OPEN-FILE REPORT 04-3

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Colorado Geological Survey
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Description of Map Units, Structural Geology, Mineral Resources, and Geologic Hazards

by

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FORWARD

The purpose of Colorado Geological Survey Open File Report 04-3, *Geologic Map of the Alma Quadrangle, Park and Summit Counties, Colorado* is to describe the geologic setting and mineral resource potential of this 7.5-minute quadrangle located in central Colorado. Staff geologist Beth L. Widmann, consulting geologist Paul J. Bartos, consulting geologist Richard F. Madole, student Kathryn E. Barba, and student Marilyn E. Moll completed the field work on this project during the summer of 2003.

This mapping project was funded jointly by the U.S. Geological Survey through the STATEMAP component of the National Cooperative Geologic Mapping Program which is authorized by the National Geologic Mapping Act of 1997, Award number 03HQAG0095, and the Colorado Geological Survey using the Colorado Department of Natural Resources Severance Tax Operational Funds. The CGS matching funds come from the Severance Tax paid on the production of natural gas, oil, coal, and metals.

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INTRODUCTION

Geologic mapping of the Alma 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.

The majority of the Alma quadrangle is located in western Park County; the southern edge of the quadrangle is less than 3 miles northwest of Fairplay (fig. 1). In the northern part of the quadrangle, the Park/Summit County line coincides with the continental divide at Hoosier Pass and along Hoosier Ridge. State Highway 9 bisects the quadrangle longitudinally. The highway passes through the town of Alma in the south-central part of the quadrangle, ascends Hoosier Pass, then drops down to Breckenridge 9 miles to the north. The town of Leadville is roughly 8.5 miles west of the quadrangle.

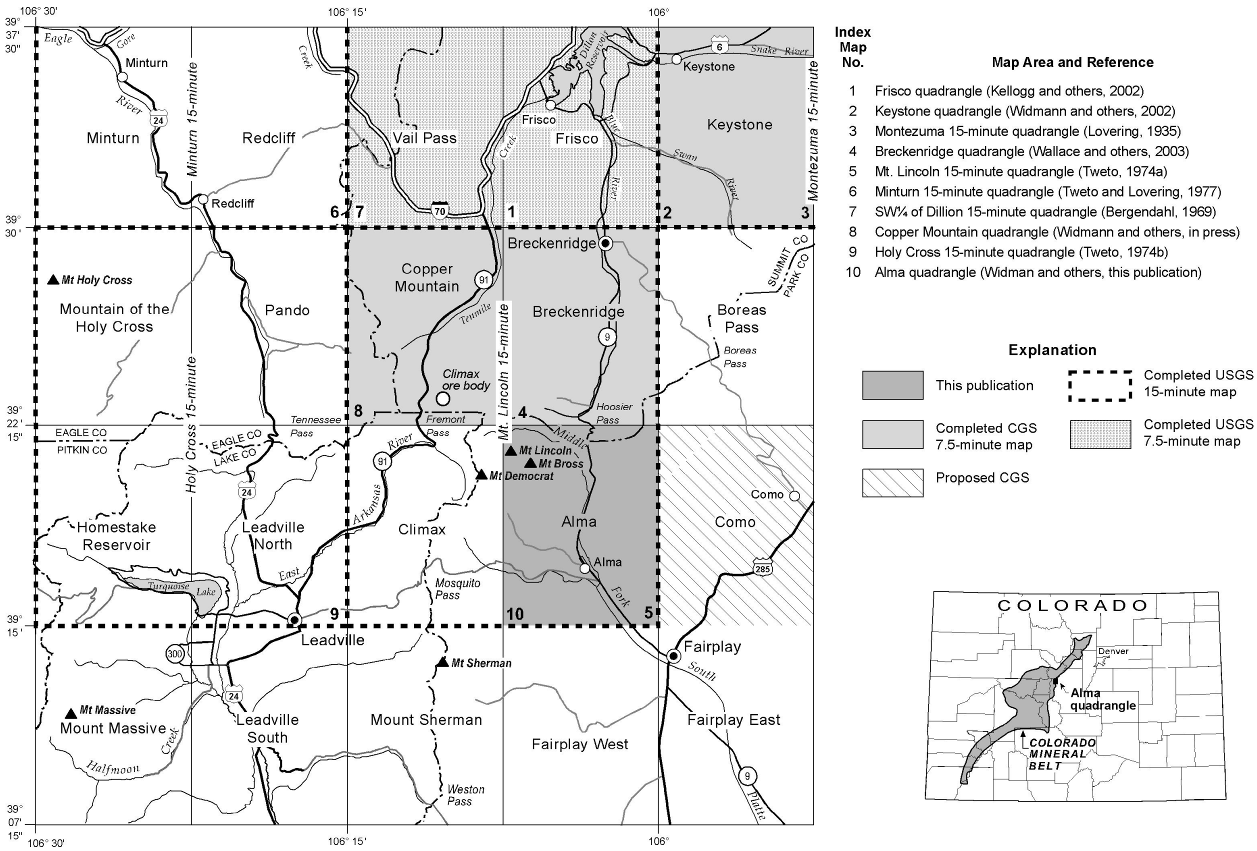

Figure 1. Location map and index of selected published geologic maps in the vicinity of the Alma quadrangle. Inset map shows the location of the Alma quadrangle in relation to the Colorado Mineral Belt.

The principal geographic features in the Alma region are the Mosquito Range to the west and South Park to the southeast (fig. 2). The Mosquito Range extends along the western half of the quadrangle and has several peaks over 14,000 ft. Within the project area these include Mounts Lincoln, Cameron, and Bross. South Park is a broad flat basin, the bulk of which is generally south of the quadrangle, although a few fingers of the park do extend northwards along the eastern margin of the quadrangle. The Middle Fork of the South Platte River flows into the northwest corner of the quadrangle, is captured at Montgomery Reservoir, and is released again into the Platte River valley (fig. 3). State Highway 9 parallels the Platte River valley in the center of the quadrangle. Buckskin, Mosquito, and Pennsylvania Creeks originate in the Mosquito Range and feed into the Middle Fork of the South Platte River. Beaver Ridge and

Beaver Creek parallel the Platte River Valley to the east. Mount Silverheels, at 13,822 ft, is the highest point in the eastern part of the quadrangle.

