OPEN-FILE REPORT 03-20

Geologic Map of the Copper Mountain Quadrangle; Summit, Eagle, Lake, and Park Counties, Colorado

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COLORADO GEOLOGICAL SURVEY

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FOREWORD

The Colorado Department of Natural Resources is pleased to present the Colorado Geological Survey Open File Report 03-20, *Geologic Map of the Copper Mountain Quadrangle, Summit, Eagle, Lake, and Park Counties, Colorado*. Its purpose is to describe the geologic setting and mineral resource potential of this 7.5-minute quadrangle, the majority of which is located in Summit County.

Beth Widmann, Paul Bartos, Jim McCalpin, and Jeff Jackson completed the field work on this project in the summer of 2002.

This mapping project was funded jointly by the U.S. Geological Survey (USGS) and the Colorado Geological Survey (CGS). USGS funds are competitively awarded through the STATEMAP component of the National Cooperative Geologic Mapping Program (Agreement No. 02HQAG0050). 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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We thank Bruce Bryant (USGS) and Eric Nelson (Colorado School of Mines) for their thorough reviews of the map and text. Bruce Bryant, Karl Kellogg (USGS), and Vince Matthews (CGS) spent a day in the field with us and are thanked for time spent in engaging discussions and debates and are praised for their willingness to hike mountain ridges in blizzard conditions. Jane Ciener was our technical editor.

Digital drafting of the map and cross sections was completed by Karen Morgan and Chris Redman (CGS). Cheryl Brchan and Chris Redman (CGS) designed the book.

INTRODUCTION

Geologic mapping of the Copper Mountain 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 Mineral Severance taxes, which are 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.

Most of the Copper Mountain quadrangle is located in Summit County (Fig. 1). The southwestern edge of the quadrangle is in Eagle County, and only the southernmost part of the quadrangle is in Lake and Park Counties. U.S. Interstate 70 (I-70) makes a sharp turn from roughly north-south to east-west at Copper Junction, which is adjacent to the northeast corner of the quadrangle. State Highway 91 (CR-91) branches from I-70 at Copper Junction and extends 24 mi south to Leadville along the eastern half of the quadrangle. Frisco is about seven mi to the north-northeast, and Vail Pass and the town of Vail are about 6 and 25 mi, respectively, to the northwest.

The Copper Mountain quadrangle is located on the western flank of the Tenmile Range and the southern end of the Gore Range. Copper Mountain ski area is situated in the northeastern corner of the quadrangle. The principal peaks of the ski area are Copper Mountain (12,444 ft) and Union Mountain (12,313 ft). Elk Ridge, a series of peaks over 12,000 ft high in the western half of the quadrangle, defines the Summit and Eagle County line. Jacque Peak, located in the north-central part of the quadrangle, has an elevation of 13,205 ft. Fletcher Mountain, Wheeler Mountain, and Bartlett Mountain, located in the southeastern corner of the quadrangle, are the only other peaks within the quadrangle over 13,000 ft. Fletcher Mountain is the highest point on the quadrangle at 13,951 ft. Tenmile Creek flows north-northeast through the central and eastern parts of the quadrangle, but is interrupted by the vast tailings ponds of the idle Climax Molybdenum mine, the workings of which extend onto the southern edge of the quadrangle.

The first detailed report in the Copper Mountain region was by Emmons (1898) who outlined the basic structure, stratigraphy and ore-deposit geology of the Kokomo-Tenmile district. The U.S. Geological Survey conducted a series of investigations in this area during the 1940s and 1950s due to renewed interest in zinc and lead resources during, and immediately following, World War II. Koschmann and Wells (1946) revised Emmons' (1898) stratigraphy and added key structural information. Bergandahl and Koschmann (1971) wrote the definitive work in this area during this post-war period, although it was not actually published until much later. Their work complemented extensive stratigraphic studies and field mapping done by Tweto (1949, 1954,1956,1974a,b) generally west of the Copper Mountain quadrangle. In 1992, a master's thesis involving geochronology, fluid inclusion, and isotope studies of Kokomo ores (primarily using samples previously collected by Koschmann) was undertaken by Mach (1992); this work also involved partial remapping of the district. Principal findings of this work were published in Mach and Thompson (1998).

Figure 2 shows the current status of geologic quadrangle mapping in the Copper Mountain area. The Copper Mountain quadrangle is coincident with the northwestern corner of the Mt. Lincoln 15-minute quadrangle mapped by Tweto (1974a). The Holy Cross 15-minute quadrangle, which is directly west of the Copper Mountain quadrangle, was also mapped by Tweto (1974b). The southwest corner of the Dillon 15-minute quadrangle, which is coincident with the Vail Pass 7.5-minute quadrangle north of Copper Mountain, was mapped by Bergendahl (1969). The Minturn 15-minute quadrangle is adjacent to the northwest corner of the Copper

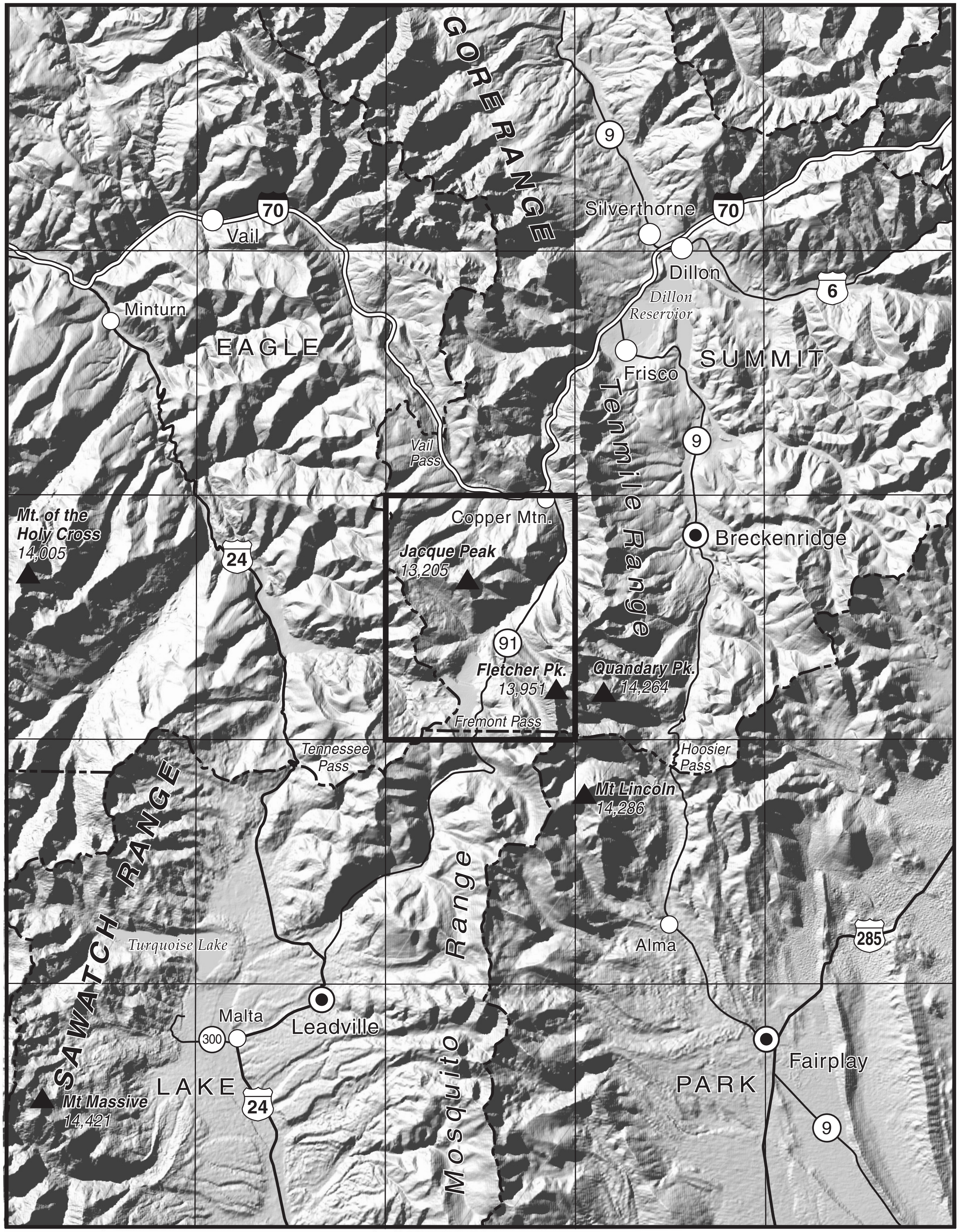

Figure 1. Shaded relief map of the region surrounding the Copper Mountain quadrangle.

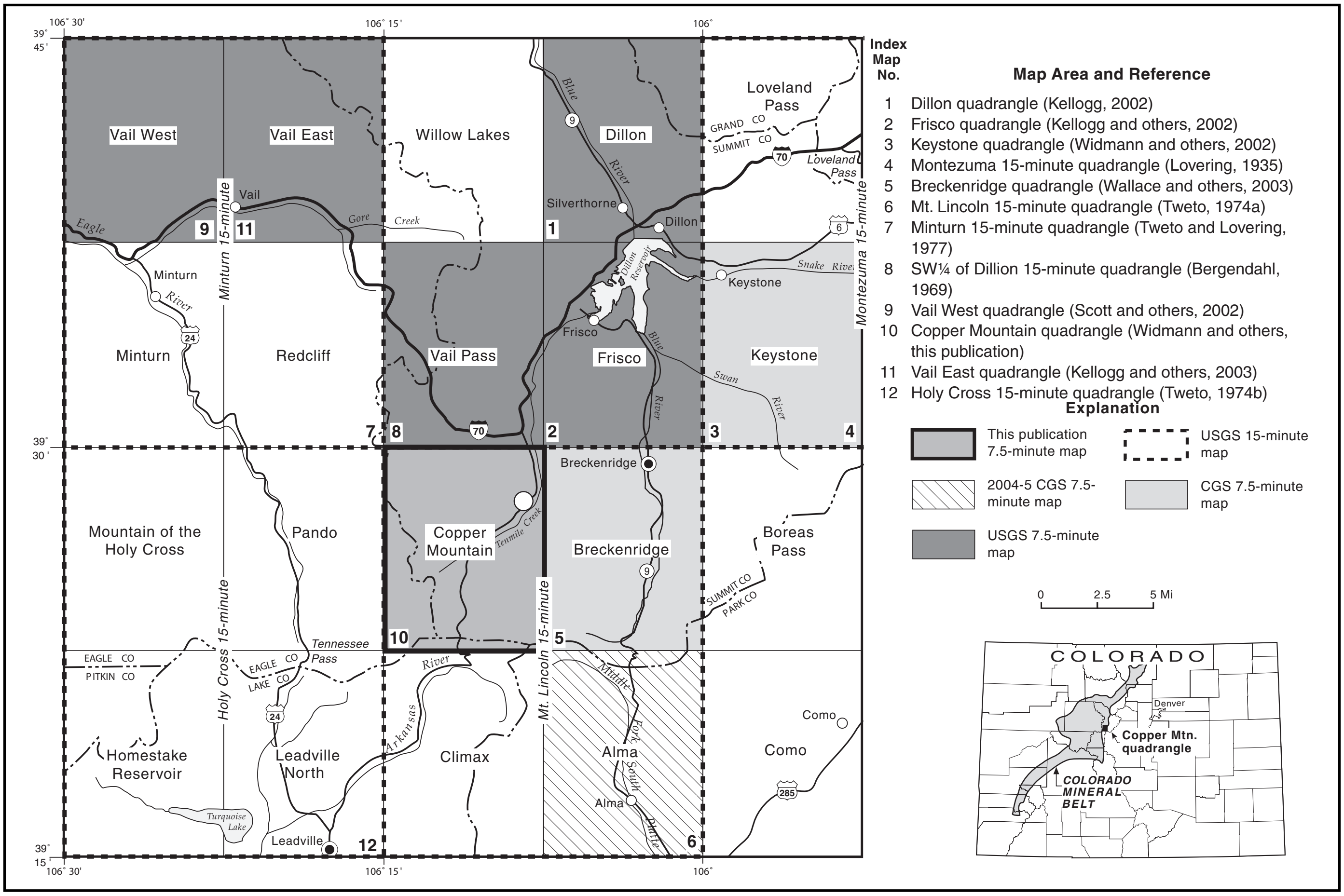

Figure 2. Location map and index of selected published geologic maps in the vicinity of the Copper Mountain quadrangle. Inset map shows the location of the Copper Mountain quadrangle within the Colorado Mineral Belt.

Mountain quadrangle and was mapped by Tweto and Lovering (1977). The Breckenridge and Frisco 7.5-minute quadrangles to the east and northeast of Copper Mountain were mapped by Wallace and others (2003) and Kellogg and others (2002), respectively.

Field mapping for the Copper Mountain quadrangle was undertaken during the summer of 2002. The bedrock north of the ridge line defined by Copper Mountain, Jacque Peak, and Sugarloaf Mountain, and the area generally east of Highway 91 (excluding the area west of the ridge from Bartlett Mountain towards Clinton Reservoir) was mapped by Beth Widmann (CGS) and Jeff Jackson (field assistant, Western State College, Colorado). Paul Bartos (Colorado School of Mines) mapped the remaining bedrock, which included the Kokomo and Climax mining areas. With the exception of the ridges and peaks exposed above tree line (roughly 11,600 ft), the area is typically covered by thick forest and pervasive soil cover. In many areas, float was judiciously used in mapping. Additionally, extensive historic prospecting in the area allows for tighter control on bedrock geology. Quaternary deposits were mapped by Jim McCalpin (GEO-HAZ Consulting, Colorado).

The Copper Mountain quadrangle contains a wide variety of rocks that range in age from Precambrian to Quaternary. Precambrian metamorphic and igneous rocks crop out generally east of CR-91 (excluding the west side of Bartlett Mountain) and on the east and north flanks of Copper Mountain. The oldest rocks are

Early Proterozoic metasedimentary and metavolcanic rocks that were originally deposited nearly 1,800 Ma (Tweto, 1987) and later intensely deformed and metamorphosed during a period of intense plutonism about 1,726 Ma (Selverstone and others, 1997). Igneous rocks associated with this first period of plutonism are part of the Routt plutonic suite (Tweto, 1987). A second period of plutonism took place roughly 1,400 Ma and emplaced granitic rocks of the Berthoud plutonic suite (Tweto, 1987). The Paleozoic sedimentary rocks in the quadrangle were deposited in Cambrian to Pennsylvanian-Permian time and include conglomerate, sandstone, limestone, shale, quartzite, and dolomite. Two major pulses of Tertiary magmatism were recognized in the quadrangle: a calc-alkaline porphyrytic pulse between 51 to 42 Ma, and possibly as young as 40 Ma, and a high silica rhyolite pulse between 35 to 29 Ma (Bookstrom and others, 1987; Marvin and others, 1989). The first magmatic pulse resulted in the locally forceful intrusion of numerous sills, dikes, and small stocks, whereas the second pulse is characterized by small, shallow stocks and plugs. Precious and base metal carbonate replacement deposits are associated with the calc-alkaline intrusives, whereas porphyry molybdenum mineralization is associated with the younger, high-silica rhyolite event. The youngest deposits in the quadrangle include glacial till of probable Pinedale and Bull Lake age, periglacial deposits, and other Quaternary surficial deposits.

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.

Quaternary units are mainly glacial tills and their associated outwash terraces, landslides, and a suite of periglacial deposits above treeline in the Tenmile and Gore Ranges. In general, the oldest Quaternary geomorphic surfaces (and corresponding deposits) are found at the highest heights above the modern valley floor. Landslide deposits are found throughout the quadrangle and at all elevations and range from small slumps in Quaternary deposits to large, quasi-intact masses of bedrock that slid off glacial valley walls. 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 of the Rocky Mountains [dated at 16,000 to 23,000 years before present (16 to 23 ka)] and correlation of adjacent subdued moraines to the Bull Lake glacial advance [dated at 130 to 150 ka]. This correlation rests 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).

The oldest glacial deposits (Qtvo, very old till) exist only on the drainage divide west of Chalk Lake and comprise a thin cover of erratic boulders lying on a low-relief surface of Paleozoic and Tertiary rocks. These Precambrian boulders must have been transported northward by ice originating southeast of the Mosquito fault in the East Fork of the Arkansas River, when that valley was only a fraction of its present depth, probably in early Pleistocene time. The oldest till related to the present system of glaciated valleys (Qto, older till) lies on upper valley sidewalls and exists in four parts of the quadrangle. On the north wall of the East Fork of the Eagle River, older till forms a bench about 300 ft above modern river level and contains some boulders of Precambrian crystalline rocks in addition to clasts of lower Paleozoic and Tertiary rocks, indicating that some ice in the East Fork was derived from south of Fremont Pass. Older till between Chalk Lake and Robinson Lake contains an even higher proportion of Precambrian rock clasts, also indicative of deposition from spillover ice. Older till is mapped in lower Tenmile Creek both southwest and southeast of Wheeler Flats and at the mouth of a large glaciated tributary northeast of Humbug Creek. In the northern part of the quadrangle, small moraines of older till exist in the central parts of McKenzie Gulch, Wheeler Gulch, and Jacque Creek. The latter two moraines were deposited by small, north-facing tributary glaciers that merged with a larger valley glacier flowing east down West Tenmile Creek from Vail Pass.

Pinedale till (Qtp) covers the largest area of any Quaternary deposit in the quadrangle. It covers most of the floor and valley walls of the Tenmile Creek valley from Fremont Pass just south of the quadrangle to Wheeler Flats at the north edge of the quadrangle and is also found in numerous glaciated tributary valleys. The main Tenmile Creek glacier was fed by ice flowing down large, north-northwest-flowing, tributary glaciers in Clinton, Mayflower, and Humbug Creeks, and the unnamed creek north of Humbug Creek, as well as by spillover ice flowing north over Fremont Pass. Tributary glaciers also existed in tributaries on the northwest side of Tenmile Creek (Kokomo Gulch, Searle Gulch, Tucker Gulch, and Copper Creek), but these glaciers were much less vigorous because they headed at lower elevations and faced south to southeast. Accordingly, their till deposits are thinner (less than 30 ft) than on the east side of Tenmile Creek (30 to 75(?) ft). At the head of the valley near Fremont Pass, most till on the eastern side of the valley is composed of a red clayey matrix (derived from erosion of the Maroon Formation) with abundant clasts of Paleozoic sandstone and Precambrian metamorphic rocks, whereas on the west side, the matrix is brown to gray and was derived from dark claystones in the Minturn Formation. Both of these matrix-rich tills are prone to landsliding (see following section).

Pinedale ice in Tenmile Creek terminated just south of Wheeler Flats and deposited a well-preserved, bouldery, lateral moraine on the east valley wall. No terminal moraine is preserved on the valley floor, although the southern (head) portion of the glacial outwash plain (unit Qat) has anomalously large boulders at its surface, possibly a lag deposit from an eroded terminal moraine. This "missing" end moraine may have been eroded away by Tenmile Creek or may have never formed if the Pinedale ice terminus calved into a temporary glacial lake in the Wheeler Flats area. Such a lake might have resulted from the tributary glacier in Officer Gulch (north of the quadrangle) damming lower Tenmile Creek during the maximum Pinedale advance.

Pinedale till was also deposited across the northern foot of Copper Mountain by a glacier that flowed east down West Tenmile Creek from Vail Pass (the creek is just north of the northern quadrangle boundary). That glacier was mainly fed by northeast-flowing tributary glaciers in Jacques, Guller, and Stafford Creeks, all of which left extensive Pinedale till deposits in their respective valleys. In contrast, no Pinedale till was deposited in Wheeler and McKenzie Gulches. The main Pinedale glacier in West Tenmile Creek deposited a lateral moraine just east of the mouth of McKenzie Gulch, but as in Tenmile Creek, no corresponding terminal moraine is preserved on the valley floor here. It appears that the Pinedale glacier in West Tenmile Creek terminated just west of Wheeler Flats and thus did not join with the Pinedale glacier in Tenmile Creek. It is possible that both Pinedale glacier terminii ended in a temporary glacial lake at Wheeler Flats. Following the Pinedale ice maximum, the Officer Gulch ice dam may have been breached, the lake drained, and retreating glaciers in West Tenmile and Tenmile Creeks then flooded Wheeler Flats with glacial outwash (Qat).

