams, M.L., 2001, Electron-microprobe monazite dating of ca. 1.71–1.63 Ga and ca. 1.45–1.38 Ga deformation in the Homestake shear zone, Colorado, origin and early evolution of a persistent intracontinental tectonic zone: Geology, v. 29, no. 8 p. 739–742.

Sheridan, D.M., and Marsh, S.P., 1976, Geologic map of the Squaw Pass quadrangle, Clear Creek, Jefferson, and Gilpin Counties, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ-1337, scale 1:24,000.

Simmons, E.C., and Hedge, C.E., 1978, Minor element and Sr-isotope geochemistry of Tertiary stocks, Colorado mineral belt: Contributions to Mineralogy and Petrology, v. 67, p. 379–396.

Sims, P.K., Drake, A.A., Jr., and Tooker, E.W., 1963, Economic geology of the Central City district, Gilpin County, Colorado, U.S. Geological Survey Professional Paper 359, 228 p.

Sims, P.K., and Gable, D.J., 1967, Geology of Precambrian rocks, Central City district, Colorado: U.S. Geological Survey Professional Paper 474-C, 52 p.

Spurr, J.E., Garrey, G.H., and Ball, S.H., 1908, Economic geology of the Georgetown quadrangle (together with the Empire district), Colorado: U.S. Geological Survey Professional Paper 63, 422 p.

Stednick, J.D., Klem, R.B., and Riese, W.C., 1987, Temporal variation of metal concentrations in biogeochemical samples over the Royal Tiger Mine, Colorado; Part I, within year variation: Journal of Geochemical Exploration, v. 29, p.75–88

Streckeisen, A., 1976, To each plutonic rock its proper name: Earth Science Reviews, v. 12, p. 1–33.

Taranik, J.V., 1974, Stratigraphic and structural evolution of Breckenridge area, central Colorado: Golden, Colorado School of Mines, Ph.D. dissertation, 222 p.

Tweto, Ogden, 1974, Geology of the Mount Lincoln 15-minute quadrangle, Eagle, Lake, Park, and Summit Counties, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-555, scale 1:62,500.

Tweto, Ogden, 1978, Northern rift guide 1, Denver-Alamosa, Colorado, *in* Hawley, J.W., ed., Guidebook to the Rio Grande Rift in New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources Circular 163, p. 13–27.

Tweto, Ogden, 1987, Rock units of the Precambrian basement in Colorado: U.S. Geological Survey Professional Paper 1321-A, 54 p.

Tweto, Ogden, and Sims, P.K., 1963, Precambrian ancestry of the Colorado mineral belt: Geological Society of America Bulletin, v. 74, p. 991–1014.

Ulrich, G.E., 1963, Petrology and structure of the Porcupine Mountain area, Summit County, Colorado: Boulder, University of Colorado, Ph.D. dissertation, 205 p.

Wallace, C.A., Keller, J.W., McCalpin, J.A., Bartos, P.J., Jones, N.N., and Route E.E., 2002, Geologic map of the Breckenridge quadrangle, Summit and Park Counties, Colorado: Colorado Geological Survey Open-File Report 02-7, scale 1:24,000.

Widmann, B.L., and Miersemann, Ulrike, 2001, Geologic map of the Georgetown quadrangle, Clear Creek County, Colorado: Colorado Geological Survey Open-File Report 01-05, scale 1:24,000.