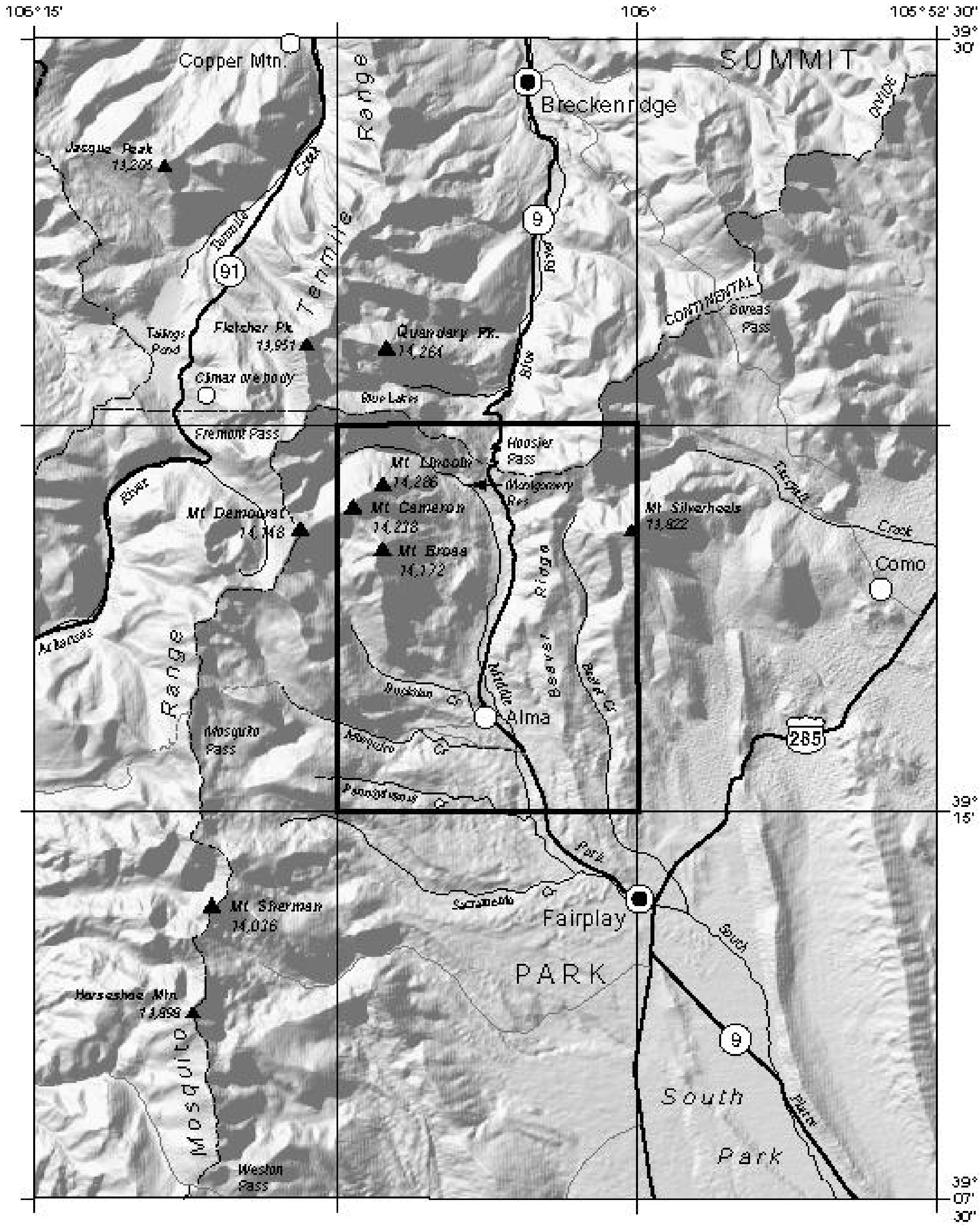

Figure 2. Shaded relief map of the region surrounding the Alma quadrangle.

Figure 3. View looking west along the Middle Fork of the South Platte River above Montgomery Reservoir. Mount Lincoln is in the clouds at the left edge of the photo.

Several mining districts are found within or adjacent to the Alma quadrangle. The region was therefore the focus of considerable study, particularly west of the South Platte River valley, during the height of the mining period in the early part of the 20^{th} century. One of the earliest geologic studies in the Alma region focused on the Alma mining district (Patton and others, 1912), which included the area west of the South Platte River Valley to the Park County line. A subsequent paper on the Leadville mining district (Emmons and others, 1927) outlined in detail the geology and ore deposits of the area encompassing the Alma mining district as well as parts of Lake and Summit Counties from south of Leadville to north of Copper Mountain. Singewald and Butler (1941) focused specifically on the ore deposits in the vicinity of the London fault, just southwest of the quadrangle, although their mapping covers much of the same area as the Patton and others (1912) report. Geologic studies by Bookstrom (1989) of the Climax ore body northwest of the Alma quadrangle are of note since he correlates many of the igneous rocks in the Climax area to those in the western part of the Alma quadrangle. More recently, several 15- and 7.5-minute-scale quadrangles have been mapped in the area (see fig. 1). The Alma quadrangle coincides with the southeastern quarter of the Mount Lincoln 15-minute quadrangle mapped by Tweto (1974a). The Copper Mountain and Breckenridge 7.5-minute quadrangles northwest and north of the Alma quadrangle were mapped by Widmann and others (in press) and Wallace and others (in press), respectively.

Field work for the Alma quadrangle was undertaken during the summer months of 2003. The geology was mapped on U.S. Forest Service color aerial photographs (1:24,000-scale) taken in September 1996. Bedrock mapping was completed by B. Widmann (CGS) and P. Bartos (Colorado School of Mines (CSM)) with the assistance of CSM students K. Barbá and M. Moll. Bartos mapped Paleozoic rocks and Tertiary intrusive bodies generally south and west of the Middle Fork of the South Platte River. Widmann mapped the remainder of the quadrangle as well as much of the Precambrian and Tertiary geology in the lower elevations along Buckskin and Mosquito Gulches. The majority of the Quaternary deposits throughout the quadrangle were mapped by R. Madole. Map unit contacts were transferred from photogrammetric models of annotated aerial photographs to the topographic map of the Alma quadrangle using the ERDAS (Earth Resource Data Analysis System) stereographic program. Bedrock units and surficial deposits that had maximum thickness of 5 ft or dimensions of less than 150 ft were generally not mapped. However, some thin bedrock units, such as limestone beds, Tertiary dikes and sills, and pegmatite dikes, are represented on the map as a single line because they add to the stratigraphic and structural understanding of the geology in the area. Note that the cultural features of the topographic base map were revised in 1994. Thus, roads, reservoirs, and buildings constructed after 1994 are not on the map base, and human-made deposits that postdate the 1996 aerial photography also are not on the map.

In broad view, the geology of the Alma quadrangle defines a north-northeast-trending, eastward-dipping monoclinal sequence in which a broad range of rocks from Precambrian to Quaternary age are exposed. The Mosquito Range extends into the western half of the quadrangle and is cored by Precambrian metamorphic and igneous rocks. These rocks are in turn overlain by a sequence of Lower Paleozoic sedimentary rocks ranging in composition from limestone and dolomite, to shale, sandstone, and conglomerate. Upper Paleozoic rocks composed of sandstone, conglomerate, siltstone and minor limestone crop out primarily, though not exclusively, east of the South Platte River valley. Several episodes of Tertiary magmatism are represented by numerous sills and dikes of calc-alkaline to high-silica rhyolite composition intruded into Precambrian and Paleozoic rocks throughout the quadrangle. Widespread precious and base metal mineralization is associated with this period of Tertiary magmatism. The area is quite structurally complex as is indicated by the numerous faults of various orientation, displacement, and magnitude shown on the map plate. Exposures, but not necessarily access, are locally excellent in the steep-walled cliffs bounding glacial valleys; in other places, thick forest and soil cover limit detailed mapping. Fortunately, the area has been extensively prospected, which provides good control on the geology. Thick deposits of till are recognized along the South Platte River valley and several of its tributaries. Numerous periglacial deposits and other surficial deposits are found throughout the quadrangle.

ACKNOWLEDGMENTS

This mapping project was funded jointly by the Colorado Geological Survey and U.S. Geological Survey through the STATEMAP program of the National Cooperative Geologic Mapping Program under agreement no. 03HQAG0095.

We extend our thanks to Bryan Lees and Dean Misantoni for providing access to and sharing detailed geologic information on the Sweet Home mine. Paul Myrow (Colorado College) contributed immensely to our understanding of the lower Paleozoic section in central Colorado and is thanked for leading a very beneficial field trip and partial review of the manuscript. Special thanks are extended to Bruce Bryant (USGS) who provided a thorough review of the report. Final preparation of the map and cross sections was by Jason Wilson (CGS).

DESCRIPTION OF MAP UNITS

SURFICIAL DEPOSITS

The surficial geologic units of the Alma quadrangle are referred to by informal names based on either genesis or landform. Use of these names on different geologic maps does not imply that the respective units have the same properties or are of the same age. The surficial deposits of the Alma quadrangle are not well exposed. Consequently, the thickness of most units is estimated and descriptions of physical characteristics such as texture, stratification, and composition are based on observations at a small number of localities. Particle size is expressed in terms of the modified Wentworth scale (Ingram, 1989), and sorting is expressed in the terminology of Folk and Ward (1957). All surficial deposits in the map area are poorly sorted to extremely poorly sorted.