In Tenmile Creek, south of Wheeler Flats, there are several groups of Pinedale recessional moraines on the valley floor that are included within map unit Qtp and which represent still-stands or small readvances during the Pinedale deglaciation (16 to 23 ka). One such group forms a one-half mi-wide band of moraines between the mouths of Humbug and Copper Creeks. Another large moraine complex lies west of the old townsite of Kokomo and is mostly buried beneath the Tenmile tailings pond, but it is visible on 1934 aerial photographs.

In Pinedale time glacier ice entered the southwestern corner of the quadrangle from a northeast-facing cirque on the east flank of Chicago Ridge. This cirque is unusually shallow but broad, with a floor 1.5 mi wide, just under one mi long, and only about 500 ft deep. Pinedale glacial ice spread thinly out of this cirque, flowed sluggishly northeastward, and deposited a mosaic of thin till cover over a glacially scoured terrain that comprises most of the southwest corner of the map.

The youngest till in the quadrangle (Qtn) is found in one small, stony, grass-covered moraine at 12,400 ft elevation in the cirque on the east flank of Bartlett Mountain. Evidently this deep, northeast-facing cirque was the only one in the quadrangle sufficiently sheltered to generate true glacier ice during any of the Holocene Neoglacial stages.

Only six small areas of lacustrine deposits (Q_l) were mapped in the quadrangle, three in depressions at the heads of landslides, and three behind Pinedale recessional or lateral moraines. The deposits are poorly exposed and are inferred to be thin (less than 15 ft) packages of well-sorted sand, silt, and clay deposited after Pinedale time.

Many of the glaciated valleys in the quadrangle are rimmed with a variety of periglacial and mass movement deposits, including rock glaciers, protalus ramparts, talus, talus fans, colluvium, and several types of landslides. The typical pattern is for talus (Qta, active talus; Qti, inactive talus) 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 active (Qtfa) or inactive (Qtfi) talus fan deposits. In many locations where talus deposits are shaded by high valley or cirque walls, the talus has been transformed into rock glaciers and was mapped as active rock glacier deposits (Qra, five deposits mapped), inactive rock glacier deposits (Qri, three deposits mapped), or as rock glacier deposits, undivided (Qr, 37 deposits mapped). Half of the rock glaciers are in the far southeastern part of the quadrangle, in the glacial valleys of Clinton, Mayflower, Humbug, and an unnamed creek, and are composed of boulders and blocks of Precambrian igneous and metamorphic rocks. Most of these rock glaciers are lobate rock glaciers, formed when postglacial snowmelt infiltrated a talus deposit, froze, and created a network of interstitial ice. However, the tongue-shaped rock glaciers on the eastern flank of Bartlett Mountain and in the unnamed glaciated tributary northeast of Humbug Creek probably formed when talus buried a stagnant cirque glacier in latest Pinedale time (about 15 ka).

West of Tenmile Creek, rock glacier deposits are found mainly in the cirque north of Jacque Peak and on the eastern flank of Elk Ridge. These rock glaciers are composed of angular rubble derived from fractured Tertiary intrusive rocks, which produce abundant talus when subjected to freeze-thaw processes at high elevations. Other periglacial deposits include solifluction deposits (Qs), generally above treeline; these are defined by stone stripes and terraces that show the surficial frost-shattered rubble is (or was) moving downslope. In contrast, if bedrock is covered by a thin veneer of frost-shattered rubble (felsenmeer) that shows no signs of downslope movement, the area was mapped as the underlying bedrock.

Landslide deposits throughout the Copper Mountain quadrangle are mostly rock slumps, rock slides, and soil slumps according to the terminology of Cruden and Varnes (1996). Sixty-three of the 67 landslides mapped in the quadrangle were mapped as “landslides, undivided,” with no subdivision by age or movement type. There are 60 mapped post-Pinedale landslides (map unit Qls), which range in area from 0.6 to 65 ha (1 hectare = 2.47 acres), with a mean area of 14 ha. Thirty-five of these 60 postglacial slides (58 percent) are smaller than 10 ha. In addition, there are three pre-Pinedale landslides (map unit Qlso) that range in area from 7 to 65 ha with a mean size of 26 ha.

Landslides involving bedrock formations typically occur in 3 geologic settings: (1) dipslope rockslides in the Minturn and Maroon Formations in the western half of the quadrangle, including widespread eastward rocksliding on the east flank of Elk Ridge and westward sliding on the northeastern valley walls of Clinton and Mayflower Creeks; (2) complex rock slumps in altered Tertiary intrusives, such as at Gold Hill, on the east and west flanks of Copper Mountain, and at the base of Jacque Peak; (3) slumps emanating from crushed rock in the Mosquito fault zone where it descends the west valley walls of Clinton and Mayflower Creeks.

Some large landslide complexes include many different types and ages of sliding, so they were mapped as landslide complexes (map unit Qlsc). There are two slide complexes so defined, both on dip slopes of Minturn Formation, one in the upper East Fork Eagle River (area = 121 ha) and another on the west side of Gold Hill (area = 93 ha).

In addition, the quadrangle contains some large and rather unique complexes of rockslides and blockslides and rock topples on the north flanks of Jacque Peak and Union Mountain. These deposits are composed mainly of huge blocks of Tertiary intrusive rock and lower Paleozoic rock that have (may still be) toppled and slid northward off Union Mountain (map unit QlsR). There are two landslides of this type, with areas of 12 and 92 ha. The larger landslide grades downslope into map unit Qlso. Similar landslides on the north flank of Jacque Peak at high elevation (11,600–112,400 ft) have been transformed into rock glaciers (map unit Qrls), either because they fell onto a stagnant glacier core or because ice formed in the interstices of the rubble above the permafrost limit.

Landslides derived from Quaternary deposits are mainly soil slumps and earthflows (although not subdivided within map unit Qls) and are typically smaller than the bedrock slides. Typically, such slides result from failure of matrix-rich till plastered onto steep valley sidewalls. The largest soil slide exists on the west flank of Carbonate Hill east of the Tenmile tailings pond. This 2,000 ft wide, 3,000 ft long, possibly greater than 50 ft thick slump-earthflow is exposed in cuts along Highway 91 and is composed of red matrix (sand, silt, and clay) eroded from the Maroon Formation, mixed with Pinedale till composed of abundant red matrix and boulders of Precambrian gneiss, deposited by spillover ice from south of Fremont Pass. Several roadcuts in this deposit have slumped subsequent to road construction in the 1970s.

Colluvial deposits (Qc) and mixed alluvial-colluvial deposits (Qac) are widespread in the quadrangle. Colluvial deposits are composed mainly of gravel with a silt and sand matrix and are typically mapped (1) at the foot of hillslopes, (2) in first- and second-order drainage swales that may extend nearly to hilltops, (3) on dip slopes of Minturn and Maroon Formations, (4) on cirque floors and walls, and (5) at the base of large bedrock escarpments such as that of the Mosquito fault at the western flank of Bartlett Mountain. Mixed alluvial-colluvial deposits (Qac, Holocene) are also sandy but better sorted and stratified than colluvium and occur in the axes of higher-order swales and gullies that contain intermittent or perennial streams. Alluvial-colluvial deposits often abut colluvial deposits.

Due to the heavy influence of glaciation in this quadrangle, alluvial deposits are somewhat under represented. The single largest area of alluvium is the late glacial outwash gravel that underlies Wheeler Flats (Qat). Narrow alluvial deposits (Qa_l) lie beneath the modern floodplains of Tenmile, Clinton, Mayflower, Copper, Guller, and Stafford Creeks; Kokomo and Searle Gulches; and the East Fork of the Eagle River. Alluvial terraces (Qat) are rare, mapped only in Jacque and Stafford Creeks and in the East Fork of the Eagle River. These terraces occur in valleys that were filled with Pinedale glacier ice, so they are presumably post-glacial (Holocene) in age.

Alluvial fan deposits (Qf) are abundant in two distinct areas in the northeastern and southeastern parts of the quadrangle. In the northeastern area, fans were deposited on the valley floor of Tenmile Creek by 14 steep tributaries (10 on the east, 4 on the west). These fans presumably accumulated after the Pinedale deglaciation, and some (such as at Tucker Gulch) have younger, inset alluvial fans at their toes. In the southeastern part of the map area, alpine alluvial fans form a continuous belt on the eastern side of Clinton Amphitheater. These fans grade upslope into active talus fans (Qtfa) and active talus (Qta).

HUMAN-MADE DEPOSITS

af

Artificial fill (late Holocene) — Unsorted silt, sand, and rock fragments deposited by humans during construction of CR-91 and earthfill dams at Oxide Pond, Robinson Lake, and other small unnamed reservoirs. Fill along CR-91 is primarily composed of reworked Pinedale till (Qtp), whereas fill in earthfill dams is primarily rock waste derived from mining at the Climax Mine. The average thickness of the unit is less than 30 ft. Artificial fill may be subject to settlement when loaded if not adequately compacted.

mw

Mine waste (late 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. Includes coarse rock waste excavated from the Climax mine shafts, tunnels, and open pit at the south-central margin of the quadrangle. The deposits may be as much as 30 ft thick.

mt

Mill tailings (late Holocene) — Mill tailings resulting from milling operations at the Climax Mine and other smaller mines in the Kokomo District. Mill tailings are composed of sand- to silt-size fragments and are several hundred feet thick beneath the larger two tailings ponds (Robinson and Tenmile ponds). The surface of the Mayflower tailings pond is covered with a thin veneer of boulder gravel.

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 Tenmile Creek and West Tenmile Creek, their tributaries, and the East Fork of the Eagle 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.

Qgo

Younger terrace alluvium (Holocene) — Consists of poorly sorted, clast-supported, cobble, pebble, and locally boulder gravel in a silty, sandy matrix underlying terraces 10 to 15 ft above modern stream channels. Fine-grained overbank deposits may be present locally. Deposits underlie alluvial terraces in Stafford Creek, Jacque Creek, and the East Fork of Eagle River. Clasts are generally unweathered and abundant on the surface. Soil development on terrace surfaces is weak. May be correlative with Pinedale outwash gravels (Qop) in places but generally post-dates the Pinedale glaciation. Maximum exposed thickness is 15 ft. The unit may be a good source of sand and gravel.

Qat

Older stream gravel (late to middle Pleistocene?) — Moderately well-sorted sand to cobble gravel that comprises two abandoned channels in a deposit of Pinedale till, west of the old Kokomo town site. The deposits are texturally and depositionally similar to Pinedale outwash deposits (Qop), but clasts are moderately weathered and not as abundant on terrace surfaces. Soil horizons are moderately well developed. Average thickness of the deposit is about 5 ft.

Qao

Old alluvium (middle to early Pleistocene) — Moderately sorted and stratified, locally derived stream deposits; finer grained than map unit Qgo. Mapped only on the drainage divide southwest of Chalk Lake at the southern edge 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. Maximum thickness probably less than 15 ft. The unit may be a potential source of sand and gravel.

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 present 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

Active talus deposits (late Holocene) — Angular, cobbly and bouldery rubble as much as 6 ft in diameter. Deposits are 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 reveals significant matrix at depth. Talus deposition is active and widespread over the southeastern part of the quadrangle, especially below the steep walls of glacial cirques. Significant talus deposits are located at the heads of Clinton, Mayflower, and Humbug Creeks, on Elk Ridge, and on the Union Peak-Jacque Mountain ridge. Unit grades into areas of frost-shattered Precambrian bedrock that are mapped as underlying bedrock unit. Thickness of the deposits may exceed 60 ft. Talus areas are subject to severe rockfall, rock-topple, and rockslide hazards.

Qtfa

Active talus fan deposits (late Holocene) — Angular, cobbly and bouldery rubble as much as 6 ft in diameter. The deposit is distinguished from talus deposits (Qta, Qti) by its steep, cone-shaped morphology and presence of an axial channel with debris-flow levees. Deposits are inferred to accumulate partly by debris flows and snow avalanches emanating from large gullies in bedrock cliffs and partly by isolated rockfalls. This unit is mapped only in the Tenmile Range on the margins of cirques in upper Clinton and Mayflower Creeks. Maximum thickness unknown, probably as much as 30 ft on the basis of morphology. Active talus fans are subject to severe debris-flow hazards.

Qrf

Rockfall deposits (late Holocene) — Very large, angular blocks of bedrock derived from a single catastrophic rockslide or rockfall avalanche (after terminology of Cruden and Varnes, 1996). This unit is mapped only on the northwest flank of North Sheep Mountain, where a cliff of Tertiary intrusive rock failed and shed rock debris down a north-facing bedrock slope. Maximum thickness about 30 ft.

Qti

Inactive talus deposits (Holocene and late Pleistocene) — Angular, cobbly and bouldery rubble containing rock fragments as much as 6 ft in diameter. Deposits are similar to active talus (Qta) but are partly to completely stabilized by grass and tree cover. Contains some sandy matrix at surface. Deposits are 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 widespread over the southeastern part of the quadrangle, especially below the steep walls of glacial cirques. Significant talus deposits are located at the heads of Clinton, Mayflower, and Humbug Creeks, on Elk Ridge, and on the Union Peak-Jacque Mountain ridge. Unit grades into areas of frost-shattered Precambrian bedrock which are mapped as underlying bedrock unit. Thickness of the deposits may exceed 60 ft. Inactive talus areas are generally not subject to severe rockfall, rock-topple, and rockslide hazards.

Qtfi

Inactive talus fan deposits (Holocene and late Pleistocene) — Angular, cobbly and bouldery rubble as much as 6 ft in diameter. The deposit is distinguished from active talus fan deposits (Qtfa) by its partial to complete cover of stabilizing vegetation (grass or trees). Deposits are inferred to accumulate partly by debris flows and snow avalanches emanating from large gullies in bedrock cliffs, and partly by isolated rockfalls. This unit is mapped only in the Tenmile Range on the margins of cirques in upper Clinton and Mayflower Creeks. Maximum thickness unknown, probably as much as 30 ft based on morphology. Inactive talus fans are generally not subject to severe debris-flow hazards.

Qls

Landslide deposits, undifferentiated (Holocene to middle? 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. Surface of deposits commonly hummocky, and source area of landsliding is generally identifiable (top of scarp area indicated on map by thick dashed lines with ticks in direction of sliding). Composed of chaotically arranged debris ranging from clay to boulder size (diamicton). May also contain partly disaggregated blocks of local bedrock in the headscarp areas that have not slid far enough downslope to completely disaggregate into debris. Larger landslide deposits may be more than 30 ft thick. Mapped in three main areas: (1) dipslope rockslides in the Minturn and Maroon Formations on both sides of the Kokomo Syncline, in the western half of the quadrangle, (2) complex rock slumps in altered Tertiary intrusives, such as at Gold Hill, on the east and west flanks of Copper Mountain, and at the base of Jacque Peak, and (3) slumps emanating from crushed rock in the Mosquito fault zone where it descends the west valley walls of Clinton and Mayflower Creeks.

Qlsc **Landslide complex deposits, undifferentiated (Holocene to middle? Pleistocene) —** Mapped in areas of many small landslides of various types interspersed with areas of stability too small to map. Includes small slumps, debris flows, and earthflows of various ages. Mapped only in the southwest corner of the quadrangle and on the south side of Gold Hill, where the Minturn Formation forms extensive dip slopes. Composed of chaotically arranged debris ranging from clay to boulder size (diamicton). Surface of deposits commonly hummocky, and source area of landsliding is generally identifiable (top of scarp area indicated by thick dashed lines with ticks in direction of sliding). Larger landslide deposits may be more than 60 ft thick.

Qlsr **Failed bedrock blocks (Holocene to middle? Pleistocene) —** Landslide composed of very large, intact masses of bedrock, some of which have only traveled a few meters to tens of meters from the source outcrop. Mapped only on the north flank of Union Mountain.

Qlso **Older landslide deposits (middle to late Pleistocene) —** Similar to map unit Qls but older than Pinedale glaciation (15–23 ka). Deposits generally lie on glacial valley sidewalls upslope of the limit of Pinedale till.

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 (Qa_1), alluvial-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.

Qf **Alluvial-fan deposits (Holocene and late Pleistocene) —** Moderately sorted sand- to boulder-size gravel in fan-shaped deposits emanating from tributary streams to Tenmile Creek and from smaller side streams in those tributaries. Deposits typically composed of both matrix-supported beds three to 5 ft thick (debris flow facies) and clast-supported beds roughly one to 2.5 ft thick (streamflow facies), often intebedded. Clasts are mostly angular to subround with varied lithologies dependant 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 lower Tenmile Creek may exceed 60 ft. Elsewhere, the deposit is typically less than 30 ft thick. 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.

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

Ql **Lacustrine deposits, undifferentiated (Holocene to late Pleistocene) —** Fine-grained sediments formed in lakes or swampy closed depressions where the water table is near or slightly above the ground surface. Typically overlain by dark-brown to black, organic-rich sediment in wetland areas; typified by standing water, beaver ponds, and dense willow stands. Surface organic sediment may be interbedded with thin, sandy alluvium. 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. Lacustrine sediments are highly compactible. Basins in which these sediments are deposited have elevated water tables and may be prone to flooding. Maximum thickness of organic sediments less than 10 ft, but may overlie much thicker lake deposits. Maximum thickness 15–30 ft.

QTl **Older lacustrine deposits (early Pleistocene to late Tertiary) —** Poorly to well-sorted, massive to well stratified, poorly to moderately consolidated, white to light-gray tuffaceous sand and silt. Underlies old (Qao) and very old (Qavo) alluvium south of Chalk Lake at the south edge of the quadrangle and is exposed by incision of Chalk Creek. Probably derived from erosion of the Chalk Mountain Rhyolite in early Pleistocene or late Tertiary time. Maximum exposed thickness is about 30 ft.

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

Qpr **Protalus-rampart deposits (Holocene) —** 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. Maximum thickness is about 15 ft.

Qs **Solifluction deposits (Holocene and late Pleistocene) —** Angular to subrounded pebbles, cobbles, and large boulders in a chiefly sandy matrix deposited in alpine and sub-alpine basins. This unit is mapped only above treeline in upper Humbug and upper Monte Cristo Creeks. Solifluction deposits result from the slow downslope flowage of surficial deposits that are water saturated and subject to seasonal freezing. Frost creep and melt-water 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 in 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. Average thickness of these deposits is typically less than about 15 ft. These deposits may be susceptible to future downslope movement and shallow groundwater.

Qra **Active rock glacier deposits (late Holocene) —** 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. Frontal slope is at or above the angle of repose so is unvegetated; boulders on frontal slope are not covered with lichen and the internal sandy matrix is exposed. Mapped only on the east flank of Bartlett Mountain, where the lower part of a rock glacier has been reactivated. Maximum thickness about 60 ft.

Qri **Inactive rock glacier deposits (middle to early Holocene) —** 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. Frontal slope is below the angle of repose. Boulders on top, sides, and front are covered with lichen and/or trees, so deposits are inferred to be stationary. Includes a tongue-shaped rock glacier on the eastern flank of Bartlett Mountain, and a thickly forested, sheetlike deposit on the western flank of Chalk Mountain. Maximum thickness about 30 ft.

Qr **Rock glacier deposits, undifferentiated (Holocene) —** 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 (Fig. 3). Frontal slope is generally below the angle of repose. Boulders on top, sides, and front are covered with lichen and/or trees, so deposits are inferred to be stationary. Includes rock glaciers that are generally inactive but that may contain some small areas of later Holocene reactivated movement too small to map. Maximum thickness about 30 ft.

Qrls **Rock glacier/landslide deposits (Holocene) —** Poorly sorted angular to sub-angular boulders, cobbles, gravel, and sandy silt. Composed mostly of very large, angular blocks of Tertiary intrusive bedrock with little to no matrix exposed at the surface. Landform has the lobate or tongue-like morphology and transverse pressure ridges and swales typical of rock glaciers, but the deposit was initially derived from a large bedrock landslide rather than from incremental accumulation of talus. Mapped only on the north flank of Jacque Peak. Maximum thickness as much as 80 ft. This unit is subject to a greater hazard from future catastrophic landslide deposition than is map unit Qr.

GLACIAL DEPOSITS — Gravel, sand, silt, and clay deposited by ice.