The terminology used for divisions of Quaternary time is shown in Table 1. The date for the end of the Pleistocene (11.68 cal ka) is the sidereal or calendar-year equivalent of 10,000 ^{14}C years. The limits used for divisions of the Holocene time are both informal and provincial. They are based chiefly on paleontological data compiled for the southwestern United States, including the Colorado Plateau, such as described by Van Devender and others (1987). As used here, early, middle, and late Holocene span the times between 11.68 and 8 cal ka, 8 and 4 cal ka, and 4 and 0 cal ka, respectively.

Numerical ages have not been obtained for any of the surficial units in the Alma quadrangle. The ages assigned to surficial units are estimates based principally on stratigraphic relations, position in the landscape, differences in degree of weathering and soil development, and inferred correlations with deposits elsewhere in the region whose ages have been determined by numerical-dating methods.

Formal time divisions		Informal time divisions	Informal nomenclature for glacial deposits	Approx. age (sidereal years)
Quaternary Period	Holocene Epoch			
			— ? — ? — ? — ? —	11,680
	Pleistocene Epoch	late Pleistocene	Pinedale	
			— ? — ? — ? — ? —	55,000
			— ? — ? — ? — ? —	128,000
		middle Pleistocene	Bull Lake	
			— ? — ? — ? — ? —	
				778,000
		early Pleistocene	Pre - Bull Lake	
				1,806,000
Tertiary Period (part)	Pliocene Epoch			

Table 1. Time terminology applied to glacial deposits in the Alma quadrangle (after Fullerton and others, 2003).

HUMAN-MADE DEPOSITS—Earth materials emplaced by human beings.

af **Artificial fill (upper Holocene)—**Earth materials (sand, silt, clay, and rock debris) emplaced to construct roads and dams. Estimated thickness is 3 to 65 ft.

mw **Mine waste (upper Holocene)—**Piles of earth materials excavated from mines or accumulated as a consequence of processing ore. The largest deposits are old placer workings along the Platter River valley. Estimated thickness is 3 to 100 ft.

ALLUVIAL AND ORGANIC DEPOSITS—Sand, silt, gravel, and clay transported and deposited by flowing water, either in stream channels or as unconfined runoff or sheet flow, interbedded in places with organic materials that formed in place. Deposits resulting from sheet flow are referred to as sheetwash alluvium. Stream alluvium, also described as fluvial, is the principal deposit underlying flood plains and stream terraces. Following Dunne and Leopold (1978), flood plain refers only to the flat area adjacent to the stream channel that was constructed by the stream in the present climate and that is flooded frequently.

Qa **Valley-floor alluvium (upper Holocene)—**Chiefly poorly sorted sand and gravel of all sizes, but primarily pebbles and cobbles, overlain in most valleys by 1.5 to 3 ft of organic-rich sediment, which in places includes peat. Unit underlies flood plains and low terraces that are only about 3 ft or less higher than streams. Estimated thickness is 3 to 15 ft.

Qao **Alluvium and organic-rich sediment, undivided (Holocene and upper Pleistocne)—** Unit consists of variable amounts of organic-rich clayey silt, peat, and gravelly alluvium. The clayey silt probably includes significant amounts of windblown sediment. Unit is in closed depressions and other poorly drained areas and also floors weakly defined ephemeral channels, some of which are relicts of Pinedale deglaciation. Wetland plant types, notably willows and sedges, delineate the unit in many places. Estimated thickness is 3 to 15 ft.

Qte **Terrace deposits (upper Pleistocene)—**Extremely poorly sorted gravelly sand underlying terraces 20 to 25 ft higher than stream level in unglaciated drainage basins. Clasts are subordinate to matrix and consist chiefly of subangular to subrounded pebbles and cobbles of durable Paleozoic sedimentary rocks and Tertiary igneous rocks. Estimated thickness is 5 to 18 ft.

GLACIAL DEPOSITS—Most of the glacigenic deposits in the Alma quadrangle are mapped as till, the term for nonsorted, nonstratified sediment deposited directly from ice without reworking by meltwater, even though in places, primarily end moraines, they contain stratified sediment and mass-wasting deposits.

Qg **Glaciofluvial deposits (upper Pleistocene)—**Subrounded to rounded pebbles, cobbles, and boulders in a sandy matrix. Some material may have been deposited by meltwater flowing within or under glaciers, but most are probably outwash (stratified drift deposited by meltwater beyond glacier margins). Clasts make up a larger percentage of unit Qg than the Qt units. Estimated thickness is 3 to 65 ft.

Qt3 **Till of post-Pinedale? age (lower Holocene and upper Pleistocene)—**Deposits are similar to those of Qt2, except they are much smaller and are restricted to the uppermost reaches of glaciated valleys. Terminal moraines of Qt3 are 15 to 30 ft high and are only about 2 miles downvalley from cirques near the head of the Middle Fork South Platte River and about 1.25 miles from the cirque at the head of Buckskin Gulch. The terminal moraines are separated from the upvalley limits of Qt2 by several kilometers of valley floor wherein glacial deposits are sparse and bedrock outcrops are extensive. Unit Qt3 probably was deposited during the Younger Dryas chronozone (13.0 to 11.7 cal ka, Fairbanks, 1990). Unit is estimated to be 3 to 30 ft thick.

Qt2 **Till of Pinedale age (upper Pleistocene)—**Chiefly gray, nonsorted, nonstratified subangular to subrounded boulders, cobbles, and pebbles in a sandy matrix. In places, end moraines contain appreciable amounts of stratified drift in the form of thinly bedded and commonly cross-stratified sand and fine gravel. Material less than 2 mm in size is estimated to make up 70 to 80 percent of the till. Unit locally includes Qls, especially along the west side of the Middle Fork of the South Platte River, and also includes small areas of bedrock outcrop on steep valley sides. Radiocarbon and cosmogenic nuclide ages (Madole, 1986; Benson and others, 2004) indicate that Pinedale glaciers (1) began forming sometime after 35 cal ka, (2) were nearing their maximum extent about 26 cal ka, and (3) had disappeared from all but the highest elevations by about 16.4 cal ka (dates are in calendar years, which differ significantly from equivalent ^{14}C dates). Cosmogenic nuclide ages indicate that the multiple end moraines common near the downvalley limit of Pinedale glaciation in many valleys are of nearly the same age. Unit may be as much as 100 ft thick in lateral and end moraines, but most ground moraine is probably less than 18 ft thick.

Qt1 **Till of pre-Pinedale age, undivided (middle Pleistocene)—**Consists chiefly of till similar to that of unit Qt2, but is present above the lateral limits and beyond the end limits reached by Qt2. Unit Qt1 is generally thin and, unlike Qt2, retains little or no constructional topography, such as sharp-crested moraines and hummocky knob-andkettle terrain, and it is much more weathered. Many clasts have much thicker weathering rinds and are easier to break than clasts in Qt2. Also, soils in Qt1are thicker, more oxidized, and have more illuvial clay in the B-horizons than soils in Qt2. In places, particularly on the west side of the Middle Fork of the South Platte River, bands of Qt1 are too narrow to show conveniently at the scale of this map, and, thus, are included in Qt2. In the eastern part of the map area, pre-Pinedale glaciers spilled over the interfluve east of the Middle Fork South Platte River and also the interfluve east of Beaver Creek near the southeast corner of the quadrangle to an extent that was not repeated during Pinedale time. Also, pre-Pinedale glaciers reached altitudes in the Hoosier Pass area that were higher than those reached during Pinedale time, allowing pre-Pinedale glaciers to spill northward through Hoosier Pass for a short distance into the headwaters of the Blue River drainage basin. Most of Qt1 is probably of Bull Lake age (see Table 1). Unit is estimated to be 3 to 20 ft thick.