Qtn **Neoglacial till (Holocene) —** Heterogen-

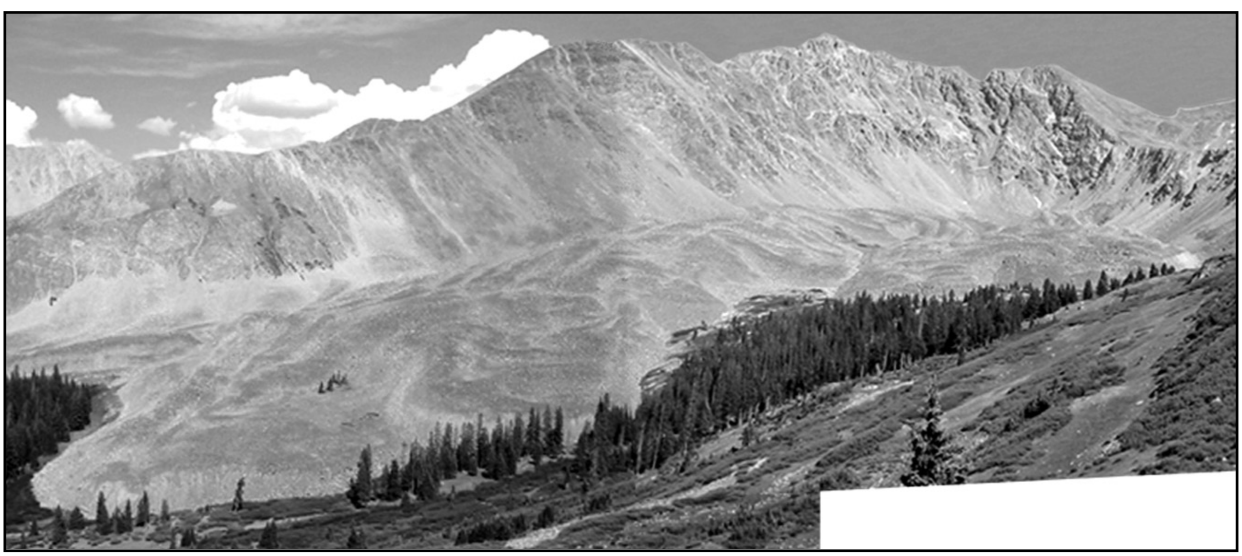

Figure 3. Massive rock glacier complex in the drainage northeast of Humbug Creek. View is to the east.

eous deposits of gravel, sand, silt, and clay deposited by ice on the floor of the north-east-facing cirque on the eastern flank of Bartlett Mountain in the southern part of the quadrangle. 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.

Qtp

Pinedale till (late 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 and unweathered. Surface topography and soil development in till throughout the quadrangle are highly variable. 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, 15–35 ka) age for these deposits. Maximum thickness is unknown, but road cuts along SH 91 expose a thickness of at least 30 ft in places.

Qto

Older till (middle? Pleistocene) — These deposits are generally similar in texture and lithology to Pinedale till (Qtp) and are exposed upslope of Pinedale lateral moraines or downvalley of Pinedale terminal moraines. 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 is older than Pinedale. The age of the deposit is considered late or middle Pleistocene, perhaps correlative with the Bull Lake glaciation elsewhere in the Rocky Mountains (Chadwick and others, 1997). Due to a lack of exposures the maximum thickness is unknown, but is probably similar to that of Pinedale till (more than 30 ft).

Qtvo

Very old till (middle to early Pleistocene) — Highly eroded deposit of boulder gravel mapped only on the drainage divide west of Chalk Lake at the south edge of the quadrangle. Composed of isolated, large erratic boulders of Precambrian crystalline rock lying on a subdued landscape of Paleozoic and Tertiary rocks. Typically only a few feet thick and discontinuous nature. Maximum thickness is less than 10 ft.

BEDROCK

TERTIARY INTRUSIVE ROCKS

Tertiary igneous rocks in the quadrangle form sills, dikes, and stocks that are predominantly porphyritic and calc-alkalic in composition. Sill intrusions predominate and range from a few feet to 300 ft or more in thickness and up to one mi or more in strike length (Bergandahl and Koschmann, 1971). Sills are typically concordant to bedding, though locally, they may crosscut bedding at low angles. A variety of age dating methods indicate that the intrusives range in age from about 29 to 51 Ma. Herein, Tertiary rocks younger than 33.7 Ma are considered Oligocene in age on the basis of the geologic time scale by Palmer and Geissman (1999).

In the Copper Mountain quadrangle, Eocene porphyritic calc-alkalic intrusions range from granodiorite to quartz monzonite. Younger Oligocene intrusions are predominately rhyolite. The chemical composition of the granodiorite and quartz monzonite porphyries are highly similar. SiO_2 contents in these rocks range from 65.67 to 69.41 weight percent, and $Na_20 + K_20$ contents range from 7.16 to 7.52 percent (table 3 in Bergendahl and Koschmann, 1971). All but the Elk Mountain porphyry were emplaced between 42 and 44 Ma.

These intrusive rocks originated from different igneous centers. A discernable path of igneous migration is not apparent. The youngest of the Eocene porphyries is the Eagle River porphyry (map unit Ter), which is only exposed on the western boundary of the quadrangle. Its center of igneous activity is west of the quadrangle in the Pando area (Tweto, 1954). Exposures of the megacrystic quartz monzonite porphyry (map unit Tqpm) are found throughout the quadrangle and the surrounding region. The center of igneous activity for this unit is apparently in the adjacent Breckenridge quadrangle (Wallace and others, 2003) and Frisco quadrangle (Kellogg and others, 2002) north and east of Copper Mountain. The Tucker Mountain quartz monzonite porphyry (map unit Ttr) is centered on Tucker Mountain (northern third, center of the quadrangle), and exposures of this rock do not extend greatly beyond its intrusive center. The Humbug stock (map unit Tqm) is a large igneous intrusive body located on the eastern boundary of the Copper Mountain quadrangle (northern third) and the western part of the adjacent Breckenridge quadrangle (Wallace and others, 2003). The Quail Mountain (map unit Tq) porphyry is recognized as a limited set of stocks and dikes centered on a 1 to 2 sq mi area in the center of the quadrangle. The Elk Mountain porphyry (map unit Te) is the oldest and most abundant Tertiary intrusive in the quadrangle. It appears to be centered on Elk Mountain near the western edge of the quadrangle where the abundance and thickness of the sills is the greatest.

The granodiorites and quartz monzonite porphyries were followed by intrusion of rhyolites at Tucker Mountain (northern third, center of the quadrangle), Tenmile Creek (east center of the quadrangle), and Chalk Mountain (near southern boundary of quadrangle), 6 to 13 million years after emplacement of the granodiorites and quartz monzonite porphyries. The Tucker Mountain rhyolite (map unit Ttr) is interpreted as a near-surface plug (Mach, 1992). The Tenmile Creek porphyry (map unit Ttc) crops out only along Tenmile Creek just south of the mouth of Tucker Gulch. The Chalk Mountain intrusion (map unit Tc) is a high silica rhyolite, similar in composition and age of emplacement to the rhyolites responsible for porphyry molybdenum mineralization at Climax (Bookstrom and others, 1987). Field relations are not definitive for the mode of emplacement of this rhyolite. Emmons (1898) believed the Chalk Mountain rhyolite to be an intrusive, whereas Koschmann and Wells (1946) felt that it was a surface flow on rough terrain. Later workers (Bookstrom and others, 1987) concluded that the Chalk Mountain rhyolite was a stock or possibly a laccolith. Herein, the Chalk Mountain rhyolite is considered a near-surface intrusive stock.

Tc

Chalk Mountain rhyolite (Oligocene) — Brilliant white rhyolite porphyry containing abundant co-equal amounts of sanidine, plagioclase, and quartz phenocrysts up to 0.2 in. in length within a white microcrystaline groundmass of plagioclase and quartz. The quartz phenocrysts are commonly smoky. The Chalk Mountain rhyolite has been dated at 29 Ma by the K-Ar method (V.E. Surface, Climax Molybdenum Company, 1970, written communication in Tweto, 1974a). Traces of topaz and fluorite were reported by Mach (1992). This unit is believed to be associated with the igneous events responsible for the formation of the Climax ore body (White and others, 1981).

Ttc

Tenmile Creek quartz monzonite porphyry (Eocene) — White to light-gray, medium grained quartz monzonite porphyry containing subequal amounts of quartz and potassium feldspar phenocrysts up to 0.2 in. long and two to four percent biotite books 0.05 in. long. The rock is pervasively sericitically and argillically altered and has an associated disseminated pyrite content of 2 to 5 percent. Locally the porphyry contains quartz-molybdenite veinlets. The unit crops out along Tenmile Creek near Climax's wastewater treatment plant. Two potassium-argon dates by the Climax Molybdenum Company yielded ages of 35.0 ± 1.4 Ma and 34.9 ± 2.0 Ma. An Eocene age of about 35 Ma is hereby ascribed for the intrusion and accompanying mineralization and alteration.

Ttr

Tucker Mountain rhyolite (Eocene) — Light-gray to white rhyolite with approximately co-equal amounts of sanidine and embayed quartz, minor amounts of plagioclase, and rare biotite. Sanidine, quartz, and plagioclase phenocrysts are up to 0.2 in. in length; biotite flakes are generally less than 0.04 in. in diameter. There is flow banding at its outer margins along with abundant xenoliths of coarse-grained sandstone. Thin dikes are present along its periphery and there is an intrusive contact breccia containing clasts of skarn, hornfelsed siltstone and shale, silicified sandstone, and rare marble (Mach, 1992). A K-Ar date of sanidine yielded a 35.2 ± 1.4 Ma age (Marvin and others, 1974), whereas a zircon yielded a fission track date of 39.5 ± 4.5 Ma (Mach and Thompson, 1998). An age of approximately 35 to 36 Ma appears indicated. This rhyolite crops out only on the southern face of Tucker Mountain in the north central part of the quadrangle and is interpreted as a near surface plug (Mach, 1992).

Ter

Eagle River porphyry (Eocene) — Greenish-gray granodiorite porphyry containing abundant phenocrysts of feldspar, quartz, and biotite in a finely crystalline matrix. Quartz phenocrysts are rounded grains roughly 0.2 in. diameter. Feldspars crystals are equant and typically 0.2 to 0.3 in. in diameter. Minor glassy tabular plagioclase is present locally. Eagle River porphyry occurs as a single outcrop on the far western edge of the quadrangle, but extends farther to the west typically as sills in the area between the East Fork of the Eagle River and Tennessee Creek in the adjacent Pando quadrangle (Tweto, 1954, 1974b). It is undated, but field relations indicate that it is younger than the megacrystic quartz monzonite porphyry and older than a rhyolite believed temporally equivalent to the Chalk Mountain rhyolite (Tweto, 1974b). On the basis of similarity in appearance to the megacrystic Quartz Monzonite Porphyry, an Eocene age is tentatively ascribed.

Tqpm

Quartz monzonite porphyry - megacrystic variety (Eocene) — Light-gray to light-bluish-gray quartz monzonite porphyry that contains prominent large phenocrysts (megacrysts) of orthoclase 0.75 to 2 in. long, and in many places, rounded bipyramids of quartz 0.2 to 0.6 in. in diameter. These phenocrysts are set in a porphyritic matrix composed of anhedral grains less than 0.2 in. long of plagioclase, quartz, orthoclase, and abundant biotite, set in a bluish-gray aphanitic matrix. This unit is widely distributed throughout the quadrangle and is dominantly cut by, but locally cuts, the northeast trending faults so prominent in the quadrangle. Many authors have correlated this unit to the Lincoln porphyry based on close similarity of appearance; however, ages (Bookstrom, 1990) and accompanying field relations indicate that the Lincoln porphyry is in fact much older (66 to 67 Ma). The megacrystic quartz monzonite porphyry of this quadrangle is correlated to the megacrystic quartz monzonite porphyry (Tqpm) in the adjacent Breckenridge quadrangle (Wallace and others, 2002), which has been dated in the adjacent Frisco quadrangle at 44.1 ± 1.6 Ma by the K-Ar method (Marvin and others, 1989). Apatite and zircon fission-track dating of two samples of megacrystic quartz monzonite porphyry from the Copper Mountain quadrangle yielded ages of 36.7 ± 3.9 Ma (apatite) and 41.5 ± 3.7 Ma (zircon), and 48.6 ± 6.6 Ma (apatite) and 40.1 ± 3.9 Ma (zircon), respectively (Mach,1992). Convergence of these data suggest a date on the order of 42 to 43 Ma, assuming no resetting by younger events.

Ttq

Tucker Mountain quartz monzonite porphyry (Eocene) — Light-gray quartz monzonite porphyry. Contains abundant subhedral plagioclase phenocrysts less than 0.2 in. long, embayed quartz phenocrysts up to 0.12 in. long, and less abundant, smaller potassium feldspar and biotite phenocrysts. Typically, the rock is argillically to sericitically altered and has a halo containing 2 to 5 percent disseminated pyrite in adjacent sedimentary rocks. Fission track dating yielded an age of 36.7 ± 3.8 Ma on apatite and an age of 41.8 ± 3.0 Ma on zircon (Mach and Thompson, 1998). An earlier K-Ar date of 42.8 ± 2 Ma on biotite was obtained by Marvin and others (1974). The Tucker Mountain quartz monzonite porphyry is cut by a dike of Tqpm suggesting that emplacement proceeded 42 to 43 Ma, but probably not significantly so.

Tqm

Quartz monzonite of the Humbug Stock (Eocene) — White to light-gray, black-mottled, medium- to coarse-grained quartz monzonite consisting chiefly of quartz, oligoclase-andesine, microcline microperthite, an aggregate of less than 10 percent biotite, hornblende, and magnetite, and accessory apatite and sphene (Bergendahl, 1963). Euhedral phenocrysts of plagioclase and potassium feldspar up to 0.2 in. in maximum dimension are common (Fig. 4). The rock has an hypidiomorphic-granular crystalline texture. The bulk of the stock is centered around Peak 9 to the east in the Breckenridge quadrangle. Marvin and others (1974) reported a K-Ar average age for the stock of 40.1 Ma. More recent Ar-Ar dating on biotite yielded an age of 42.05 ± 0.23 Ma (Wallace and others, 2003).

Tq

Quail porphyry (Eocene) — Dark greenish-gray granodiorite porphyry containing abundant plagioclase, hornblende and lesser biotite in an aphanitic groundmass. The porphyry crops out as small stocks, sills, and dikes in a localized area in center of quadrangle and is cut by megacrystic quartz monzonite porphyry (Tqpm). Two samples were dated by the fission track method yielding ages of 41.6 ± 10.4 Ma (apatite), 44.4 ± 5.3 Ma (zircon), and 46.1 ± 8.2 Ma (apatite), 40.4 ± 4.5 Ma (zircon), respectively (Mach and Thompson, 1998). An age of 43 to 44 Ma is suggested.

Te

Elk Mountain porphyry (Eocene) — Gray granodiorite porphyry containing rounded quartz grains 0.15 to 0.3 in. in diameter, rounded bypyramids of quartz less than 0.15 in. in length , potassium feldspar phenocrysts 0.15 to 0.3 in. in length, and plagioclase, hornblende, biotite less than 0.15 in. in maximum dimension. This porphyry crops out principally as sills centered in the northwestern part of the quadrangle and is the most widespread of the Tertiary igneous rock in the quadrangle and in the Pando area to the west (Tweto, 1954, 1974b). The sills locally inflate the Minturn Formation as much as 1,500 feet in the western part of the quadrangle. Contact effects associated with intrusion of the sills are minimal Two samples of Elk Mountain porphyry have been age dated by the fission track method. These samples yielded dates of 51.5 ± 12.3 Ma (apatite), 37.6 ± 3.7 Ma (zircon), and 41.9 ± 9.5 Ma (apatite), 50.9 ± 5.2 Ma (zircon), respectively (Mach, 1992). A primary date on the order of 50 to 51 Ma is suspected.

PALEOZOIC SEDIMENTARY ROCKS

Regionally includes the Sawatch Quartzite and Peerless Shale (Upper 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 (Upper Devonian), Leadville Limestone (Lower Mississippian), Belden Shale and Minturn Formation (Pennsylvanian), and Maroon Formation (Pennsylvanian and Permian). The Minturn and Maroon Formations are by far the most widespread of the Paleozoic sequence in the map area

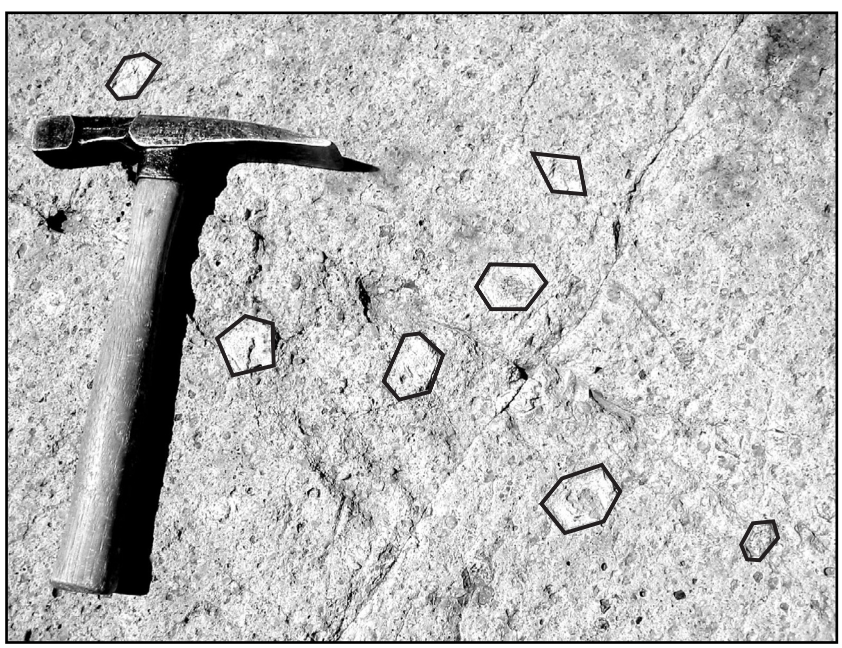

Figure 4. Quartz monzonite of the Humbug stock. Note euhedral phenocrysts of plagioclase and potassium feldspar outlined in black.

and crop out primarily, though not solely, west of Colorado Route (CR)-91. Relatively thin beds of Sawatch Quartzite and other undivided Cambrian to Mississippian rocks crop out only locally in the southeast corner of the quadrangle east of CR-91 and on the flank of Chalk Mountain.

An extensive (>8,000 ft thick) section of non-marine coarse clastic sedimentary rocks containing interbedded marine carbonates covers most of the quadrangle. These have been divided into two units; the Middle Pennsylvanian Minturn Formation and the Upper Pennsylvanian-Permian Maroon Formation. The Jacque Mountain Limestone Member of the Minturn Formation serves as the marker bed that separates these two units. These formations have been interpreted by Tweto and Lovering (1977) as having been deposited at the margin of the Eagle Basin during uplift of the Ancestral Front Range.

Cambrian to Mississippian rocks crop out at a few locations in the southern part of the quadrangle. Sawatch Quartzite on Little Bartlett Mountain and an outcrop of Leadville Limestone in Mayflower Gulch are the only exposures that could be identified with any certainty. Other pre-Pennsylvanian sedimentary rocks in the area were not identifiable. Rocks of the Cambrian to Mississippian system are interpreted as having been deposited in a shallow marine to beach or near-shore environment (Tweto and Lovering, 1977). Detailed descriptions of these formations can be found in Tweto (1949), Koschmann and Wells (1946), and Tweto and Lovering (1977).

The extent to which lower Paleozoic rocks underlie the Copper Mountain quadrangle is uncertain. At Pando, approximately 8 mi west of the quadrangle, there are exposed approximately 500 ft of shallow marine shelf dolostone, quartzite, sandstonec and shale of lower Paleozoic age (Tweto, 1949). However, on the northeast flank of Copper Mountain, Bergendahl and Koshmann (1971) mapped the Robinson Member of the Minturn Formation directly on top of Precambrian migmatite, which indicates that at least 4,200 ft of the lower Minturn Formation was never deposited or was eroded away, possibly in association with syndepositional movement on the Mosquito and/or Gore faults. Further to the east, exposures of the Mississippian Leadville Limestone at the Boston mine in Mayflower Gulch are only 25 ft thick (Koschmann, 1949) as compared to a thickness of nearly 100 ft thick at Pando (Tweto, 1949). It is unclear if the abrupt thinning at this location is due to faulting out by the Mosquito fault or by pre-Pennsylvanian erosion.

PIPm

Maroon Formation (Early Permian to Late Pennsylvanian) — Predominantly dark- to bright-red sandstone, siltstone, and mudstone, pinkish-gray pebble- to cobble-conglomerate, and a few thin (generally less than 2 ft thick) beds of dark-gray to reddish-gray limestone or limey siltstone and mudstone. The multicolored (greenish-gray, bright-green, purple, pinkish-gray, and black) rocks on Union Mountain are hornfels. Mineral composition of the formation includes detrital grains of quartz, feldspar, and biotite altered to hematite, and muscovite (Taranik, 1974). Medium- to fine-grained varieties tend to be very micaceous and exhibit tabular and trough cross-stratification and sub-parallel laminations (Fig. 5). Taranik (1974) also noted ripples, mud cracks, raindrop imprints, and other sedimentary structures in fine-grained sandstone and siltstone in the Breckenridge area east of the quadrangle. Coarse-grained sandstone and conglomerate commonly is present in channels scoured into finer grained sediments. Channel material also exhibits tabular and trough cross-stratification and grades quickly upward to medium- and fine-grained sandstone and siltstone.

The Maroon Formation in the Kokomo and Copper Mountain area is distinguished from the underlying Minturn Formation primarily by the dominant red color, finer grained nature (typically fine sandstone and siltstone as opposed to dominant medium to coarse sandstones), and absence of significant carbonate units. In many places, the top of the Jacque Mountain Limestone Member of the Minturn Formation serves as a marker bed that defines the contact between the Minturn and Maroon Formations. Computer-aided projection of the Jacque Mountain Limestone Member was also used to help determine the approximate boundary between the two formations

Figure 5. Cross-stratification in micaceous sandstone and pebble conglomerate in the Maroon Formation.

in areas where the contact could not be located due to poor exposure.

The Maroon Formation conformably overlies the Minturn Formation. The top of the Maroon Formation, however, is not preserved in the quadrangle so total thickness cannot be determined. Additionally, intrusion by multiple Tertiary sills has inflated the apparent thickness of the formation. On Jacque Mountain the formation is about 2,000 ft thick. Northwest of the quadrangle near Minturn, the formation reaches up to 4,200 ft thick (Tweto and Lovering, 1977). Near the south end of the Breckenridge quadrangle the formation is estimated to be about 3,350 ft thick but thins abruptly to less than 600 ft at the north end of the quadrangle (Wallace and others, 2003).

IPm

Minturn Formation, undivided (Middle Pennsylvanian) — Dominantly tan to greenish-gray, arkosic, micaceous conglomerate, sandstone and shale. The lower 500 ft and upper 800-1,800 ft of the formation tend towards varying shades of red. Detrital units are comprised primarily of quartz, feldspar, biotite, muscovite, and minor hornblende (Taranik, 1974). Biotite is commonly altered to hematite, though not as extensively as in the Maroon Formation. Epidote may be prevalent in areas where Tertiary intrusive material has reacted with iron silicates, such as biotite and hornblende, particularly in siltstone units where these minerals are more abundant. Pervasive channel structures are filled with relatively thick (average of 30 ft) coarse-grained sandstone and conglomerate (Fig. 6) that exhibits tabular and trough cross-stratification. Medium- to fine-grained sandstone and siltstone exhibit tabular and trough cross-stratification and sub-parallel laminations. Beds are commonly highly lenticular and difficult to trace over any significant distance.

Seven relatively persistent beds of carbonate are contained within the Minturn Formation. From top to bottom they are the Jacque Mountain Limestone, the White Quail Limestone Member, the Elk Ridge Limestone Member, the Robinson Limestone, the Resolution Dolomite, the Hornsilver Dolomite, and the Wearyman Dolomite Members, as designated by Tweto (1949). Where distinguishable from each other, these are indicated on the map. Each member is described briefly below. The top of the uppermost carbonate unit, the Jacque Mountain Limestone Member, defines the conformable contact with the overlying Maroon Formation.

West of the quadrangle near the towns of Pando and Minturn the Minturn Formation is about 6,000 ft thick (Tweto and Lovering, 1977; Bergendahl and Koschmann, 1971). Overall thickness within the quadrangle could not be determined

Figure 6. Conglomerate beds in the Minturn Formation range from gray to grayish-red in color.

because a complete sequence is not exposed. However, the formation is known to thin considerably to the east and to the north against a paleo-highland (Bergandahl and Koschmann, 1971). Estimated thickness of the Minturn Formation in the Breckenridge quadrangle is only about 1,500 ft (Wallace and others, 2003). On Copper Mountain, at least 4,200 ft of the lower Minturn Formation is missing as indicated by the presence of the Robinson Member of the Minturn Formation directly on top of Precambrian migmatite. In Mayflower Gulch, the Minturn Formation rests unconformably on Mississippian Leadville Limestone. Estimated thickness of the Minturn Formation in the western part of the quadrangle is about 6,000 ft. Intrusion of Tertiary sills has inflated the section an additional 1,000 to 1,500 ft. In the eastern part of the quadrangle, the Minturn Forma-tion is only about 2,500 to 3,000 ft thick.

IPmj

Jacque Mountain Limestone Member — Gray to bluish-gray oolitic limestone 15 to 25 ft thick. It is slightly fossiliferous and locally contains large cephalopods. The member is typically lenticular and commonly splits into several thin limestone beds separated by shale. The limestone marks the top of the Minturn Formation and is an important host for lead-zinc-silver replacement ore bodies.

IPmq

White Quail Limestone Member — Two to three dark-gray to black fossiliferous limestone beds, each 5 to 30 ft thick, separated by 25 to 150 ft of coarse red sandstone and shale. The unit is commonly oolitic and has abundant gastropods, pelecypods, and brachiopods. The uppermost limestone bed, which is strongly argillaceous, is commonly absent within the quadrangle. This member is approximately 5,000 ft above the base of the formation in the Pando area.

IPme

Elk Ridge Limestone Member — Two thin, locally sandy, limestone beds separated by 200 to 225 ft of red sandstone and conglomerate. The upper limestone bed is mottled pink and gray and is five to 7 ft thick. The lower limestone bed is dark bluish-gray and 10 to 15 ft thick. This member is approximately 4,800 ft above the base of the formation in the Pando area.

IPmr

Robinson Limestone Member — Two to five, but generally three, beds of dark-gray to black, light-bluish-gray-weathering limestone 15 to 35 ft thick. Fusulinids are common. This member is approximately 4,200 ft above the base of the formation in the Pando area and is an important host for lead-zinc-silver replacement ore.

IPms

Resolution Dolomite Member — One to three beds of dark-gray dolomite with abundant black chert, separated by gray coarse sandstone and shale. This member is approximately 3,700 ft above the base of the formation in the Pando area.

Pmh

Hornsilver Dolomite Member — Massive and thin-bedded gray dolomite, 18 to 28 ft thick. This member is approximately 2,900 ft above the base of the formation in the Pando area.

IPmw

Wearyman Dolomite Member — Massive gray to buff reef dolomite 15 to 75 ft thick. This member is approximately 2,600 ft above the base of the formation in the Pando area.

IPml

Unidentified limestone beds.

Ml

Leadville Limestone (Mississippian) — Dark- to medium-gray, finely crystalline dolomite or dolomitic sandstone with moderately well-preserved bedding. At the Boston Mine in Mayflower Gulch (the only exposure in the quadrangle), the unit is about 25 ft thick and is highly fractured and silicified. West and northwest of the quadrangle, the Leadville Limestone is up to 140 ft thick, but it thins dramatically and is locally absent eastward towards the Gore and Mosquito fault systems (Tweto and Lovering, 1977; Bergendahl and Koshmann, 1971).

Ꞓs

Sawatch Quartzite (Late Cambrian) — White to light-gray, vitreous quartz-pure quartzite. The unit is typically composed of moderately well-rounded to very well-rounded, moderately well-sorted quartz grains. Basal beds, as seen on Little Bartlett Mountain, tend to be somewhat coarser, approaching conglomerate, and appear to lie on a planar Precambrian surface. The entire unit is nowhere exposed in the quadrangle, but in the adjacent Pando quadrangle to the west, it ranges from 185 ft in the northern part of the quadrangle to approximately 140 ft thick in the south (Tweto, 1974b). The Sawatch Quartzite further thins southward of the quadrangle to approximately 100 ft thick in the vicinity of Leadville (Tweto, 1974a; Tweto and Lovering, 1977). Bergendahl and Koshmann (1971) mapped Sawatch Quartzite on the southeast flank of Copper Mountain both above and below a wedge of Minturn Formation. Although fragments of quartzitic sandstone were found in float and in mine dumps in this area, the quartz-rich unit was not observed in outcrop. Thin section analysis reveals the quartz-rich fragments are remarkably similar in grain size and composition to the Sawatch Quartzite found on Little Bartlett Mountain.

MCr

Leadville Limestone (Mississippian), Chaffee Formation (Devonian), Fremont Dolomite, Harding Quartzite, and Manitou Limestone (Ordovician), and Peerless Formation and Sawatch Quartzite (Cambrian), undivided — Fragmentary outcrops of pre-Pennsylvanian sedimentary rocks. On the flank of Chalk Mountain, white to red, poorly sorted arkosic and quartzitic sandstone is poorly exposed. Along the lower ridge of Mayflower Hill weathered exposures consist primarily of highly fractured, partly silicified limestone and dolomitic sandstone. The rocks at this location may correlate, in part, with the Dyer Dolomite (K. Kellogg, oral communication) or lower part of the Leadville Limestone as described by Nadeau (1972). Exposures at Chalk Mountain and Mayflower Hill were ultimately insufficient to definitively assign a formation name.

PROTEROZOIC INTRUSIVE ROCKS

Proterozoic intrusive rocks of Colorado 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 Copper Mountain quadrangle are correlated only to the Routt and Berthoud plutonic suites.

Yqm

Quartz monzonite (Middle Proterozoic) — Pink to pinkish-gray, massive to moderately foliated, medium- to coarse-grained quartz monzonite rock consisting of roughly equal proportions of microcline, quartz, and plagioclase with lesser amounts of biotite and muscovite (Fig. 7). The rock is typified by a seriate porphyritic texture defined by alignment of tabular microcline phenocrysts, many of which exhibit Carlsbad twinning. Some euhedral laths of microcline exceed one inch in length. Quartz is present as anhedral grains and as aggregates of small sutured grains. Bergendahl (1963) noted apatite and rutile as accessory minerals. Weathered surfaces have a somewhat rusty coloration. The rock is similar in texture and composition to the Silver Plume Granite described by Ball (1906). Near the type locality at Silver Plume, roughly 25 mi northeast of the quadrangle, this granite yielded a uranium-lead zircon age of 1,422 ± 2 Ma (Graubard and Mattison, 1990).

YXp

Pegmatite, aplite, and related rocks (Middle to Early Proterozoic) — Light-pink to pinkish-gray, pegmatite comprised of quartz, microcline, andesine, and minor amounts of muscovite and biotite. Magnetite and beryl crystals up to a few in. long are found locally. Aplite dikes and veinlets are light pink and have a fine-grained sugary texture formed predominantly by quartz and feldspar crystals.

YXm

Mafic dikes (Middle to Early Proterozoic) — Dark-gray, dark-brown, or black,

Figure 7. Quartz monzonite correlated with the Silver Plume granite. Note tabular, euhedral laths of microcline show weak to moderate alignment parallel to pen.

fine-grained, massive to weakly foliated lamprophyre dikes comprised primarily of hornblende and/or biotite, plagioclase and/or potassium feldspar, epidote, and chlorite. Lesser constituents include pyroxene, quartz, magnetite and other opaque minerals, and traces of apatite (Wallace and others, 2003). The dikes commonly exhibit small dark or light blebs consisting of fine-grained aggregates of hornblende or potassium feldspar.

Xgg

Granitic gneiss (Early Proterozoic) — Light-gray, medium- to coarse-grained, massive to moderately foliated monzogranite comprised of microcline, plagioclase, quartz, and biotite. Locally, magnetite is visible in outcrops. Accessory minerals include garnet, zircon, and apatite. The rock has a hypidiomorphic to xenomorphic texture and commonly exhibits short, thin biotite-rich aggregates parallel to foliation (Fig. 8). Biotite may be altered to chlorite; oligoclase is locally altered to sericite and epidote (Kellogg and others, 2002). The granite contains numerous lengthy inclusions of amphibolite or hornblende gneiss, particularly near the margins of larger masses. Cross-cutting relationships indicate the granitic gneiss is younger than the quartz monzonite (Yqm), which agrees with an age assignment to the Routt plutonic suite by Kellogg and others (2002) on the Frisco quadrangle. Bergendahl (1963) mapped this unit (which he called granulite on the basis of lithology, not metamorphic facies) in the core of an anticline north of Wheeler Junction and suggested it was stratigraphically the lowest unit in the metasedimentary sequence at that location. Mapping by Kellogg and others (2002) and Wallace and others (2003) did not support this interpretation; the granitic gneiss was considered an igneous body emplaced synorogenically rather than syndepositionally. Field evidence on the Copper Mountain quadrangle supports the conclusions of the Kellogg and Wallace mapping teams.

Xgp

Porphyritic granodiorite (Early Proterozoic) — Medium- to dark-gray, well foliated to massive porphyritic granodiorite consisting of a medium- to coarse-grained groundmass of oligoclase, potassium feldspar, quartz, and biotite and porphyroblasts of potassium feldspar up to 2 in. long (Fig. 9). Accessory minerals include magnetite, ilmenite, pyrite, apatite, sphene, zircon, and muscovite (Tweto and Lovering, 1977).

Figure 8. Moderately foliated granitic gneiss. Foliation, parallel to pencil is defined by biotite-rich aggregates.

Potassium feldspar makes up as much as 50 percent of the rock and exhibits microcline grid-twinning and Carlsbad twins. At many localities, the largest of the porphyroblasts appear to be younger than the other constituents of the rock as they exhibit a random or fluxion structure that is not necessarily parallel to foliation in adjacent rocks. Where porphyroblasts are largest and most abundant the granodiorite has a gneissic texture; where porphyroblasts are smaller and less abundant the rock texture is more granitic. Much of the porphyritic granodiorite in the southeastern part of the quadrangle is gneissic. A small body mapped in Spaulding Gulch tends more towards the granitic variety. Granodiorite crops out as small plugs or elongate bodies that are roughly parallel to or slightly oblique to compositional layering in adjacent migmatite.

Bergendahl (1963) described a similar rock in the Breckenridge quadrangle as "porphyroblastic migmatite." However, Tweto and others (1970) and Tweto and Lovering (1977) considered porphyritic granodiorite to be a border phase of the Cross Creek Granite, which they mapped north and northwest of the Copper Mountain quadrangle. There, they described an intimate layering of granite, diorite, and migmatite, gradational into one another, that was the result of major plutonism and associated metamorphism. Tweto and Lovering (1977) contended that this episode of plutonism was expressed as a large batholith that is exposed in, and inferred to be continuous beneath, the Sawatch and Gore Ranges. The majority of the batholith is northwest of the northeast-trending Homestake shear zone, which is adjacent to the northwest corner of the quadrangle. Tweto and Lovering (1977) thought it likely that the shear zone acted as the southern border of the batholith, but they acknowledged the possibility of a southern extension of the batholith southeast of the shear zone. Porphyritic granodiorite mapped in the southeastern part of the quadrangle is nearly identical in appearance to the border phase of the Cross Creek Granite mapped northwest of the shear zone, which suggests the batholith may in fact extend southeast of the shear zone. Exposure of possible Cross Creek Granite border-phase rocks south of the shear zone and generally east of the main batholith agrees with left-lateral displacement on the shear zone described by Tweto and Sims (1963). The Cross Creek Granite is correlated with the Boulder Creek Granite of the Front Range (Tweto and others, 1970), which has a U-Pb age of 1,714.4 ± 4.6 Ma (Premo and Fanning, 2000).

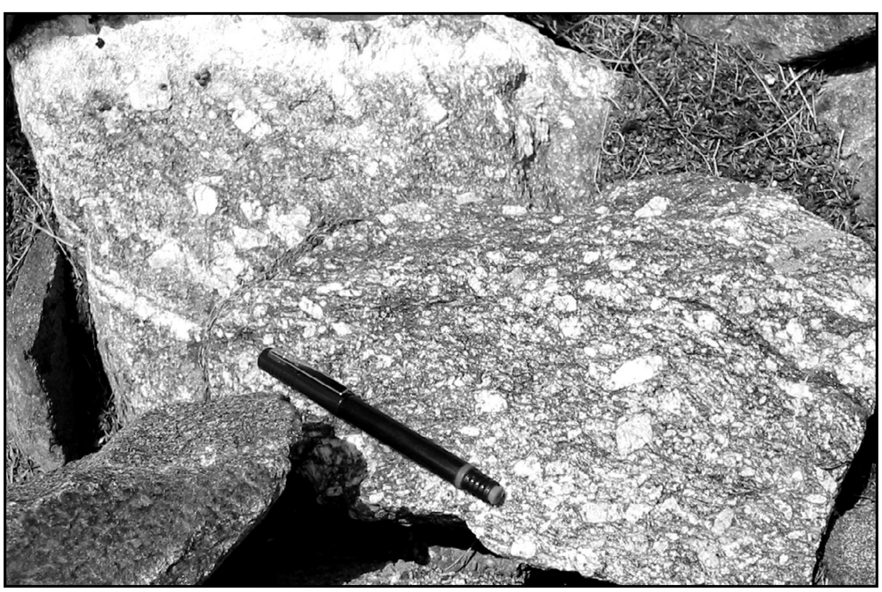

Figure 9. Porphyritic granodiorite with roughly aligned porphyroblasts of potassium feldspar.

PROTEROZOIC METAMORPHIC ROCKS — Includes metasedimentary and metavolcanic rocks of the Proterozoic gneiss complex of Tweto (1987). These rocks were originally deposited or erupted about 1,800 Ma or less (Premo and Fanning, 1997, Tweto, 1987). Regional peak metamorphism and deformation coincided with syntectonic plutonism during the Early Proterozoic (Selverstone and others, 1997).

Xm

Migmatite (Early Proterozoic) — Medium- to dark-gray, dark-brownish-gray, or rust-colored, medium-grained biotite-hornblende-plagioclase-quartz laminae intimately layered with white to light-gray, medium-grained to pegmatitic quartz-plagioclase-microcline granitic material. The granitic material is the result of metamorphic segregation through partial melting and/or layer-by-layer igneous injection. Accessory minerals include sillimanite, garnet, muscovite, apatite, epidote, and sericite (Bergendahl, 1963). Migmatite is well foliated and exhibits numerous ptygmatic folds and boudinage and sigmoidal structures (Fig. 10). Locally, this unit grades to, or includes, layers of porphyritic granodiorite). Additionally, a thin (less than 5 ft thick), discontinuous layer of metaquartzite was observed within the migmatite unit on the flank of Bartlett Mountain.

Bergendahl and Koshmann (1971) mapped a “pink migmatite” unit in the northeast part of the quadrangle. The migmatite in this area contains a greater percentage of light-colored granitic and pegmatitic material than the surrounding areas but is otherwise similar in texture and mineralogy. The pink coloration is an indication of the abundance of pink “dust” or inclusions (possibly hematite) in the plagioclase (Bergendahl and Koshmann, 1971). The stratigraphic relationship between the two migmatites is unclear and the contact between them gradational and intertonguing. Due to the close similarity of and poorly defined boundary between the pink migmatite and the more brownish migmatite, the units were not mapped separately herein.

Figure 10. Complexly folded compositional layers typical of migmatite.

Xh

Hornblende gneiss (Early Proterozoic) — Medium- to dark-gray, fine-grained gneiss consisting chiefly of hornblende and plagioclase with lesser amounts of quartz, biotite, pyroxene, and locally, garnet. The rock is massive and has a slight olive-green tinge. This unit crops out only in the northeastern corner of the quadrangle. In thin section, the minerals comprising this rock unit were found to be angular and fragmented, highly fractured, and chaotically arranged, thus giving the appearance of a rock that has been shattered through brittle tectonism. This brittle deformation may be associated with a northwest-trending zone of faulting which is expressed more clearly in the Breckenridge quadrangle to the west (Wallace and others, 2003). Hornblende gneiss may have originated as a gabbroic igneous rock (Lovering, 1935).

Xph

Layered plagioclase and hornblende gneiss (Early Proterozoic) — Light-gray, medium-grained quartz-microcline-plagioclase or quartz-plagioclase gneiss interlayered with dark-gray to black, medium- to coarse-grained amphibolite to hornblende-plagioclase gneiss. Light-gray gneiss is comprised of anhedral quartz, subhedral andesine-labradorite and oligoclase, and minor biotite. The primary constituents in the darker layers are subhedral hornblende and andesine-labradorite. Minor and accessory minerals include quartz, biotite, clinopyroxene, chlorite, epidote, and apatite (Bergendahl, 1963). Both light and dark layers range in thickness from less than one in. to several feet. Light layers deformed through flowage, whereas dark layers behaved in a more brittle fashion as evidenced by numerous boudinage structures within the enclosing quartz-plagioclase gneiss (Fig. 11). Layered gneiss crops out primarily in the vicinity of Mayflower and Humbug Gulches and probably represents early Proterozoic andesitic lava flows interlayered with rhyodacitic and quartz-latitic tuffs (Tweto, 1987).