MASS-WASTING DEPOSITS—Earth materials that were transported downslope primarily by gravity. Mass wasting differs from other modes of material transport in that the material moves as a mass rather than as individual fragments borne along by a transporting medium such as wind or flowing water. Although water is an important constituent of most mass movements and commonly triggers movement, water is part of the moving mass rather than the transporting agent. Following the definitions of Hilgard (1892) and Merrill (1897), colluvium is used here as a general term for all earth materials transported chiefly by mass wasting. Many deposits in the Alma quadrangle are the product of multiple mass-wasting processes (for example, rock falls and slides, snow avalanching, and debris flows), in which case they are mapped simply as colluvium rather than being identified by the name of a landform or a specific mass-movement process.

Qta **Talus deposits (upper Holocene)—**Chiefly angular rock debris, a small percentage of which is as large as 6 to 12 ft, deposited on and at the base of steep slopes. The debris came from cliffs primarily by rock falls and slides, debris flows, and snow avalanches. Areas of scree (rock rubble) are widespread in the map area on steep slopes that are not surmounted by cliffs or terrain from which rocks could fall. These deposits were not mapped because they are generally not more than 5 ft thick. Further, they are the product of frost wedging of subjacent bedrock rather than mass wasting (i.e., they formed in place rather than having come from elsewhere under the force of gravity) and are more properly referred to as block slopes, a variant of blockfields, also known as felsenmeer. Talus deposits may be as much as 100 ft thick in footslope localities.

Qc **Colluvium (Holocene and upper Pleistocene)—**Deposits consist of sand, silt, clay, and angular to subangular clasts ranging from pebble-size to boulders. Most deposits are on terrain that slopes between about 15º and 35º. In many places where slopes are greater than or equal to 25º, the colluvial veneer is less than 5 ft thick and, thus, is not shown on the map. In the upper reaches of glaciated valleys (Buckskin Gulch, for example), Qc merges across valley floors from opposing valley walls. This Qc is a primarily a complex of old talus deposits and debris-flow deposits that postdate glaciation but predate unit Qt. Unit Qc also includes solifluction deposits that form sheets, lobes, and terraces in the more poorly drained areas of the alpine tundra and tundra-subalpine forest ecotone. These deposits were derived chiefly from subjacent bedrock by frost cracking, wedging, and heave, and moved downslope primarily by frost creep and gelifluction (flow over a perennially frozen substrate). In places, Qc probably includes old landslide deposits that have been so modified by erosion and creep that their slope-failure origin is difficult to recognize. Unit typically is 3 to 10 ft thick, but may be as thick as 50 ft in places.

Qrgw **Valley-wall rock-glacier deposit (Holocene)—**This landform—known by a variety of other names, the more common of which are lobate rock glacier and protalus lobe—consists of a veneer, typically less than 5 ft thick, of angular boulders devoid of matrix overlying a thicker mass of bouldery rock in a finer grained matrix that may be perennially frozen and contain interstitial ice and ice lenses. The deposits characteristically have a steep front (35º-40º) and a hummocky, commonly corrugated (curvilinear ridges and furrows) upper surface that slopes away from the valley wall at a relatively low angle. The steep front and the ridges and furrows on the upper surface, which approximately parallel the valley wall, and the composition and location of Qrgw indicate that it consists of talus deposits that have flowed away from the base of the valley wall. The flow of Qrgw is similar to, but slower than, that of glacier ice, and it is generally attributed to interstitial or intergranular ice creep (Giardino and Vick, 1987). Unit may be as much as 130 ft thick.

Qrgf **Valley-floor rock-glacier deposit (Holocene)—**This landform (known also by other names, the most common of which is tongue-shaped rock glacier) consists of a thin cover (less than 5 ft) of primarily angular boulders devoid of matrix over a thicker mass of bouldery rock rubble that contains interstitial finer grained material. The rock rubble and interstitial fines may be perennially frozen (permafrost) or ice-cemented and may overlie an ice core. Some valley-floor rock glaciers actually may be debris-covered glaciers. The genesis and rheology of valley-floor rock glaciers are subjects of ongoing debate. The rock debris in Qrgf was derived from steep slopes primarily by mass-movement processes, including rock falls, slides, and avalanches, and snow avalanches. Valley-floor rock glaciers characteristically have steep flanks and a front that may be as steep as 35º to 40º. The upper surface of the deposits exhibits furrowing indicative of flow, and it slopes downvalley at relatively low angles. The flow of frozen rock rubble is similar to but slower than that of a glacier. Annual flow rates at five localities—three in the Front Range (Outcalt and Benedict, 1965; S.E. White, 1971; Benedict and others, 1986), and one each in the Elk Range (Bryant, 1971) and San Juan Mountains (P.G. White, 1979)—vary from 5 to 100 cm yr^{-1}, which is comparable to rates measured in several other parts of the world (Vitek and Giardino, 1987; Barsch, 1987)). The viscosity of rock glaciers is slightly higher than that of glaciers because they contain a greater amount of rigid rock debris. Unit Qrgf may be as much as 160 ft thick.

Qls **Landslide deposits (Holocene and upper Pleistocene)—**Nonsorted, heterogeneous mixtures of surficial materials and fragmented rock debris in a wide range of sizes. The deposit matrix (material less than 2 mm in size) and the lithologies and sizes of rock fragments vary according to the nature of the bedrock involved in the slide. In places above timberline, Qls may include material that was emplaced by solifluction and frost creep. This is because it is commonly difficult to distinguish between (1) materials emplaced by slow mass movement, (2) translational landslides, and (3) old landslide deposits whose topographic expression has been modified by erosion and creep. Unit Qls may include small areas of exposed bedrock in slide paths and in scarps at the heads of slides. A variety of human activities can trigger slope failure in old, seemingly stable, landslide deposits (see discussion in section on geologic hazards). Unit thickness is estimated to range from 3 to 130 ft.

ALLUVIAL AND MASS-WATING DEPOSITS—These deposits contain major amounts of material of both alluvial and colluvial origin that are mapped as a single unit because (1) they are interbedded, as in debris fans, (2) they are juxtaposed but are too small to show individually, or (3) they are interspersed and have contacts that are not clearly defined.

Qac **Alluvium and colluvium, undivided (Holocene and upper Pleistocene)—**Extremely poorly sorted sand, silt, clay, and pebble- to boulder-size rock fragments that were transported and deposited primarily by debris flows, snowmelt runoff, and thunderstorm-generated floods. Debris-flow deposits are the dominant constituents of Qac in narrow valleys above timberline, especially those cut in sedimentary rocks. Unit is estimated to be 3 to 20 ft thick.

Qaco **Older alluvium and colluvium**, **undivided (upper and middle Pleistocene)—**Deposits are similar to those of Qac. They cap remnants of debris fans and terraces at the head of Beaver Creek, and are 20 to 65 ft higher than the creek. Estimated thickness is 10 to 40 ft.

Qf **Debris-fan deposits (Holocene)—**Extremely poorly sorted clast- and matrix-supported sandy gravel in fan-shaped deposits at the mouths of steep, first- and second-order drainage basins. The unit is particular widespread along the Middle Fork of the South Platte River. Most clasts are angular to subangular and range from 2 mm to 20 cm in maximum dimension; small boulders also are present in places. These deposits are primarily products of debris flows and runoff from intense thunderstorms and snowmelt, processes that, in places, are ongoing and potentially hazardous to human-made structures. Unit is estimated to be 3 to 65 ft thick.

DIAMICTON—A nongenetic term for poorly sorted terrigenous sediment containing a wide range of particle sizes (Flint, 1960). It is used here to avoid inferring genesis for till-like deposits whose origin is uncertain. Till-like deposits of nonglacial origin are widespread in the Front Range, Gore Range, and Park Range (Madole, 1982, 1991a, 1991b), northeast and north of the map area.

QTd **Diamicton (lower Pleistocene? and upper Tertiary)—**Subangular to subrounded boulders, cobbles, and pebbles in a sandy matrix. Most boulders are less than 3 ft in maximum dimension, although some are larger, and were derived from Precambrian and Paleozoic rocks that crop out farther west. The deposit of QTd on Bald Hill (southwestern part of map area) is higher than the levels reached by late and middle Pleistocene glaciers. Any glacier thick enough to overtop Bald Hill would have advanced into upper Pennsylvania Gulch through the saddle at the west end of Bald Hill, but till is not present in or near this saddle. Similarly, the deposit near the southwest corner of the map area is higher than the level reached by late Pleistocene glaciers in that area. Qtd exposed in landslide headwall scarps in the southwestern part of the map area and also just south of the map area is as much as 50 to 65 ft thick.

BEDROCK

TERTIARY INTRUSIVE ROCKS

Within the quadrangle, at least 7 different units of porphyritic intrusive rocks were emplaced during latest Cretaceous or Paleocene time through Oligocene time. These intrusive rocks are associated with at least three igneous centers, and there does not appear to be a discernable igneous migration path. The igneous centers are: the Mongomery Gulch-Mount Silverheels area, which was heavily intruded by monzonite and rocks ranging from diorite to quartz monzonite roughly 42 to 43 Ma; the Mount Lincoln and Bross area, which is the type locality for the Lincoln porphyry, 65 Ma (although, as indicated below, this date is controversial); and the Buckskin Gulch area, which is characterized by episodic monzonitic to granodioritic intrusions 72 to 42 Ma. Descriptions of the rock units are primarily on the basis of hand sample petrography and limited thin section analysis.

Porphyritic rocks were intruded as sills, dikes, laccoliths, and stocks, although sills were the predominant style of intrusion. Sills are both concordant and discordant to bedding, range in thickness from mere feet to 300 feet thick or more, and have strike lengths the can exceed 1 mile. Dikes tend to be much narrower (generally less than about 20 fts) and much less common than sills. The Lincoln porphyry (which we term megacrystic quartz monzonite porphyry) appears to be a laccolith within the lower part of the Minturn Formation. Stocks were observed in Buckskin and Montgomery Gulches. There appears to be a gross spatial association between quartz monzonite porphyry and significant mine workings. Whether this association is genetic (as the authors suspect), is impossible to definitively tell at this time.

A group of rhyolite porphyries associated with the Climax ore body (northwest of the quadrangle, see figure 1), was termed the Climax late dikes by Bookstrom (1989). Similarly porphyry dikes crop out in Quartzville Creek (where it was called the St. Louis dike by Singewald and Butler, 1931) and in the upper cliffs of Moose Creek, but both were too thin to be shown at the 1:24,000 scale of this map. These dikes are light-gray and contain 10 to 20 percent phenocrysts of subequal quartz, plagioclase, and orthoclase 1 to 2 mm in diameter. Rare biotite and coarse-grained pink orthoclase phenocrysts distinguish the Climax late dikes from White

Porphyry (Singewald and Butler, 1931). Locally, fluorite is present near the ends of the dikes and accessory minerals include topaz, zircon, rutile, and monzonite (Bookstrom, 1989). This suggests a chemical affinity to Climax high-silica rhyolites. At Climax, similar dikes cut the major orebodies, but are weakly mineralized with quartz – molybdenite veinlets were dated at 25.5 Ma (Bookstrom, 1989). The rhyolite porphyry dike in Moose Creek has been K-Ar dated at 25 Ma (Bookstrom, 1983, Climax private report). Thinning and branching of these dikes away from Climax as well as flow lineations on the dike margins that plunge back towards Climax have been interpreted by Bookstrom (1989) as indicating that these dikes originated from the magmatic system centered at Climax.

Tlw **Later white porphyry (Eocene) —**White to light-gray, fine-grained rhyolite porphyry typically in north-northeast trending dikes less than 10 ft thick. Sparse phenocryst content ranges from 2 to 5 percent and is typically composed of roughly subequal, 1 to 2 mm rounded quartz phenocrysts, orthoclase, and lesser plagioclase set in an aphanitic matrix. Originally termed "white porphyry" by Patton and others (1912), the term was changed to "later white porphyry" by Singewald and Butler (1941) and Behre (1953) to avoid confusion with the Pando porphyry of the Leadville district to the south (which was historically known as "white porphyry"). A sample of the later white porphyry taken from north of Kite Lake in Buckskin Gulch just west of the quadrangle has been dated at 34.9 ± 3.8 Ma by using the fission track method (Bookstrom, 1989). The age and chemistry of these dikes suggest that they were the immediate magmatic precursor to the high-silica rhyolites associated with molybdenum mineralization at Climax, which were emplaced starting at 33 Ma (Bookstrom, 1989). Most of the later white porphyry dikes crop out north of Mount Lincoln.

Tsqm **Sparse quartz monzonite porphyry (Eocene?) —**Grayish-tan, fine- to medium-grained porphyritic rock containing 20 percent orthoclase phenocrysts, 3 percent hornblende laths, and only 1 to 2 percent quartz phenocrysts. Euhedral biotite forms approximately 1 percent of the rock mass and is typically less abundant than hornblende. Phenocrysts range from 1 to 3 mm in any direction. Field relations suggest that the sparse quartz monzonite porphyry cuts and is cut by megacrystic porphyry (Tqpm). Therefore, general contemporaneousness between the two is indicated. Sparse quartz monzonite porphyry crops out on Mount Lincoln and south of Buckskin Gulch.

Tqpm **Quartz monzonite porphyry – megacrystic variety (Eocene)—**Light-gray to light-bluish-gray quartz monzonite porphyry that contains prominent large phenocrysts (megacrysts) of orthoclase 2 to 5 cm long, and in many places, rounded bipyramids of quartz 5 to 15 mm in diameter (fig. xx). These phenocrysts are set in a porphyritic matrix composed of anhedral grains 2 to 5 mm long of plagioclase, quartz, orthoclase, and abundant biotite, set in a bluish-gray aphanitic matrix. In the vicinity of Mounts Lincoln and Bross, this porphyry appears to form a large laccolith that intruded close to the lower contact of the Minturn Formation. The large body observed in the north-central part of the quadrangle generally east of Hoosier Pass is also somewhat laccolithic in form. Elsewhere the megacrystic porphyry forms small plugs or relatively thin sills and dikes. Many authors have correlated this unit to the Lincoln porphyry based on close similarity of lithology and appearance. However, there is an age discrepancy between what has been mapped as Lincoln porphyry (Tl) in the Leadville region (Pearson and others, 1962) and megacrystic quartz monzonite (Tqpm) mapped in the adjacent Breckenridge and Copper Mountain quadrangles (Wallace and others, in press; Widmann and others, in press) and the Frisco quadrangle farther north (Marvin and others, 1989). The Lincoln porphyry has been assigned an age of 64.6 Ma by Bookstrom (1983, private report) based on a K-Ar date from a sample taken in upper Buckskin Gulch; this locale has been interpreted as the possible feeder for the laterally extensive laccolithic arms structurally above it on Mts. Bross and Lincoln (Bookstrom, 1983, private report). However, a megacrystic porphyry, identical in appearance to that found on the summits of Mts. Bross and Lincoln, has been dated in the nearby Frisco quadrangle at 44.1 ± 1.6 Ma by the K-Ar method (Marvin and others, 1989). Further, apatite and zircon fission-track dating of two samples of identical-appearing megacrystic porphyry from the Copper Mountain quadrangle immediately to the northwest also yielded young 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). An attempt was made to resolve this issue by submitting samples of the Lincoln porphyry from the summit of Mount Lincoln for age dating. Unfortunately, these samples proved too altered to provide a reliable Ar/Ar date. Thus, the relationship between the Lincoln porphyry and the megacrystic quartz monzonite porphyry remains unclear. Detailed and systematic dating of these porphyry rocks throughout the region will be necessary in order to determine if they originated from the same magmatic event. Until these age uncertainties are resolved, we have chosen to eliminate the term “Lincoln porphyry”. These rocks, wherever they occur within the quadrangle, are referred to as megacrystic quartz monzonite porphyry, a non-locale-specific term which accurately describes their overall composition.