Figure 11. Light-colored plagioclase gneiss interlayered with darker hornblende gneiss.

STRUCTURAL GEOLOGY

The Copper Mountain quadrangle is located in a structurally complex area (Fig. 12) that has experienced multiple episodes of tectonism from Precambrian to as recently as Quaternary time, locally. Two principal structural blocks exist within the quadrangle: the Tenmile Range fault block comprised of Precambrian rocks to the east, and a block comprised mainly of Paleozoic sedimentary rocks to the west. Strata in the western block dip mostly to the northeast on the eastern limb of the Sawatch Range, a major anticlinal structure southwest of the quadrangle. Several major structures intersect in the vicinity of Copper Mountain, creating a complicated structural regime. The north- to northwest-trending Gore and Mosquito faults form the western boundary of the Gore and Tenmile fault blocks, respectively, and merge on the east flank of Copper Mountain. Although the main trace of the northeast-trending Homestake shear zone passes northwest of the quadrangle, a southern east- to east-northeast-trending splay of the shear zone may extend as far as Tucker Mountain or the Gore-Mosquito fault intersection. This splay of the Homestake shear zone is predominantly expressed as a pronounced swarm of northeast-trending faults in Paleozoic rocks along most of its inferred trace. An overthrust of Precambrian rocks on the southeast side of Copper Mountain further complicates the geology in this area.

FAULTS

Faults cutting the Copper Mountain quadrangle can be grouped roughly into two categories: those that trend north to northwest, and those that trend east to northeast. North- to northwest-trending faults are typically deep-seated structures, such as the Mosquito and Gore faults, that originated in Precambrian time (Tweto and Sims, 1963), many of which were reactivated in Laramide and younger time. These structures are commonly characterized by a wide zone of fractures, crushed and sheared rock, breccia, gouge, and/or intense silicification. East- to northeast-trending faults typically show only minor displacement (less than a few hundred feet) and are more likely Pennsylvanian or Laramide and younger in age. These younger faults have a tendency to be more planar, often rupturing on a single plane with little deformation to the adjacent wall rocks and only minor accumulations of fault gouge.

MOSQUITO FAULT

The Mosquito fault forms the western boundary of the Tenmile Range block uplift and is a major structural feature in Colorado, with a strike length of at least 33 mi (Behre, 1953). The Mosquito fault typically trends north-northeast and separates Precambrian rocks to the east from Paleozoic rocks to the west. Wallace and others (1968) estimated approximately 1,500 ft of left-lateral, strike-slip motion and approximately 9,000 ft of normal displacement on the Mosquito fault in post-Oligocene time in the Climax area. This measurement is based on offset of the Climax orebody discovered in deep drilling (Wallace and others, 1968) and is supported by stratigraphic reconstructions made by Bergandahl and Koschmann (1971). Farther to south, Behre (1939, 1953) documented a lesser amount of downdip displacement and evidence of reverse movement. Tweto and Sims (1963) have speculated on a Precambrian origin for the Mosquito fault, noting that in many places the present trace of the Mosquito fault is superimposed on a Precambrian shear zone.

A key age constraint is that the Mosquito fault truncates the Climax orebody, which indicates the most recent movement on the fault is younger than the 24 to 33 Ma Climax orebody (Bookstrom and others, 1987). Quartz plus minor fluorite vein filling encountered at depth by drilling (Wallace and others, 1968) and the jasperoid alteration of the footwall show that some mineralization occurred after latest movement in the fault zone. An excellent example of the jasperoid alteration can be seen on the drill roads north of the Climax pit, where a block of Pennsylvanian limestone, which is unaltered west of

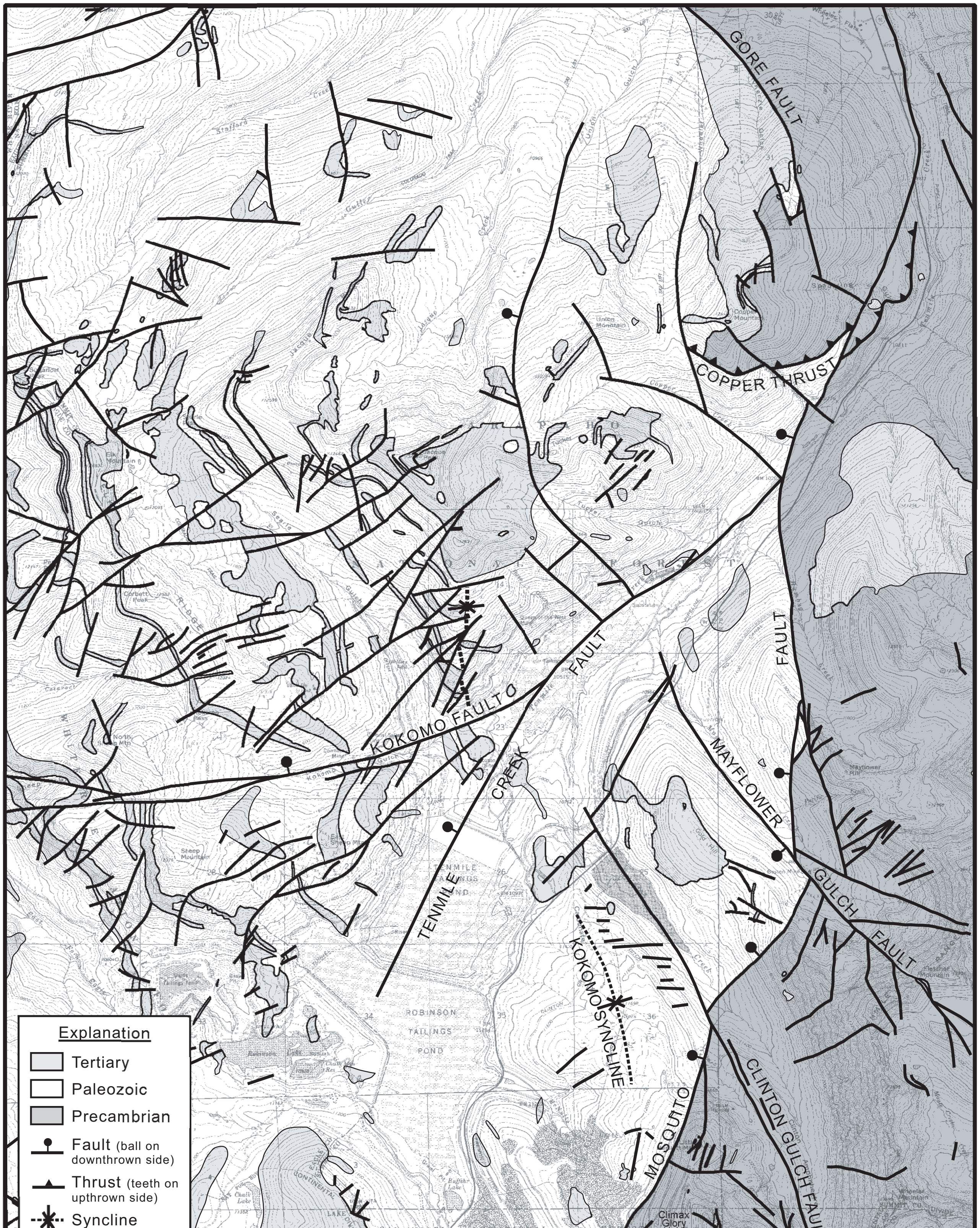

Figure 12. Generalized map of the Copper Mountain quadrangle showing geology and structural features.

the fault, is intensely silicified, brecciated, and converted to jasperiod within the fault. Bergandahl and Koschmann (1971) previously considered this outcrop to be a fault sliver of Sawatch quarzite, however, rounded quartz grains are absent in this locale.

The Mosquito fault is well exposed in the north wall of the Climax pit (Fig. 13). Here it dips steeply west and is at least 50 ft wide. The eastern margin of the fault zone is a 1.0- to 1.5-ft-thick zone of light-gray to white, clayey fault gouge, probably derived from crushing and pulverizing of the Climax stock on the footwall. The footwall has been altered to a jasperoid rock mass for a distance of at least 50 ft from the fault. The remainder of the fault zone is composed of 3.0- to 6.5-ft-wide slivers of Minturn Formation which have been caught up in the fault zone. These slivers are lensoid and elongated parallel to the fault zone, and appear to have tapered ends that dovetail into each other up- and down-dip. Each sliver is bounded by a thin (less than 5 in.) gouge zone, composed mainly of black shale. Most slivers contain bands of different color and texture that parallel the fault zone, but it was unclear in reconnaissance whether these bands were original bedding in the Minturn Formation, or internal shear bands within each sliver.

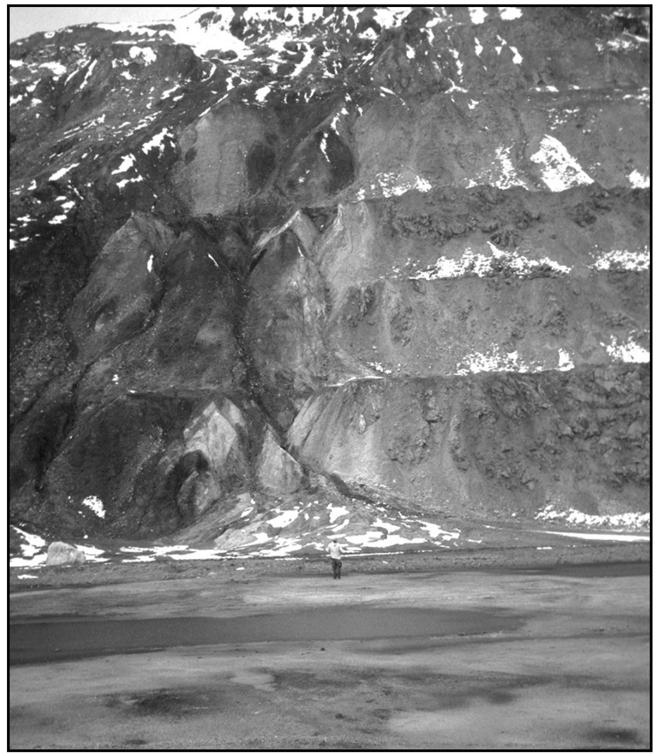

Figure 13. The Mosquito fault in the Climax pit offsets dark purple Pennsylvanian rocks (left) against light-colored Precambrian granite and Tertiary porphyry (right). The sharp color contrast in the foreground is also a representation of the Mosquito fault. J. McCalpin for scale. Photo by V. Matthews III.

GORE FAULT

The Gore fault forms the western boundary of the Gore Range block uplift. Precambrian movement on the structure is evident in a complex north-northwest-trending zone several hundred feet to as much as three mi wide, north of the quadrangle, of sheared and mylonitized predominantly Precambrian rock. This Precambrian zone of weakness was referred to as the Gore shear zone by Tweto and Sims (1963). Syn- and post-Pennsylvanian movement along this trend was restricted to a narrower region along the more planar Gore fault which has brought Pennsylvanian and Permian redbeds into contact with Precambrian gneiss and granite. Along much of its trace, the Gore fault is essentially a steeply dipping normal fault with a generally southwest-dipping plane (Tweto and others, 1970). Locally, it exhibits reverse displacement and dips as little as 45° southeast (Kellogg and others, 2003). At Booth Creek, about 14 mi northwest of Copper Mountain, the amount of displacement on the Gore fault since deposition of the Minturn Formation is a minimum of 2,100 ft; most of that movement is considered to have taken place during the Laramide (K. Kellogg, 2003, written communication). At the fault's northern end, roughly 35 mi northwest of Copper Mountain, the fault displaces Miocene sediments of the Trouble-some Formation (Tweto, 1973). The amount of post-Miocene displacement at this locality is not known.

The trace of the southern end of the Gore fault in the vicinity of Copper Mountain is not clear. Bergendahl and Koshmann (1971) mapped a stratigraphic contact but no fault between the Minturn and Maroon Formations in the saddle between Copper and Union Mountains. Later, Tweto (1974a) and Tweto and others (1978) mapped the southern extension of the Gore fault in this saddle. However, at most localities north of the quadrangle, the main trace of the Gore fault juxtaposes Paleozoic rocks against Precambrian rocks. Furthermore, extension of the Gore fault through the Copper – Union saddle requires a significant change in strike from an overall northwest strike to a north and even north-northeast strike.

If the Gore fault does not pass between Union and Copper Mountains, then where does it go? The contact pattern between Precambrian and Paleozoic rocks on the north flank of Copper Mountain is intriguing. Although this contact is nowhere exposed in outcrop, bedrock exposures and float indicate a blocky inter-fingering of the two units along a northwest trend generally in line with the trace of the Gore fault as it is mapped just north of the quadrangle (Begendahl, 1969). Inferred faults bounding the blocks are likely part of the Gore fault system. The northern of these faults is through going and appears to terminate against the Mosquito fault near the mouth of Spaulding Gulch. Where exposed along this trend, Precambrian rocks are highly deformed, intruded by granitic and pegmatitic material, and locally sheared and mylonitized – characteristics that are widely observed in Precambrian rocks along the Gore fault north of the quadrangle (Tweto and Lovering, 1977; Tweto and others, 1970; Tweto and Sims, 1963).

COPPER THRUST FAULT

The Copper thrust fault (named herein for ease of discussion) wraps around the south and southeast flanks of Copper Mountain and juxtaposes Precambrian migmatite over sedimentary rocks of the Pennsylvanian Minturn Formation. The presence of fragments of Precambrian migmatite and Paleozoic sandstone and limestone in mine dumps along the trace of the thrust fault agrees with an overhang of this nature. The fault is roughly coincident with a northeastward projection of the southern splay of the Homestake shear zone as mapped by Tweto (1974b). Independent movement on the Gore and Mosquito faults could have created a space problem near the oblique intersection of these two faults. This space problem could have been accommodated through development of a generally south-verging thrust possibly exploiting the Homestake shear zone. The thrust fault offsets the Minturn Form-ation indicating it is Late Pennsylvanian or youn-ger, and development of this type of thrust is not generally compatible with the extensional nature of the post-Laramide. Thus, movement on the fault is constrained between Late Pennsylvanian and Laramide time.

Koschmann and Wells (1946) and Bergendahl and Koshmann (1971) described a thin quartzite bed coincident with the trace of the Copper thrust fault. They tentatively correlated the unit with the Cambrian Sawatch Quartzite, an interpretation that was supported during this study. Samples were collected and thin sections cut from Sawatch Quartzite on Little Bartlett Mountain, a metaquartzite bed in Precambrian migmatite on the east flank of Bartlett Mountain, fault silica associated with the Mosquito fault at the Climax Mine, and quartz-rich rock fragments found on the flank of Copper Mountain. The Precambrian metaquartzite was found to be composed chiefly of fine-grained, intergrown, amorphous quartz overprinted by secondary growths of amorphous, coarse-grained quartz. The fault silica contained mineral fragments from Tertiary porphyry and Minturn Formation in a grungy matrix of highly fractured and strained, fine-grained primary and coarse-grained secondary, angular and amorphous quartz. The quartzites from Little Bartlett Mountain and Copper Mountain were found to be nearly identical, consisting almost entirely of equigranular, well-rounded, clean quartz grains. This suggests the quartzitic fragments on Copper Mountain are probably not Precambrian metaquartzite or fault silica and may in fact correlate with the Sawatch Quartzite. This would require an overturned to recumbent fold. This type of deformation is hinted at in the variable orientations of attitudes on the south flank of Copper Mountain, but the true structure of these rocks was not discernable due to limited exposures in the area.

MAYFLOWER GULCH FAULT

In the southeast quarter of the quadrangle a wide, northwest-trending zone of intensely fractured quartz-vein material crops out in the headwall of Mayflower Gulch on the west flank of

Fletcher Mountain. The main fault zone is several tens of feet wide but there are several related veins generally one to 5 ft thick that also crop out in the area. Fine-grained pyrite oxidized to iron oxide is conspicuous in dark-purple to black veinlets that ubiquitously cut the quartz veins (Fig. 14). On the flank of Fletcher Mountain, the fault strikes N45°W and is vertical. The vein does not maintain its thickness down the head-wall of Mayflower Gulch, which suggests the fault plane is irregular down dip. Offset of the trace of the Mosquito fault in the lower reaches of Mayflower gulch suggests a significant amount of down-to-the northwest displacement, and a possible lesser component of left-lateral slip, on the Mayflower Gulch fault (Geraghty and others, 1988). Additionally, unpublished geophysical data from Climax shows the Mosquito fault to be offset by the Mayflower fault. The brittle nature of deformation associated with the Mayflower fault suggests it is a relatively young structure. However, the Mayflower fault also contains Kokomo-style mineralization in the form of gold-bearing, lead-zinc, massive sulfide mantos deposits and quartz-pyrite-gold vein systems. Gold, in this case, is a key indicator of Kokomo-style mineralization, as the Climax-type systems are notoriously poor in gold (White and others, 1981). The inference is that mineralization along the Mayflower fault was roughly coincident in time with mineralization in the Kokomo district (38 to 40 Ma). This is considerably older than the Climax orebody (23 to 33 Ma), which is cut by the Mosquito fault. How, then, to reconcile the crosscutting relations of the Mosquito and Mayflower faults with the conflicting ages of their associated mineralization? We propose that the Mayflower fault crosscut the Mosquito fault, or was used for movement along the Mosquito fault, sometime in early Laramide time. Somewhat later, quartz-pyrite-gold mineralization filled open spaces within the Mayflower fault, probably in association with a calc-alkaline porphyry intrusion. This hydrothermal system may have been the ultimate source of the placer gold encountered in McNaulty Gulch. At a later point in time, the Climax orebodies were established. Still later, portions of the Mosquito fault were reactivated in response to incipient Rio Grande rifting. This offset the Climax orebody. Fault movement of this young extensional event was, in this case, principally restricted to the Mosquito fault, although the complex field relations at Climax necessitate that other faults must have been involved (Geraghtery and others, 1988).

NORTHEAST-TRENDING FAULTS

Faulting in the quadrangle is dominated by a swarm of high-angle normal faults striking N30° to 75°E (Koschmann and Wells, 1946). Dip-slip displacement on these faults is typically minor

Figure 14. Fault breccia associated with the Mayflower Gulch fault. Dark areas are iron oxidized pyrite, light areas are quartz.

and rarely exceeds 100 ft (Bergandahl and Koschmann, 1971). This fault swarm, which is concentrated in the Kokomo district proper, is a direct continuation of a zone of similar faults mapped by Tweto (1949, 1956) in the Pando and Tennessee Pass areas west and southwest of the quadrangle. This fault swarm defines a structural corridor within Paleozoic and Tertiary rocks which is interpreted as reflecting an underlying Precambrian shear zone which has been reactivated in Laramide time. These northeast-trending faults served as ore controls in the Kokomo district, channeling hydrothermal fluids to favorable carbonate beds, which were then replaced by sulfides (Bergendahl and Koschmann, 1971).

Field relations associated with the northeast-trending series of faults indicate the follow-ing relationships. (1) North-east trending faults cut and offset east-trending faults, although faults of both orientations appear to be part of an overall, linked fault system. (2) North-trending faults (such as the Mosquito fault) cut northeast-trending faults and appear to be related to later extension. (3) Northeast-trending faults cut and offset Elk Mountain and Quail porphyries. Northeast trending faults dominantly cut and offset the megacrystic quartz monzonite porphyry (Tqpm). However, there are places where the megacystic quartz monzonite porphyry cuts northeast-trending faults or is emplaced along them. These relations suggest that most northeast-trending faults formed toward the end of megacrystic quartz monzonite porphyry emplacement, at approximately 42 Ma. (4) Northeast-trending faults controlled the localization of carbonate replacement ore bodies at Kokomo. However, consistent syn-mineralization brecciation within Kokomo ore bodies as well the fault truncation of these orebodies suggest that northeast-trending faulting was also syn- to slightly(?) post-mineralization. This would suggest another period of northeast-trending faulting occurring around 37 to 38 Ma, possibly extending to somewhat younger times. All told, the field evidence and associated dating of the Tertiary igneous rocks (Mach and Thompson, 1998; Marvin and others, 1974) suggests a relatively short lived pulse of northeast-trending faulting 36(?) to 42 Ma. This pulse of faulting in large part followed a pulse of calc-alkalic magm-atism and is roughly coincident with a period of base and precious metal mineralization. Similar faulting, magmatism, and mineralization relations are seen elsewhere in the region (Wallace and others, 2003) and appear to define a magmatic and structural evolutionary trend.