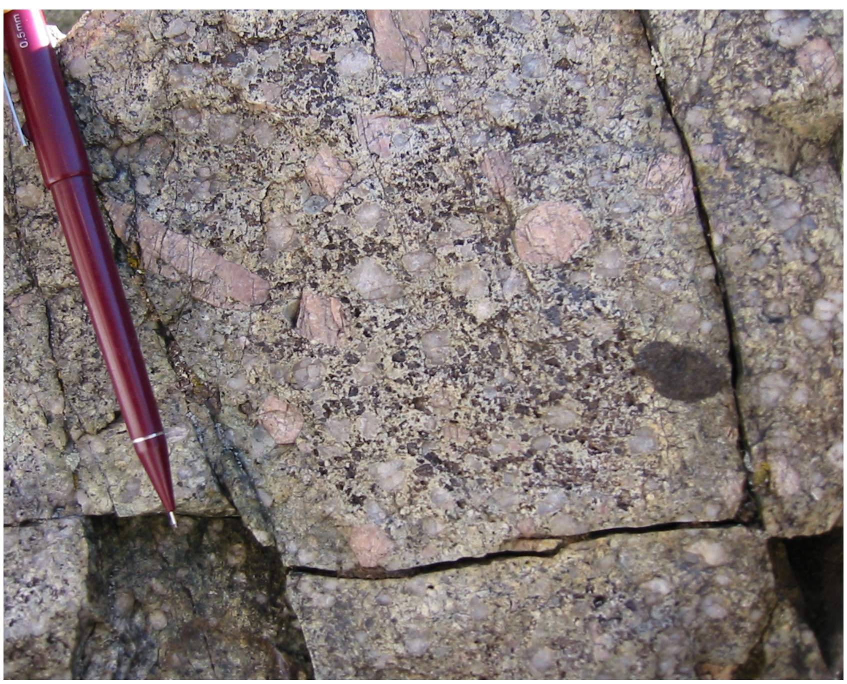

Figure 4. Megacrystic variety of the quartz monzonite porphyry (Tqpm). Note large orthoclase phenocryst (pink), and smaller, somewhat rounded quartz phenocryst (grayish-white).

Tqp **Quartz monzonite porphyry (Eocene)—**Grayish-tan- to light-brown-weathering porphyritic quartz monzonite comprised primarily of quartz, plagioclase, orthoclase, biotite, and hornblende (fig. 5). Orthoclase phenocrysts comprise as much as 20 percent of the rock and quartz phenocrysts about 10 percent. Euhedral biotite forms 1 to 3 percent of the rock volume and is much more abundant than the sparse hornblende. Phenocrysts range in size from 1 to 3 mm and are set in fine-grained matrix. The quartz monzonite porphyry is highly similar to the megacrystic porphyry (Tqpm) in appearance except for the presence of megacrysts in the Lincoln porphyry; for this reason, the quartz monzonite porphyry is believed roughly contemporaneous with the megacrystic quartz monzonite porphyry (Tqpm).

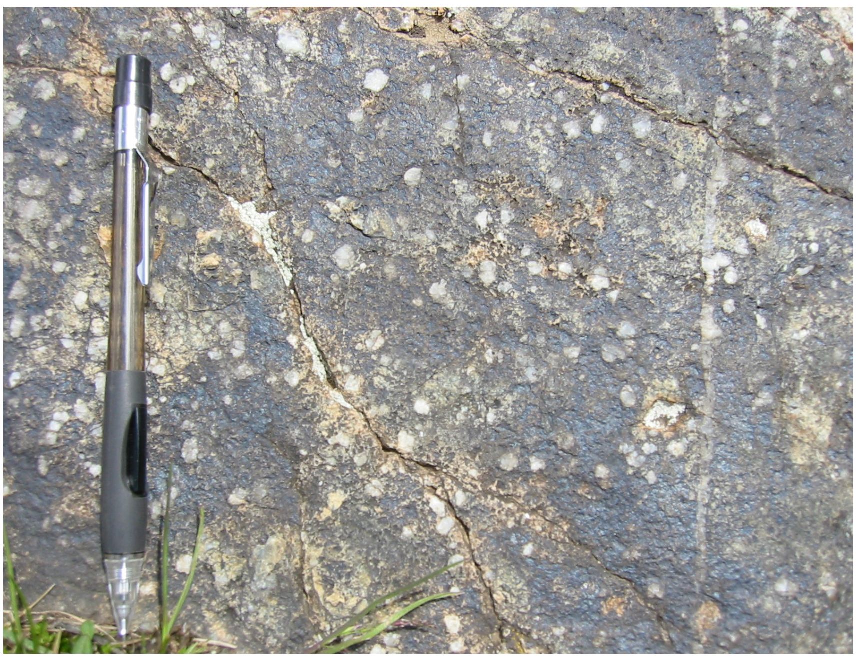

Figure 5. Quartz monzonite porphyry (Tqm). Resistant quartz phenocrysts (white) stand out against a weathered fine-grained matrix (dark purple).

Tmd **Monzodiorite porphyry (Eocene?)—**Dark-gray-green rock with 7 to 10 percent hornblende in laths 1 to 5 mm long, 3 to 5 percent orthoclase 1 to 3 mm across, and minor plagioclase set in a fine grained matrix (fig. 6). Quartz is generally absent. The monzodiorite porphyry is typically unaltered and forms sills and minor dikes in the western part of the quadrangle, particularly in Mosquito Gulch and the upper part of the Middle Fork of the South Platte River (up stream from Montgomery Reservoir). This unit has not been dated but is intruded by the later white and sparse quartz monzonite porphyries and is therefore older than 42 to 44 Ma.

Figure 6. Hand sample of monzodiorite porphyry (Tmd). Note darker greenish-gray color and greater percentage of hornblende (black) than observed in monzonite porphyry (below). Base of sample is about 6 cm across.

Tmp Monzonite porphyry (Eocene?)—Pale-gray or green to tan monzonite porphyry with 10 percent plagioclase 1 to 5 mm across, 3 to 5 percent hornblende laths 1 to 4 mm long, 3 percent biotite books 2 mm across, and 0 to 3 percent quartz 2 to 5 mm in diameter (fig. 7). Hornblende is commonly chloritized. The monzonite is characterized by sills and small stocks in the eastern portion of the quadrangle and is most abundant in the

Montgomery Gulch-Mount Silverheels area. Here, a composite stock, dominantly monzonite in composition but ranging from diorite to locally quartz monzonite in the stock's center was emplaced (Singewald, 1942). The dikes and sills which constitute a large portion of the northern slopes of Mount Silverheels appear to be the upward fingers of this stock. There is a large contact metamorphic areole associated with this stock; the gold in the Tarryall placer district (Singewald, 1942) appears derived from this contact areole. Ransome (1911) and Lovering (1934) considered the monzonite porphyry to be nearly contemporaneous with the megacrystic quartz monzonite porphyry (Tqpm), which was dated at 42 to 43 Ma.

Figure 7. Mafic minerals are visible in this sample of monzonite porphyry (Tmp) taken from the Mount Silverheels area.

Td **Diorite rocks of Buckskin Gulch (Paleocene and Eocene)—**Includes stocks and dikes ranging in composition from monzonite to granodiorite near the head of Buckskin Gulch. These rocks are typically medium- to light-gray in color and range from fine to coarse grained (fig. 8). The principal minerals include plagioclase (ranging from andesine to labradorite), hornblende, quartz, and biotite. Orthoclase was found in monzonitic rocks on the west side of Buckskin Gulch (just west of the Alma quadrangle) by Patton and others (1912). Plagioclase is the dominant matrix mineral but also forms tabular grains up to about 3 or 4 mm in maximum dimension. Hornblende is present in most rock varieties as elongate laths 2 to 3 mm long and constitutes as much as 10 percent of the rock. Quartz is generally very fine-grained and comprises less than 5 percent of the rock. Quartz content is slightly higher in coarse-grained rocks where it is visible in hand specimen as rounded grains up to 3 mm in diameter. Biotite flakes up to 3 mm in diameter were found only in a few samples and represented less than 5 percent of the rock. Magnetite, apatite, and titanite are accessory minerals noted by Patton and others (1912). Monzonite intrusions appear to have predominated early (between 72 and 67 Ma) and were followed by granodiorite (until 42 Ma); although magmas of both composition were episodically emplaced throughout the 72 to 42 Ma interval (Bookstrom, 1989). At one locality on the east side of Buckskin Gulch, these rocks were observed grading to quartz monzonite (Tqp) and megacrystic quartz monzonite (Tqpm) over a distance of less than one meter.

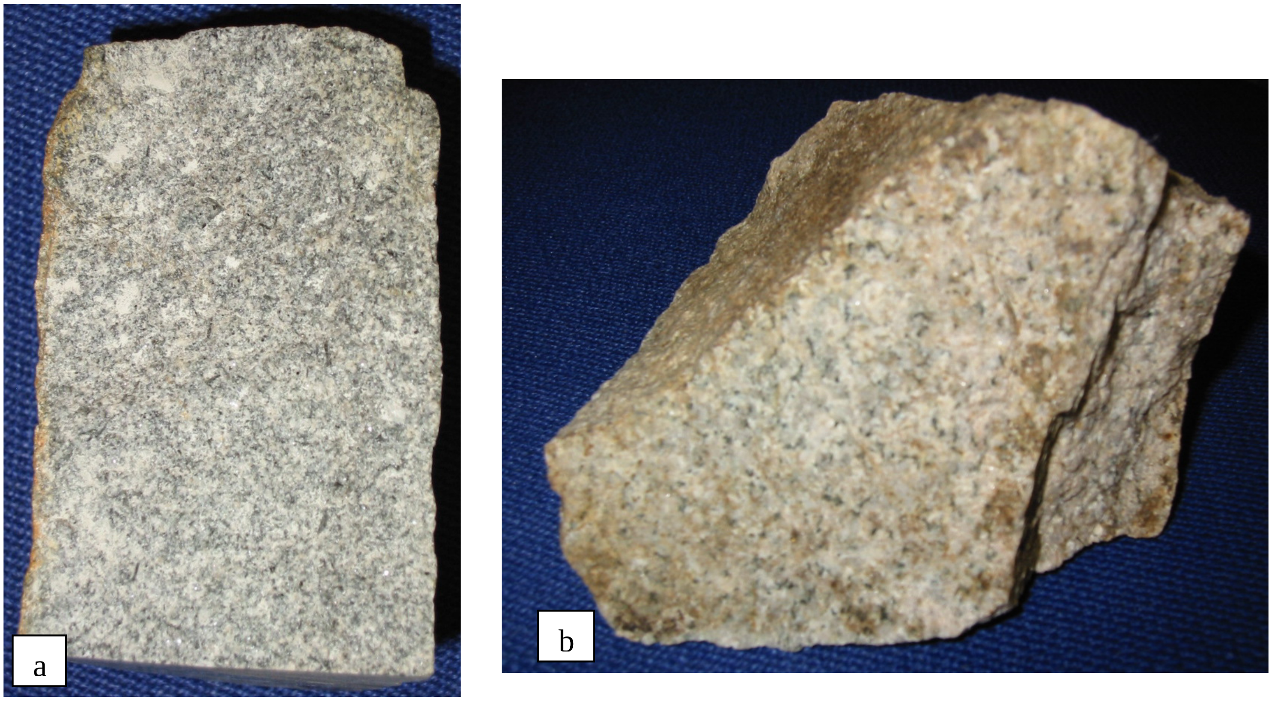

Figure 8. Examples of the variation in the Buckskin diorite group (Td). Samples are of (a) fine-grained granodiorite (4 cm across) and (b) medium-grained quartz-hornblende diorite (11 cm across).

Tpd **Pebble dike (Eocene?)—**Single feature mapped in section 33 of the west edge of the quadrangle comprised entirely of well rounded to sub-rounded, flat to spherical clasts of Precambrian gneiss and granite, and quartzite of unknown age, strongly cemented together by hydrothermal quartz (fig. 9). It was not determined if clasts of Tertiary rock were also present. Most of the clasts are pebble to cobble sized, although some clasts are more than 1.5 meters in maximum dimension. The dike is about 3 meters wide at its east end and over 7 meters wide at its west end. Numerous N60°W-oriented fractures are present in the host rock (Xb) adjacent to the dike, and yellow-orange to rusty-red iron staining is pervasive. The rounded clasts comprising the dike were formed during forceful hydrothermal events likely related to Tertiary intrusion and hydrothermal alteration of the nearby Sweet Home mine area.

Figure 9. Rounded clasts, primarily Precambrian in age, are cemented by hydrothermal iron-stained quartz (orange) in a forcefully intruded pebble dike on the west side of Buckskin Gulch.

PALEOZOIC SEDIMENTARY ROCKS

Regionally, the Paleozoic sedimentary rocks consist of the Sawatch Quartzite and Dotsero Formation (Upper Cambrian), Manitou Formation (Ordovician to Upper Cambrian), 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). However, the Harding Quartzite, Fremont Dolomite, and Belden Formation were not found to crop out within in the Alma quadrangle.

Paleozoic sedimentary rocks within the Alma quadrangle generally dip less than 30° eastward. The oldest sedimentary stratigraphic unit, the Sawatch Quartzite, rests nonconformably on the Proterozoic basement rocks that form the core of the Mosquito Range. West of the Platte River valley, the Lower Paleozoic section is nearly complete with the exception of the Harding Quartzite and Fremont Dolomite. These two units either were not deposited in the map area or they were eroded prior to deposition of the Chaffee Group. The Upper Paleozoic section is most extensive in the eastern part of the quadrangle and is dominated by the Minturn and Maroon Formations.

Carbonate-rich sandstone and shale beds overlying the Sawatch Quartzite were originally designated the Peerless Shale Member of the Sawatch Formation by Behre (1932), and were later upgraded to formation rank by Singewald (1947). This nomenclature was adopted for rocks of similar appearance in the Front Range by Berg and Ross (1959). However, detailed analysis of numerous measured sections of Lower Paleozoic rocks throughout Colorado by Myrow and others (1995, 1999, 2003) showed that the Peerless Formation, as mapped in the Front Range, does not correlate chronologically or stratigraphically with the Peerless Formation at its type section at Peerless Mountain. Instead, these strata are time-equivalent to glauconite-rich beds of the Middle Member of the Sawatch Quartzite. As a means of preventing future confusion, Myrow and others (2003) dropped the term Peerless Formation and reassigned the strata above the Sawatch Formation to the Dotsero Formation, thereby establishing a correlation to similar units mapped in the White River uplift by Bass and Northrop (1953). The “red cast beds” (Emmons, 1886), a local marker horizon formerly used to indicate the top of the Peerless Formation (Behre, 1953), is now considered to constitute the lowermost part (Taylor Pass Member) of the Manitou Formation (Myrow and others, 2003). Furthermore, the Myrow and others (1995, 1999, 2003) studies also identified the stratigraphic location of the Cambrian-Ordovician boundary in the lower part of the Manitou Formation. The stratigraphic nomenclature put forth by Myrow and others (2003) is adopted herein.