While the vast majority of northeast-trending faults have minimal displacements, several faults, in particular the Tenmile and Kokomo faults, appear to be more significant structures. The Tenmile fault, which owing to cover by Climax tailings ponds, cannot be directly observed in the field, was described by Koschmann and Wells (1946) as a broad shear zone 220 ft wide, striking N30° to 40°E with a southeast dip of 75°. Exposures within the New York mine suggest dip separation on the Tenmile fault was 335 ft (Koschmann and Wells, 1946) whereas later drill results in the vicinity of the Victory mine (0.75 mi to the northeast) indicated an 800 ft dip separation on the Tenmile fault (Mach, 1992). Geraghty and others (1988), using unpublished Climax drill data from the area north of Kokomo, suggested Neogene displacement on the Tenmile fault was in fact considerably more: 2,200 to 3,050 ft. These observations, if accurate, suggest increasing dip separation on the Tenmile fault to the northeast as it approaches the intersection with the Mosquito fault. Koschmann and Wells (1946) considered the Tenmile fault to be a deep-seated trunk channel directly influencing the localization of Kokomo ore bodies.

KOKOMO FAULT

The Kokomo fault is an east-trending structure (N70° to 80°E) with dips ranging from 70° north to near vertical. A 1975 Climax report stated that the Kokomo fault, then exposed in a recent road cut, was 12 ft wide, highly pyritized, and accompanied by abundant clay gouge. Bergandahl and Koschmann (1971) estimated 800-1,000 ft of left-lateral, strike-slip displacement on the Kokomo fault, on the basis of the offset of a large porphyry sill (map unit Tq) in the east end of Kokomo Gulch. Strike slip displacements on the Kokomo fault appear to diminish to the west. At the upper end of Kokomo Gulch, directly south of North Sheep Mountain, strike separation on the

Kokomo fault of a bed of Hornsilver dolomite is only 500 to 700 ft. Farther west, on the western boundary of the quadrangle, the Kokomo fault appears to dissipate into a splay of lesser faults, and strike separation on these does not exceed 200 ft. These observations suggest increasing strike-slip displacement to the east on the Kokomo fault as it approaches the intersection with the Tenmile fault.

FOLDS

The Precambrian rocks on the quadrangle have experienced multiple episodes of deformation. The dominant mode of deformation was flowage, although some more competent layers behaved in a less ductile fashion and appear as boudin structures or pinch-outs within the masses of migmatite. The rocks exhibit a strong foliation that is generally parallel to compositional layering. East of the quadrangle, this foliation shows a pronounced north-northeast trend (Wallace and others, 2003). However, attitudes on the Copper Mountain quadrangle are variable and show only a faint north-northwest trend. No large-scale structures were recognized in Precambrian rocks, but ptygmatic folds oriented in many directions are prolific in migmatite. Bergendahl and Koshmann (1971) described an antiformal structure centered near Mayflower Hill. There, they described a metasedimentary stratigraphic sequence of "granulite" (herein, Xgg) in the core of the anticline overlain by "banded gneiss" (herein, Xph) then migmatite. As discussed previously, this stratigraphic interpretation has not been supported by more recent mapping adjacent to the quadrangle (Kellogg and others, 2002; Wallace and others, 2003). Rather, the "granulite" is considered to be an Early Proterozoic intrusive body, intrusion of which may account for the apparent doming of overlying rocks at Mayflower Hill.

In the western part of the quadrangle, the Paleozoic sedimentary rocks have a consistent northeast dip. This homoclinal feature represents the northeast flank of the Sawatch Range uplift, a major regional feature west of the quadrangle with an axis length of 34 mi. Locally, the attitude of the sedimentary rocks is disrupted by intrusions of igneous rocks, particularly the Elk Mountain porphyry, but in general, the 20° to 30° northeast dips are maintained.

In contrast, the eastern edge of Paleozoic exposures in the quadrangle define a north-northwest-trending synclinal feature termed the Kokomo syncline by Koschmann and Wells (1946). This feature is well exposed on Carbonate Hill where it is defined by the outcrops of the Jacque Mountain limestone, which marks the contact between the Minturn and Maroon Formations. On the south flank of Jacque Peak, the Kokomo syncline can be traced for a short distance before it disappears within the igneous rocks of Jacque Peak and Tucker Mountain. Field relations suggest an early Laramide age for the formation of the Kokomo syncline. Small-scale, east-west faults locally cut the syncline and its eastern limb is truncated by the Mosquito fault. In addition, the axis of the syncline appears offset by the northeast-trending Tenmile fault.

STRUCTURAL EVOLUTION

The Precambrian metamorphic rocks in the core of many Colorado mountain ranges were laid down up to 1,800 Ma as sedimentary deposits, volcanic flows, and ash-flow tuffs (Tweto, 1987). A major episode of plutonism 1,790 to 1,660 Ma (locally, for example, the Cross Creek Granite) caused amphibolite-grade metamorphism and intense, large-scale folding of these early rocks (Selverstone and others, 1997). During Early to Middle Proterozoic time, a series of linked northeast-trending shear zones developed between the southwestern part of the Colorado near La Plata and the area near Boulder in the Front Range. West of Copper Mountain, this zone of shearing is known as the Homestake shear zone (Tweto and Sims, 1963), which Shaw and others (2001) concluded was established in the Early Proterozoic and reactivated during the Middle Proterozoic. The main trace of this shear zone is recognized as a 7 to 8 mi wide zone of fracturing and mylonitic foliation in the Sawatch Range west of the quadrangle. This band of deformation, which is coincident with Homestake Creek west of the quadrangle, extends northeastward into the Gore Range to the north, but it does not cross the Copper Mountain quadrangle (Tweto, 1974b; Bergendahl, 1963). A southern branch of the shear zone trends more easterly and becomes buried beneath Paleozoic rocks on the Copper Mountain quadrangle in the vicinity of Corbett Peak. Tweto and Sims (1963) reported four to six mi of left-lateral displacement along the main trace of the shear zone. A concurrently or slightly later-developing structure than the Homestake shear zone was the north-northwest-trending Gore shear zone described by Tweto and Sims (1963). The Gore shear zone was the precursor to the later Gore and Mosquito faults and is characterized by localized shearing and mylonitization of Precambrian rocks on the west side of the Tenmile and Gore Ranges. The Homestake shear zone abuts the Gore shear zone near Vail Pass north of the quadrangle.

Continued tectonic activity in the area is evident in the sequence of Paleozoic rocks that cover much of the western part of the quadrangle. These rocks exhibit abrupt changes in depositional environment, thickness, and orientation that cannot be accounted for by simple wedging out along the margins of the basinal area between the paleo-highlands of the Tenmile-Gore Range and the Sawatch Range. The ideal stratigraphy in the region includes a complete stratigraphic sequence of Paleozoic rocks overlying a relatively planar foundation of Precambrian rocks. However, this Precambrian foundation is crossed by a network of faults roughly parallel to both the Homestake and Gore shear zones (Tweto and Sims, 1963), thus creating a highly irregular surface of ridges and depressions. Near the Homestake shear zone, Pennsylvanian-Permian to Triassic strata are less than 1,000 ft thick, but farther south, near Leadville, Pennsylvanian to Triassic strata exceed 10,000 ft in thickness (Tweto and Sims, 1963). Leadville Limestone is 140 ft thick west of the quadrangle and, although nowhere fully exposed, is probably less than 40 ft thick in the Copper Mountain quadrangle. On Little Bartlett Mountain in the southeast corner of the quadrangle, Sawatch Quartzite overlies Precambrian bedrock. However, at Copper Mountain, Pennsylvanian rocks rest directly on Precambrian rocks and the entire Cambrian to Mississippian section is absent. These field relations strongly suggest a paleo-high in the area in either early Paleozoic time, which would have resulted in non-deposition of the lower Paleozoic sequence, or in late Paleozoic time, which would indicate erosion of the lower Paleozoic strata prior to deposition of Pennsylvanian and younger strata.

Much of this Paleozoic highland was eroded prior to Laramide time when the Mosq-uito and Gore faults rejuvenated along the western margin of the Gore shear zone (Tweto and Sims, 1963) to form another topographic high. The Copper thrust fault likely originated at this time as independent movement on the Gore and Mosquito faults forced crustal failure along a zone of possible weakness coincident with the Homestake shear zone. Younger reactivation of the shear zone may be evident in the numerous northeast-trending faults in Paleozoic rocks overlying the shear zone near Corbett Peak and Searle Gulch. A late Laramide deformation event may be represented by north-northwest trending folds, such as the Kokomo syncline. Field relations are unclear as to whether folding proceded calc-alkaline igneous activity. Both were followed by east-west- and northeast-trending faults.

Magmatic activity occurred during, and for a short period following, the Laramide orogeny. Hydrothermal fluids associated with these calc-alkalic intrusions formed a variety of ore deposits along and adjacent to northeast-trending Precambrian shear zones such as the Homestake shear zone, thus establishing the Colorado Mineral Belt. In the Copper Mountain area, porphyries were injected parallel to Paleozoic bedding or as dikes, plugs, and stocks in both Paleozoic and Precambrian rocks from roughly 51 to 29 Ma. The Climax and Kokomo mineralized areas are both within the Colorado mineral belt. The high-silica rhyolite stocks associated with the Climax ore body were emplaced between 24 to 33 Ma (Bookstrom and others, 1987) and are believed to be associated with incipient extension of the Rio Grande Rift (Geraghty and others, 1988). A noticeable jog in the mineral belt (as defined by Tweto and Sims, 1963) north of the Copper Mountain quadrangle coincides with the intersection of the Homestake shear zone and the Precambrian Gore shear zone.

The long history of movement on the Gore and Mosquito faults continued beyond

Laramide time. Late Tertiary sediments offset at the northern end of the Gore fault indicate syn- or post-Miocene movement on that fault (Tweto, 1973), but younger movement on the fault has not been recognized. Similarly, on the basis of offset of the Climax ore body, Wallace and others (1968) reported as much as 9,000 ft of vertical and 1,500 ft of left-lateral post-Oligocene displacement along the Mosquito fault. Kirkham and Rogers (1981) reported at least 40 ft of offset in Wisconsinan-age (10 to 130 ka) deposits on the Mosquito fault just south of the quadrangle. Neogene and younger activity on both the Mosquito and Gore faults likely represents a northern continuation of the late Cenozoic Rio Grande Rift system (Tweto, 1979).

ECONOMIC GEOLOGY

METALLIC MINERALS

Two major districts (and ore types) are present within the quadrangle: lead-zinc-silver carbonate replacement deposits within the general Kokomo area, and the porphyry molybdenum deposits at Climax. Each deposit type has a distinct geology and origin and each will be discussed separately. In addition, the quartz monzonite porphyries at Tucker Mountain and Tenmile Creek (Bald Mountain porphyry) are locally potassically altered and have quartz veinlets containing rare molybdenite. Limestone adjacent to the Tucker Mountain intrusive contains garnet-molybdenite skarn. Both hydrothermal systems have been explored by drilling, but there has been no production from them to date.

HISTORY

Prospectors first entered the region during the Pikes Peak gold rush. In 1860, the placer deposits at the mouth of McNulty Gulch were discovered. The values encountered were spotty, but rich areas as small as 20 sq ft locally yielded $10,000 to $20,000 in gold (in 1860 gold prices) (Hollister, 1867). Individual pans were said to contain $100 worth of gold (Parker, 1974). Shortly thereafter, argentiferous galena veins were discovered in the high peaks of the Tenmile range near Climax; remote access and low grades restricted development to a small scale. Significant hard-rock mining did not occur until 1878 when prospecting teams fanning out from Leadville discovered similar bonanza silver ore in the carbonate rocks at Robinson and Kokomo (Henderson, 1926). By 1879, two- to three-thousand people were said to be in the district. On Sheep Mountain alone there were some 50 mines with ore averaging 280 ounces silver per ton (Engineering and Mining Journal, Mar. 1879). Many mines were also being developed on Elk Mountain, Chalk Mountain, and Jacque Peak during this time (Bergendahl and Koschmann, 1971). In 1880, production of lead and silver was estimated at $200,000; this increased to $2,000,000 by the following year (Henderson, 1926).

The towns of Kokomo, Recen, Robinson, Carbonateville (at the mouth of McNulty Gulch) and Wheelers (now Copper Mountain ski resort) were founded during this period. In 1882, the town of Kokomo burned down. The population moved to nearby Recen, which then renamed itself "Kokomo" (Dempsey and Fell, 1986). However, the high-grade supergene bonanza blankets were rapidly being mined out and production soon diminished.

During this time, smelters were penalized for the presence of zinc in ores they produced. As a result, the sphalerite-bearing primary ores were not generally economical. Various methods to separate the sphalerite were tried. The most successful of these was developed by Arthur R. Wilfley, who in 1895 invented a concentrating table by which zinc could be separated from lead in crushed ore. This invention, known as the Wilfley table, was first pioneered at the Wilfley mill in Kokomo in 1896. It soon became the worldwide standard in ore dressing (prior to flotation) and continues to be used to the present day. Successful use of the Wilfley table and overall increase in metal prices kept the district going during the early 1900s.

Meanwhile, activity at Climax was starting up. Charles Senter had discovered a silvery gray metallic mineral, first identified as galena, graphite, or native silver, in 1879 on Bartlett Mountain. In 1895, the mineral was finally correctly identified as molybdenite by Dr. George of the Colorado School of Mines (Wallace and others, 1968). At the time, there was not a significant market for molybdenum and the discovery remained undeveloped. By 1913, the use of molybdenum as a hardener to steel was known; however, the total world demand at that time was estimated as only one ton of molybdenum concentrates (Wallace and others, 1968). This was supplied by small, but high-grade vein deposits in Norway, and Climax, with its large tonnage but relatively low molybdenum grades, could not compete. World War I greatly stimulated interest in hardened steel for artillery armor, and from 1915 to 1917 small shipments were made from Bartlett Mountain for pilot plant metallurgical testing. Full-scale production commenced in 1918, but closed the following year owing to lack of a market. When World War I had ended, the demand and price for molybdenum crashed. For the next five years, company metallurgists attempted to develop peacetime uses for molybdenum, and by 1924 a small market was developed in the automobile industry (Dempsey and Fell, 1986). The mine reopened in 1924. In 1929, the Climax mine instituted a new system of underground block-caving mining (Voynick, 1996, Cappa, 2001). This allowed significantly greater efficiencies and production climbed to over 6,000 tons per day. By 1940, the Climax mine was supplying 90 percent of the world's molybdenum. World War II and the Korean War then accelerated uses for molybdenum.

World War II also ushered a boom period in the Kokomo District. Throughout the early part of the Twentieth Century, the district had limped along with minor production (excluding a brief flurry during World War I). World War II, with its unprecedented demand for metals, reactivated interest in the district. Production greatly increased from an estimated $6,572 in 1940 to nearly $4.6 million in 1948, a level that had not been reached since its early boom days in the 1880s (Bergandahl and Koschmann, 1971). By 1951, the boom at Kokomo was over. Production in that year totaled a mere $10,209. There was some small-scale mining in the district until 1957 at which point, mining in the district ceased, never to return. All told, approximately 514,000 tons were mined from the Kokomo district yielding 27,000 ounces gold, 1.8 million ounces silver, 500,000 pounds copper, 30 million pounds lead, and 75 million pounds zinc with a total value of nearly $16 million in metal prices for that period (Bergandahl and Koschmann, 1971). These figures only cover the period 1905 to the present day. Koschmann (1948) conservatively estimated that another $10 million was generated from Kokomo mines during its early boom period.

In contrast, by 1957 Climax was the world's largest underground mine at 35,000 tons per day and expanding. Production ramped upward in the 1960s and 1970s, reaching 50,000 tons per day. However, this greatly increased production created a space problem. Where to put the tailings and waste rock generated from the Climax operation (Fig. 15)? It was ultimately decided to use the entire Tenmile Valley for tailings emplacement, in effect burying the Kokomo district (and associated towns of Recen, Kokomo, Robinson, and Carbonateville.) All the towns but Recen were defunct by then; Recen had to have a special election (in November, 1965) in order to vote itself out of existence (Dempsey and Fell, 1986). The Recen residents (who were mostly all miners at Climax) passed the resolution, and the town now lies under Climax tailings.

The 1970s and early 1980s were glory years for Climax as the company made record profits owing to the high cost of molybdenum. However, this sowed the seeds of its own destru-

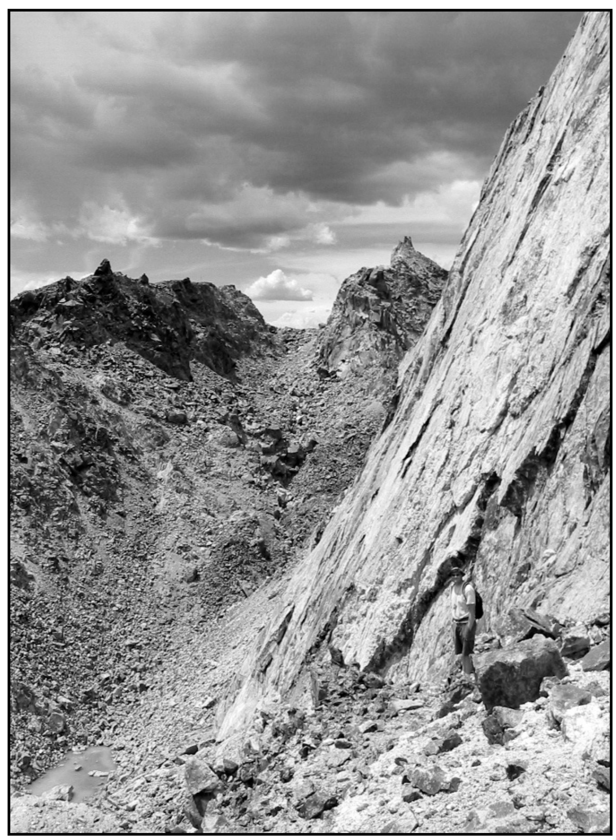

Figure 15. Major subsidence above the Climax mine is evidenced by the numerous vertical slickenlines on this slip face above J. Jackson at the peak of Bartlett Mountain. The ridge on the left has moved downward several hundred feet along this slip face.

ction. As a consequence of the high molybdenum price, many porphyry copper mines installed secondary circuits to recover byproduct molybdenum, thus flooding the market. Climax, as a low-grade primary producer, could not compete. There were a series of layoffs, ultimately leading to total mine closure in 1995. All told, Climax produced approximately 500 million tons of ore yielding a million tons of molybdenum with year-mined value of $4 billion (Cappa, 2001). Remaining reserves are estimated at 145 million tons, averaging 0.23 percent molybdenum (Phelps Dodge, 2001 annual report). The mine is presently on standby status.

CLIMAX MINING AREA

Climax is the world's largest molybdenum deposit with an initial geologic reserve estimated at 1 billion tons averaging 0.24 percent Mo (Carten and others, 1993). Climax is considered the type example for a specific class of molybdenum deposits, known as the "Climax- type". Mineralization at Climax is spatially, temporally, and genetically related to a series of porphyritic granite intrusions into Precambrian granitic rocks. The intrusions are high silica differentiates containing elevated amounts of F, Mo, Sn, Sr, U, Th, and Nb. Predominant minerals are quartz, potassium feldspar, and albite; accessory minerals include biotite, fluorite, topaz, garnet, zircon, ilmenorutile, rutile, columbite, brannerite, uranite, thorite, monazite, apatite, and xenotime.

The Climax orebody consists of three separate shells of quartz-molybdenite stockwork (Cerasco, upper, and lower) which have coale-sced. Each ore shell is associated with the intrusion of a separate granite porphyry, which collectively formed a composite stock. The Cerasco, and a small portion of the upper orebody, crop-ped out and were mined from the surface. The upper orebody formed the bulk of the open pit mining at Climax whereas the lower orebody was mined underground (Wallace and others, 1968). The composite nature of the mineralization at Climax was not understood until the 1960s; insi-ghts gained there led directly to the discovery of the Henderson orebody in the early 1970s (White and others, 1981).

Mineralization at Climax is typically contained within thin (less than 0.1 in.), moderately to steeply dipping, quartz-molybdenite veinlets. A high density of these veinlets produces a stockwork. Typically, veinlet density and the grade of the ore is highest in the core of the stockwork, progressively decreasing outwards. These veinlets typically show complex crosscutting relationships indicating a dynamic structural, igneous, and hydrothermal environment. The molybdenite stockwork is coincident with a zone of intense potassium feldspar alteration and occurs just above a zone of massive silica flooding. Molybdenite mineralization is interpreted as being directly tied to the exsolution and cooling of molybdenum–rich high-silica magmatic systems.

The molybdenite orebodies are overlain by a quartz-sericite-pyrite (QSP) alteration zone, containing up to 10 percent pyrite. This alteration style is what is observed on surfaces within the open pit and remains of the Glory Hole. In a zone of argillic alteration, which is outside the ASP zone, plagioclase is replaced by montmorillinite, kaolinite, and sericite, and biotite is replaced by muscovite and sericite.

The magmatic activity at Climax occurred over an 11 million year period, between 24 and 33 Ma (White and others, 1981). The chemistry of these magmas is distinctly different from the calc-alkaline igneous rocks seen in the rest of the quadrangle (excluding the Chalk Mountain rhyolite, which is believed associated with the Climax intrusions). Climax-type magmas have been associated with the early stages of extensional faulting, whereas the calc-alkaine intrusives that characterize the rest of the quadrangle are more associated with subduction-related activity (Geraghty and others, 1988).

KOKOMO MINING AREA

Ore deposits of the Kokomo mining district consist of silver-bearing, lead-zinc, massive sulfide mantos that have replaced limestone beds in the Minturn Formation. The ores themselves are remarkably similar in appearance and texture to ores at the nearby Leadville and Gilman districts. Each district's ores have a high pyrite content and large amounts of black marmatitic sphalerite. Other Kokomo ore minerals include galena, chalcopyrite, tetrahedrite, barite, pyrrhotite, marcasite, siderite, quartz, rhodochrosite, manganocalcite, and calcite (Bergendahl and Koschmann, 1971; Mach and Thompson, 1998). Overall hypogene grades of the Kokomo deposits were 7 percent Zn, 3 percent Pb, 0.05 percent Cu, 120 ppm Ag, 1.8 ppm Au (Beatty and others, 1990). Grades of supergene-enriched deposits were as high as hundreds of ounces of silver per ton.

Individual orebodies ranged from 100 to more than 2,000 ft long, 3 to 300 ft wide, and as much as 30 ft thick, although most were less than 10 ft thick (Koschmann and Wells, 1946). The upper surfaces of ore bodies were typically defined by the tops of individual carbonate beds whereas the bottoms were commonly undulatory with unreplaced limestone or dolomite (Koschmann and Wells, 1946). The principal ore control was the intersection of high-angle, northeast-trending faults with favorable carbonate beds; secondary controls such as small anticlinal flexures or breccia karst(?) channels have also been noted (Bergendahl and Koschmann, 1971). The principal ore-bearing horizons were the Robinson and the White Quail limestone members, although smaller deposits have also been found in the Jacque Mountain limestone (Koschmann, 1948). The lower dolomite members of the Minturn Formation appear to be barren of mineralization (Bergendahl and Koschmann, 1971). Whether this is due to unfavorable permeability or chemistry is unclear. A few sphalerite-pyrite-galena veins were within Minturn Formation sandstone, but production from these has been minimal (Bergendahl and Koschmann, 1971). Orebodies are laterally zoned from a central pyrite-pyrrhotite core, outward to sphalerite-galena-chalcopyrite massive sulfides, followed by manganosiderite or jasperiod impregnated with sulfides, then barren jasperoid, and lastly, dolomite and unaltered limestone (Emmons,1898). In other places, the contact between ore sulfides and barren wallrock is knife-sharp (Bergendahl and Koschmann, 1971). Rocks immediately adjacent to feeder faults tend to be argillically and sericitically altered. District-scale zonation is unclear. Bergendahl and Koschmann (1971) believed that pyrrhotite content of Kokomo deposits decreased to the south, whereas Mach and Thompson (1998, p. 627) denied that a systematic district scale zonation of sulfides exists.

Paragenetic studies of Kokomo ores (Mach and Thompson, 1998) suggest four stages of mineral deposition. During stage 1, wallrock limestone was altered to jasperoid and/or dolomite plus minor pyrite. During stage 2, massive iron sulfides (pyrite, pyrrhotite, marcasite) along with siderite and somewhat late quartz were deposited. Sphalerite along with carbonates such as siderite, ferroan dolomite, and rhodochrosite were deposited during stage 3. During stage 4, galena, chalcopyrite, tetrahedrite, minor sulfosalts, barite, and late calcite and dolomite were deposited. Fluid inclusion studies indicate that temperatures averaged 350 degrees Centigrade during the early stages of ore deposition, decreasing with time to about 160 degrees Centigrade (Mach and Thompson, 1998). Salinities of ore fluids initially were 4.6 percent NaCl equivalent, decreasing with time to less than 2 percent NaCl equivalent (Mach and Thompson, 1998). Isotopic studies (carbon, oxygen, sulfur) suggest an early input of magmatic ore fluid, with later dilution by cooler, meteoric waters (Mach and Thompson, 1998).

The age of formation of the Kokomo deposits is not well defined. A limited apatite-zircon fission track study by C. Naeser (included within Mach, 1992 and Mach and Thompson, 1998) was interpreted as suggesting a date of formation at around 40 Ma, coincident with the thermal center on Tucker Mountain. (The appa-rent younger age of the Tenmile Creek quartz monzonite and its associated hydro-thermal alteration system does not appear to have been known to these authors). Review of the data, particularly of samples close to known manto deposits, reveals several samples with significantly lower ages, such as a sample of megacr-ystic quartz monzonite porphyry with an apatite date of 36.7 ± 3.9 Ma, and a sample of Elk Moun-tain porphyry with a zircon date of 37.6 ± 3.7 Ma. These data are permissive (but hardly definitive) toward suggesting a thermal event (presumably mineralization) at around 37–38 Ma; this date would be closely coincident with the ages of formation of the Leadville and Gilman deposits, which are respectively, 34 and 36 Ma (Beatty and others, 1990).

At Kokomo, the last major exploration campaign in the district proper occurred in the late 1940s by ASARCO. This drill campaign (over 30,000 ft of core drilling) encountered another limestone bed within the White Quail limestone member (Dempsey and Fell, 1986); the orebody discovered associated with this bed comprised most of the production during the last operating years of the district (Bergendahl and Koschmann, 1971). The possibility of significant carbonate replacement orebodies at depth beneath the Kokomo mines within the Leadville Limestone (if present) remains open. ASARCO drilled several deep holes in the general vicinity of the Lucky Strike mine during the end phases of their operation (late 1940s to 1950) in order to test for the presence of Leadville Limestone at depth; these failed to reach the appropriate stratigraphic depth (D. M. Smith, Jr. personal communication, 1995 in Mach and Thompson, 1998). In 1968, Climax Molybdenum Company drilled a hole in Tenmile Valley near Mayflower Gulch that penetrated 147 ft of skarned and brecciated Leadville(?) Dolomite at a vertical depth of 2190 ft (Climax Molybdenum Co., 1968, unpublished report in Mach, 1992). Thus, the Leadville Limestone probably underlies a portion of the quadrangle; whether it is mineralized with carbonate replacement ore bodies is unknown.

TENMILE CREEK MINERALIZED AREA

A strongly altered quartz monzonite porphyry which crops out along the west bank of Tenmile Creek locally contains quarz-molybdenite veinlets. There is also a strong disseminated pyrite halo associated with the quartz monzonite porphyry intrusion and the adjacent sedimentary rocks. This intrusion was the focus of a drill campaign by Climax Molybdenum Company searching for molybdenum resources. Broad intervals of 0.01 to 0.03 percent MoS_2 were encountered; a small area in excess of 0.08 percent MoS_2 was discovered. These grades were insufficient to justify mining. The age of this system (two separate dates centering on 35 Ma) is of particular interest as it occurs within a transition period between Kokomo and Climax mineralization. The chemistry of the quartz monzonite porphyry (as determined from hand specimen petrology) supports the transition concept as it is clearly a quartz monzonite porphyry with two to four percent biotite and not a high-silica rhyolite.

TUCKER MOUNTAIN MINERALIZED AREA

Local, patchy skarn alteration is found within calcareous clastic sedimentary rocks and limestones over a broad area centered on Tucker Mountain and Copper Mountain. In both areas, there is garnet-pyroxene-plagioclase skarn containing local, subeconomic amounts of molybdenum-bearing chalcopyrite, pyrite, magnetite, and specular hematite (Bergendahl and Koschmann, 1971). This skarn appears associated with weak, potassic alteration (K-feldspar flooding and minor shreddy biotite) associated with molybdenum-bearing quartz veins within the Tucker Mountain quartz monzonite porphyry. The garnet skarn has been explored by several Climax Molybdenum Company drillholes; results are unknown.

A broad area of epidote-actinolite-chlorite alteration is present distal to the garnet skarn and extends south to slightly beyond Cresson Gulch (with isolated occurrences in Serles and Kokomo Gulch), westward to Jacque Peak, eastward to Tenmile valley, and northward beyond Copper Mountain (see Bergendahl and Koschmann, 1971, Figure 14).

The garnet-epidote skarn area was interpreted by Bergendahl and Koschmann (1971) as indicating a zoned thermal area possibly related to emplacement of the Tucker Mountain quartz monzonite. Apatite and zircon fission track dating of samples from this area suggests that this event occurred at approximately 40 Ma (Mach, 1992; Mach and Thompson, 1998). Confirmation is provided by contact breccia of the Tucker Mountain rhyolite which contains fragments of skarn mineralization (Mach, 1992). The Tucker Mountain rhyolite was K-Ar dated at 36.1 ± 1.4 Ma by Marvin and others (1974), which indicates the skarn must be older than this date.

As can be seen from figure 16, there is a general correspondence between the garnet and

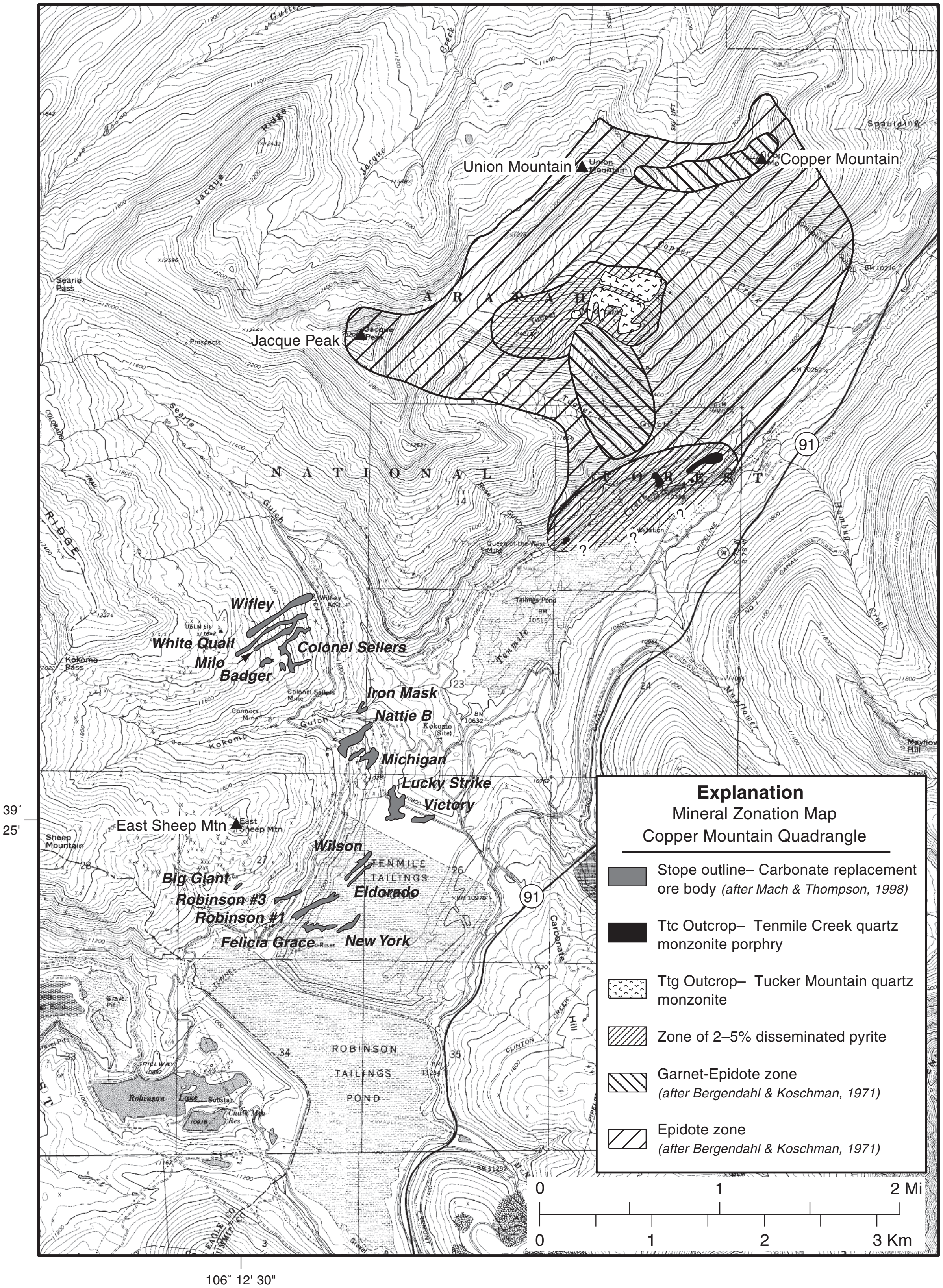

Figure 16. Map showing mineral zonation, carbonate replacement ore bodies, and selected Tertiary intrusives in part of the Copper Mountain quadrangle.

epidote zones and outcrops of the Tucker Mountain quartz monzonite porphyry. However, there is a better association between disseminated pyrite alteration (± silicification) and the Tucker Mountain and Tenmile Creek quartz monzonite porphyries. It is believed likely that the disseminated pyrite halos represent specific hydrothermal systems superimposed on a broader thermal anomaly associated with a buried intrusive center of which the Tucker Mountain quartz monzonite porphyry is only a part. Bergendahl and Koschmann (1971) used the inferred decreasing pyrrhotite content of Kokomo deposits away from the igneous center and skarns at Tucker Mountain to suggest a linkage between the two. Mach and Thompson (1998) denied that a systematic district scale zonation of sulfides at Kokomo exists, but they maintained the idea that the Kokomo deposits represent an updip, cooler expression of the Tucker Mountain hydrothermal system. In contrast, our work suggests that the Kokomo manto deposits represent a separate hydrothermal system, temporally and spatially distinct from the Tucker Mountain garnet-molybdenite skarn and Tenmile Creek porphyry molybdenite deposit.

When either the epidote or disseminated pyrite line is used as a measure, a considerable spatial gap (more than a linear mile) exists between the outer limit of the overall Tucker Mountain and Tenmile Creek hydrothermal systems and the location of significant Kokomo manto deposits. This spatial gap is of sufficient magnitude to suggest that the Kokomo manto deposits represent a separate hydrothermal system centered on an as-yet-unknown igneous source, as opposed to being related to one of the other two hydrothermal systems. This interpretation is supported by the available age data as well. Using this model, exploration would then preferentially focus on deeper extensions of known Kokomo mantos as opposed to filling in the gap between known mantos and the inferred heat, metal, and sulfur source at Tucker Mountain or Tenmile Creek.

INDUSTRIAL MINERALS

Although there are currently no active industrial mineral permits within the Copper Mountain quadrangle, there is industrial mineral resource potential. Sand and gravel resources may be found in glacial deposits and stream alluvium throughout the quadrangle. These deposits have been quarried in the past from the area near Robinson Lake and at a few sites along Tenmile Creek. Additionally, there are numerous historic gravel pits in the Wheeler Flats area immediately north of the quadrangle. Precambrian migmatite and granite, both of which are exposed in the eastern half of the quadrangle, are typically good sources of rip-rap and crushed rock aggregate. Numerous beds of limestone are found within the Minturn Formation and a few are present in the Maroon Formation. These limestone units are most commonly discontinuous and only about 2 to 15 ft thick, so they are generally not considered a significant resource. They may, however, be suitable for some local uses.

GEOLOGIC HAZARDS

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

LANDSLIDES

Landslide deposits are present throughout the Copper Mountain quadrangle. Although most of these landslides do not appear to have moved in historic time (the past 150 years), they may become reactivated in the future by triggers such as rapid snowmelt (Chleborad, 1997), intense rainfall, or earthquake shaking. Previous landslide mapping at a scale of 1:250,000 (Colton and others, 1975) identified many large areas of slope instability in the Copper Mountain quadrangle. However, their mapped "landslides" included talus and rock glacier deposits as well as landslide deposits, and they made no distinction between old (inactive) and younger (active) landslides.

Most landslides portrayed on this map do not pose a threat to infrastructure because they are far removed from any buildings, roads, or utilities. However, two large landslides in the south-central part of the map area do cross or abut CR-91. This highway was cut into the toe of a pre-existing landslide directly north of Clinton Reservoir. The Colorado Department of Transportation performed considerable earthmoving and remediation to stabilize the roadcut. Several roadcuts on CR-91 between Clinton and Mayflower Creeks have failed, mainly those cut into till overlying Maroon Formation. On the eastern margin of Clinton Reservoir a large part of the slope is a landslide complex in the Minturn Formation. Although this complex probably moves slowly when reactivated, on the basis of its slump-earthflow morphology, a catastrophic failure could displace water from Clinton Reservoir and force it over CR-91. In addition, several small landslides cross pipelines in this area.

Several landslides exist within the boundaries of the Copper Mountain ski area, but most of them are not located in areas of sensitive infrastructure such as ski lifts or maintenance facilities. For example, the large landslide complexes on the north flank of Union Mountain do not encroach upon sensitive facilities. According to Copper Mountain ski officials, slope instability has not caused any significant damage to facilities since the ski area began operation in 1972.

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. Most of the area in the quadrangle mapped as Holocene alluvium (Qa_1) lies on modern flood plains and is potentially subject to flooding. However, the existence of large tailings dams in the headwaters of Tenmile Creek may reduce the flooding hazard directly downstream. A separate hazard is that of debris flows in ephemeral and intermittent streams and resulting deposition on alluvial fans. All mapped Holocene alluvial fans (Qf) are potentially subject to debris-flow deposition over most of their surfaces. Fans with the highest hazard are those whose drainage basins are very steep and extend above treeline (such as east of Tenmile Creek in the Tenmile Range) or that contain landslides (such as Spaulding and Tucker Gulches).

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 old Kokomo mining district. Elsewhere in Colorado, mine water has been demonstrated to be acidic and commonly contains toxic levels of heavy elements such as zinc, cadmium, lead, and arsenic. Therefore, mine water should be considered potentially unsafe unless and until otherwise documented. Soil contaminated by acid mine drainage may be corrosive to metal and concrete and pose a constraint to building foundations.

SEISMICITY

The Copper Mountain quadrangle lies near the northern end 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 in the Eastern, Central, and Mountain States of the U.S. (1534–1986 A.D.) reveals only a single earthquake in the quadrangle (23 May 1964), but the magnitude and depth were not recorded.

Despite the low level of historic seismicity, geologic evidence suggests that some faults have been active in Quaternary time. The 33-mile-long Mosquito fault is considered a late Cenozoic fault by Widmann and others (1998). They cite Kirkham and Rogers (1981), who described offset of Wisconsinan age (10 to 130 ka) deposits south of the Copper Mountain quadrangle, but who also stated that Holocene deposits are not offset by the fault. The latest movement on the fault is thus considered to have occurred during the late Pleistocene. Widmann and others (1998) also estimated a slip rate of about 0.008 in./yr from fault scarps up to 40 ft high in morainal and landslide deposits of Wisconsinan age (10 to 130 ka). On the basis of this evidence, the Mosquito fault should be considered capable of generating future large earthquakes, but the probability of occurrence cannot presently be calculated due to a lack of detailed paleoseismic studies. If the entire 33 mi length of the fault were to rupture in a future earthquake, empirical relationships (Wells and Coppersmith,1994) indicate a likely earthquake magnitude of about Mw=7.1.

In addition to the Mosquito fault there may be other Quaternary faults in the quadrangle. Gutierrez and Matthews (2002) described a scarp across the rock glacier on the east flank of Bartlett Mountain, which they ascribed to Holocene faulting. However, this scarp may have been formed by nontectonic collapse of the rock glacier ice core, as described by Hauessler (1997) in Alaska. No detailed studies of Quaternary faulting have yet been performed in the Copper Mountain quadrangle.

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COLORADO GEOLOGICAL SURVEY
DIVISION OF MINERALS AND GEOLOGY
DEPARTMENT OF NATURAL RESOURCES
DENVER, COLORADO

OPEN FILE MAP 03-20
GEOLOGIC MAP OF THE COPPER MOUNTAIN QUADRANGLE,
SUMMIT, EAGLE, LAKE, AND PARK COUNTIES, COLORADO
Booklet accompanies map

Base from U.S. Geological Survey, 1970
Polyconic projection, 1927 North American Datum
10,000-foot grid based on Colorado coordinate system, central zone
1,000-meter Universal Transverse Mercator grid ticks, zone 13

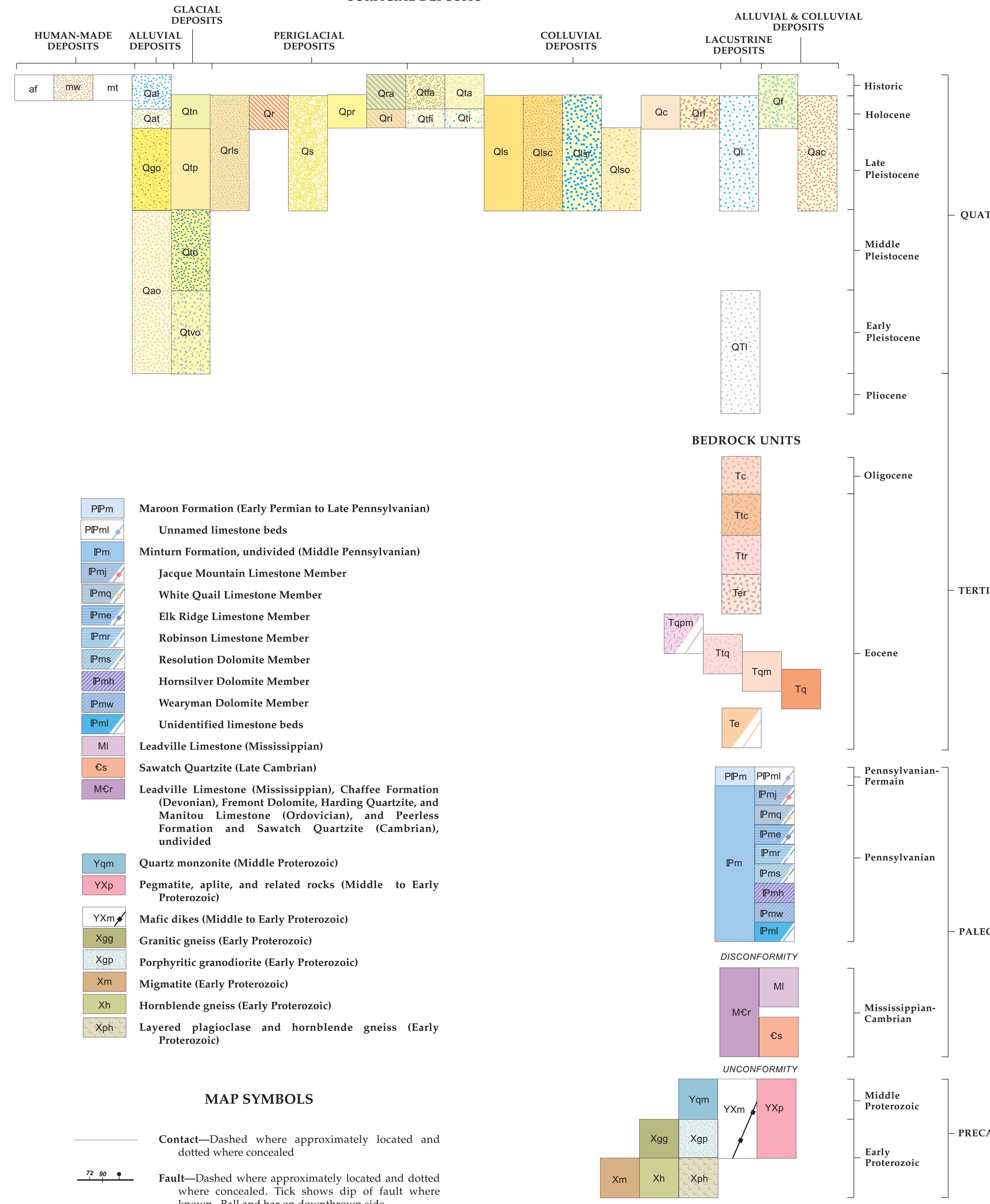
UTM GRID AND 1987 MAGNETIC NORTH DECLINATION AT CENTER OF MAP
DIAGRAM IS APPROXIMATE

SCALE 1: 24,000

QUADRANGLE LOCATION

Geology mapped in 2002
GIS and cartography by Karen Morgan

CORRELATION OF MAP UNITS



LIST OF MAP UNITS

The complete description of map units and references are in the accomp--anying booklet.

SURFICIAL DEPOSITS

HUMAN-MADE DEPOSITS

af	Artificial fill (late Holocene)
mw	Mine waste (late Holocene)
mt	Mill tailings (late Holocene)

ALLUVIAL DEPOSITS

Qal	Stream-channel, flood-plain, and low-terrace alluvium (Holocene)
Qat	Younger terrace alluvium (Holocene)
Qgo	Older stream gravel (late to middle Pleistocene?)
Qao	Old alluvium (middle to early Pleistocene)

COLLUVIAL DEPOSITS

Qc	Colluvium (Holocene and late Pleistocene)
Qta	Active talus deposits (late Holocene)
Qtfa	Active talus fan deposits (late Holocene)
Qrf	Rockfall deposits (late Holocene)
Qti	Inactive talus deposits (Holocene and late Pleistocene)
Qtfi	Inactive talus fan deposits (Holocene and late Pleistocene)
Qls	Landslide deposits, undifferentiated (Holocene to middle? Pleistocene)
Qlsc	Landslide complex deposits, undifferentiated (Holocene to middle? Pleistocene)
Qlsr	Failed bedrock blocks (Holocene to middle Pleistocene)
Qlso	Older landslide deposits (middle to late Pleistocene)

ALLUVIAL AND COLLUVIAL DEPOSITS

Qac	Alluvium and colluvium, undivided (Holocene and late Pleistocene)
Qf	Alluvial-fan deposits (Holocene and late Pleistocene)

LACUSTRINE DEPOSITS

Ql	Lacustrine deposits, undifferentiated (Holocene to late Pleistocene)
QTl	Older lacustrine deposits (early Pleistocene to late Tertiary)

PERIGLACIAL DEPOSITS

Qpr	Protalus-rampart deposits (Holocene)
Qs	Solifluction deposits (Holocene and late Pleistocene)
Qra	Active rock glacier deposits (late Holocene)
Qri	Inactive rock glacier deposits (middle to early Holocene)
Qr	Rock glacier deposits, undifferentiated (Holocene)
Qrls	Rock glacier/landslide deposits (Holocene)

GLACIAL DEPOSITS

Qtn	Neoglacial till (Holocene)
Qtp	Pinedale till (late Pleistocene)
Qto	Older till (middle? Pleistocene)
Qtvo	Very old till (middle to early Pleistocene)
Q	Quaternary deposits, undifferentiated—Shown only on cross sections

BEDROCK DEPOSITS

Tc	Chalk Mountain rhyolite (Oligocene)
Ttc	Tenmile Creek quartz monzonite porphyry (Eocene)
Ttr	Tucker Mountain rhyolite (Eocene)
Ter	Eagle River porphyry (Eocene)
Tqpm	Quartz monzonite porphyry - megacrystic variety (Eocene)
Ttq	Tucker Mountain quartz monzonite porphyry (Eocene)
Tqm	Quartz monzonite of the Humbug Stock (Eocene)
Tq	Quail porphyry (Eocene)
Te	Elk Mountain porphyry (Eocene)
PIPm	Maroon Formation (Early Permian to Late Pennsylvanian)
PIPml	Unnamed limestone beds
IPm	Minturn Formation, undivided (Middle Pennsylvanian)
IPmj	Jacque Mountain Limestone Member
IPmq	White Quail Limestone Member
IPme	Elk Ridge Limestone Member
IPmr	Robinson Limestone Member
IPms	Resolution Dolomite Member
IPmh	Hornsilver Dolomite Member
IPmw	Wearyman Dolomite Member
IPml	Unidentified limestone beds
Ml	Leadville Limestone (Mississippian)
Єs	Sawatch Quartzite (Late Cambrian)
MЄr	Leadville Limestone (Mississippian), Chaffee Formation (Devonian), Fremont Dolomite, Harding Quartzite, and Manitou Limestone (Ordovician), and Peerless Formation and Sawatch Quartzite (Cambrian), undivided
Yqm	Quartz monzonite (Middle Proterozoic)
YXp	Pegmatite, aplite, and related rocks (Middle to Early Proterozoic)
YXm	Mafic dikes (Middle to Early Proterozoic)
Xgg	Granitic gneiss (Early Proterozoic)
Xgp	Porphyritic granodiorite (Early Proterozoic)
Xm	Migmatite (Early Proterozoic)
Xh	Hornblende gneiss (Early Proterozoic)
Xph	Layered plagioclase and hornblende gneiss (Early Proterozoic)

MAP SYMBOLS

Contact—Dashed where approximately located and dotted where concealed

Fault—Dashed where approximately located and dotted where concealed. Tick shows dip of fault where known. Ball and bar on downthrown side.

Thrust fault—Dotted where concealed

Scarp

Syncline—Trace of axial surface. Dashed where approximately located.

Strike and dip of inclined beds—Angle of dip shown in degrees

Strike and dip of foliation—Angle of dip shown in degrees

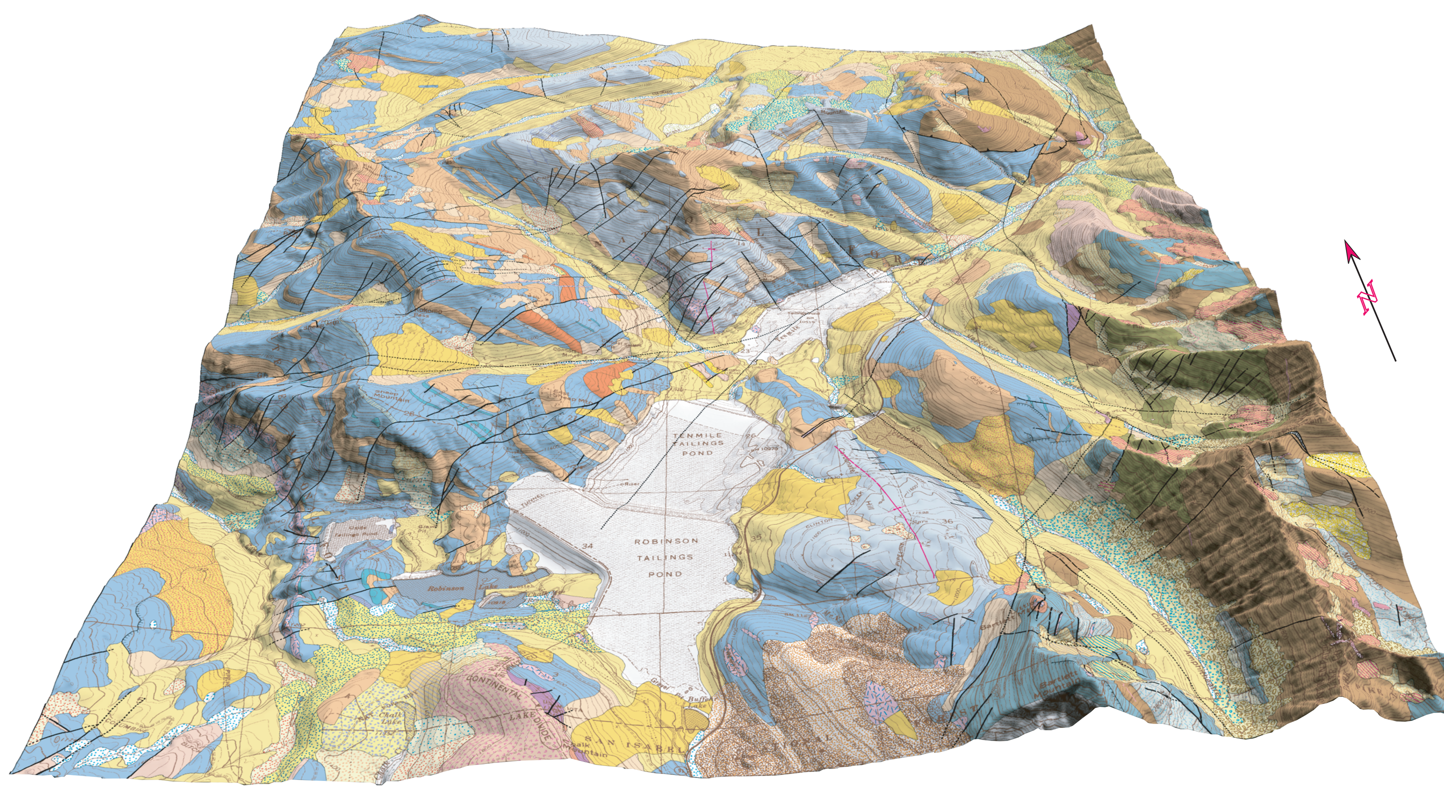
Inclined

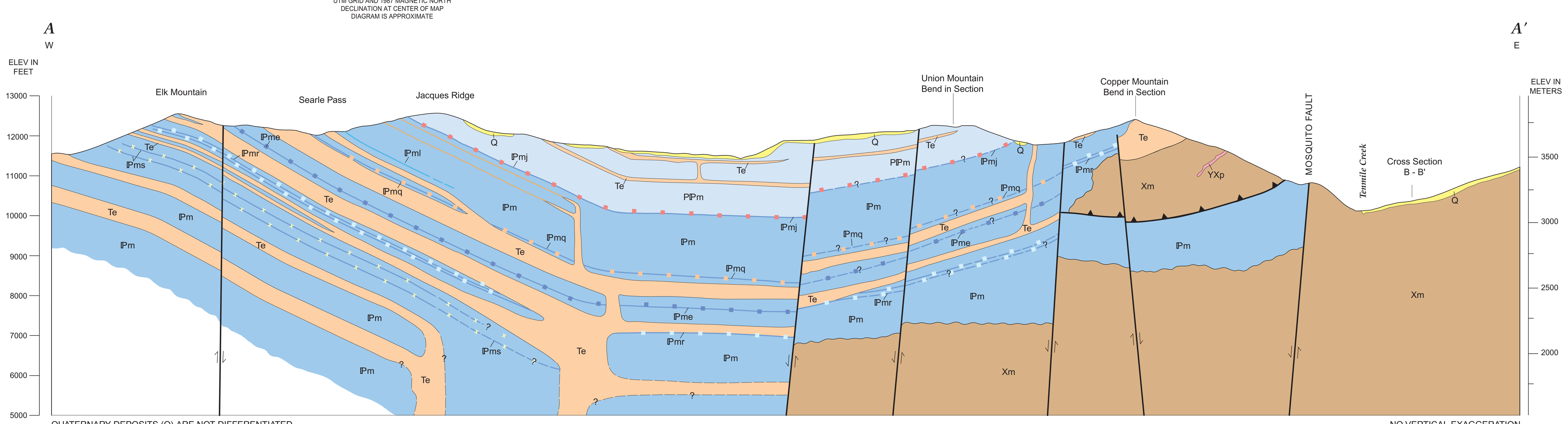
Vertical

Fracture zone

Alignment of cross sections

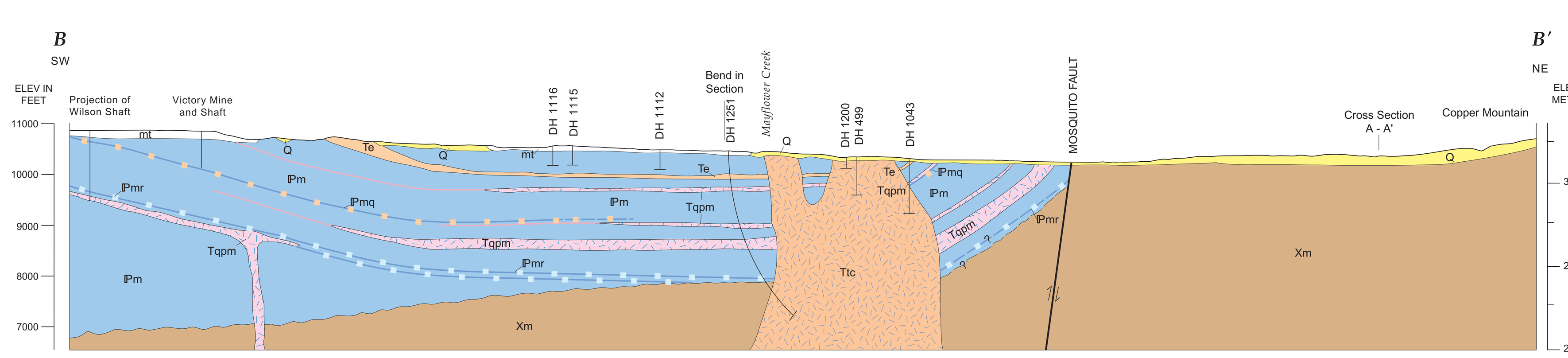
SHADED-RELIEF MAP OF THE COPPER MOUNTAIN QUADRANGLE WITH GEOLOGY OVERLAY; OBLIQUE VIEW LOOKING NORTH





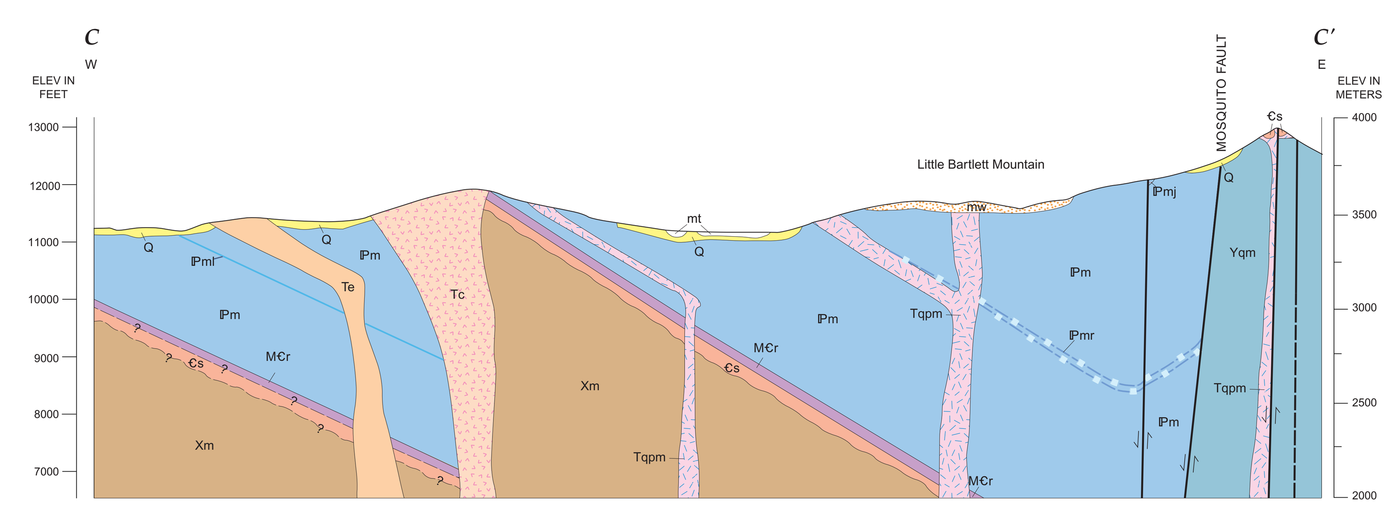
QUATERNARY DEPOSITS (Q) ARE NOT DIFFERENTIATED

NO VERTICAL EXAGGERATION



QUATERNARY DEPOSITS (Q) ARE NOT DIFFERENTIATED

NO VERTICAL EXAGGERATION



QUATERNARY DEPOSITS (Q) ARE NOT DIFFERENTIATED

NO VERTICAL EXAGGERATION

COLORADO DEPARTMENT OF NATURAL RESOURCES
Bill Owens, Governor
State of Colorado
Greg Walcher, Executive Director,
Department of Natural Resources

COLORADO DIVISION OF MINERALS AND GEOLOGY
Ronald W. Cattany, Director,
Division of Minerals and Geology

GEOLOGIC MAP OF THE COPPER MOUNTAIN QUADRANGLE, SUMMIT, EAGLE, LAKE, AND PARK COUNTIES, COLORADO

By Beth L. Widmann, Paul J. Bartos, James P. McCalpin , and Jeffrey Jackson

2003