There is a great deal of controversy as to how best to map the highly variable and often exceedingly thick package of sedimentary rocks shed from the rising Ancestral Rocky Mountains during Pennsylvanian to Permian time (controversy outlined in Wallace and others, in press). Recent mapping north and northwest of Alma (Scott and others, 2002, Kellogg and others, 2003, Widmann and others, in press) has relied on the stratigraphic section defined by

Tweto (1949), which consists of, from bottom to top: black shale and sandstone of the Belden Formation, generally gray clastic rocks and limestone beds of the Minturn Formation, and redbeds of the Maroon Formation. The contact between the Minturn and Maroon Formations was designated to be the top of the Jacque Mountain Limestone Member, the uppermost persistent marine limestone bed in the Pennsylvanian and Permian section. Murray (1950) recommended elevating the Jacque Mountain limestone to formation status on account of its widespread lateral extent in the Eagle County region. Unfortunately, outside of this region (particularly to the south and southeast) correlation of any one limestone bed with the Jacque Mountain limestone has proved difficult or not possible. Taranik (1974) spent a great deal of time trying to correlate limestone units in the Breckenridge and surrounding regions to the limestone members described by Tweto (1949) but was only partially successful. He cited numerous vertical and lateral lithofacies changes and a lenticular nature as being considerable obstacles in correlating carbonate beds with any certainty. Wallace and others (in press) faced this same uncertainty and ultimately chose not to make any correlations in the Breckenridge area.

Given that the Alma and Breckenridge areas during Pennsylvanian time were situated in a narrow, tectonically active part of the Central Colorado trough (DeVoto, 1980), it is entirely possible that the Jacque Mountain limestone either underwent a lithofacies change, was not deposited in this area, or was eroded prior to subsequent deposition of overlying rocks. Without being able to clearly define the Jacque Mountain limestone, one may be tempted to simply map the Minturn/Maroon contact at the uppermost limestone bed in the area. However, that bed may not be (in fact, is probably not) the time-stratigraphic equivalent of the Jacque Mountain limestone, since even at the type locality of Jacque Mountain, Widmann and others (in press) noted several thin limestone beds in the base of the Maroon Formation above the Jacque Mountain limestone. Thus, in the absence of the Jacque Mountain marker bed, there often exists little or no lithologic basis for distinguishing the Minturn and Maroon Formations. This lack of lithologic distinction has been noted elsewhere by authors such as Tweto and Lovering (1977), DeVoto (1965), and Singewald (1942).

The Minturn Formation is commonly described as predominantly gray, whereas the Maroon Formation is described as bright- or brick-red. However, there are numerous red beds in the Minturn Formation, and grayish sandstone and conglomerate are not uncommon in the lower part of the Maroon Formation. Although some of the red coloration may have been inherited during deposition (Tweto and Lovering, 1977), the majority of the red staining is thought to be a product of alteration of iron-bearing minerals in an arid environment after the sediments were deposited (Raup, 1966; Walker, 1967). As a post-depositional alteration effect, the red color can cross stratigraphic horizons, and is therefore not a reliable indicator for formation contacts.

Despite early reports (e.g. Johnson, 1934) warning that color change was not a reliable way to pick the Minturn/Maroon contact, Taranik (1974), tried to map the contact on the basis of a locally observed change in color from predominantly gray rocks of the Minturn Formation to the predominantly red strata of the Maroon Formation. In doing so, Tarnik mapped a contact that cut across stratigraphic marker beds. Wallace and others (in press) indicated that there was a "significant" change in grain size associated with the color change in the Breckenridge quadrangle and used that difference to map the contact between the two formations. However, this color-associated grain size change was not observed in the Alma quadrangle. Furthermore, Wallace and others' (in press) mapped contact is generally coincident with Taranik's contact based on color and also cuts across stratigraphic marker beds.

Within the Alma quadrangle, the Jacque Mountain Limestone Member cannot be identified with any certainty and the transition from gray to red typically takes place over as much as one hundred meters and is not everywhere within the same stratigraphic horizon. The Minturn/Maroon contact has been mapped differently on each of four historic maps that encompass parts of the quadrangle (Emmons and others, 1927, Singewald, 1942, Taranik, 1974, Tweto, 1974a), further evidence that there is no clear distinction between the two units in this area. In fact, only general statements may be made about the Pennsylvanian-Permian sedimentary package in the Alma quadrangle. The lower part of the sequence (Minturn Formation) tends to have a greater percentage of black shale and course sandstone. Siltstone and fine-grained sandstone predominate in the upper part of the sequence (Maroon Formation), although conglomerate is still fairly widespread. This observation contradicts observations made by Taranik (1974) and Wallace and others (in press) in the Breckenridge area, and further suggests that variations in color, grain size, and locally, even lithology are not laterally continuous and serve as poor indicators to define formation boundaries within the Penn-Permian sequence. Defining the Minturn/Maroon contact is even more difficult in the northeastern part of the quadrangle because igneous activity has greatly altered the rocks.

We map the Minturn/Maroon contact is mapped at the uppermost limestone bed with the caveat that this stratigraphic horizon may or may not coincide with that of the Jacque Mountain Limestone. At best, it can be stated that the uppermost limestone bed in any area simply represents the point at which the depositional environment in that area transitioned from alternating marine (shale, limestone) and terrestrial (sandstone, conglomerate) deposition (Minturn Formation) to predominantly terrestrial (siltstone, sandstone, conglomerate) deposition (Maroon Formation). On the southern flank of Mount Silverheels, this contact is not difficult to locate. In the vicinity of Mount Silverheels, however, hornfelsing has made it impossible to delineate a contact between the two formations. Thus, that area has been mapped as Minturn and Maroon Formations, undivided (P*P*mu). In the northern part of the quadrangle, the Minturn/Maroon contact as mapped in the Breckenridge quadrangle (Wallace and others, in press) was not carried south into the Alma quadrangle. Rather, that contact is inferred to be northeast and east of the Alma quadrangle on the basis of mapping by Wallace and others (in press) and Singewald (1942), which showed several prominent limestone beds on Red Peak (just north of the Alma quadrangle) up section from the contact mapped by Wallace and others (in press).

P*P*m Maroon Formation (Early Permian to late Pennsylvanian)—Predominantly light- to orange-red, fine-grained micaceous sandstone and thinly laminated siltstone and mudstone, pinkish-gray pebble- to cobble-conglomerate, and a few thin (generally less than one meter thick) beds of dark-gray to reddish-gray limestone or limey siltstone and mudstone. Sandstone beds are arkosic, highly micaceous, and commonly exhibit tabular and trough cross-stratification and sub-parallel laminations. Locally, sandstone units weather medium-gray, dark-purplish-red, or black. Bed-parallel burrows are discernable near the base of a few sandstone beds. Taranik (1974) also noted ripples, mud cracks, raindrop imprints, and other sedimentary structures. Sandstone beds are consist primarily of detrital grains of quartz, feldspar, biotite altered to hematite, and muscovite. Wallace and others (in press) classified much of the siltstone in the Breckenridge quadrangle as feldspathic arkose. Locally, siltstone is limey and exhibits weak bioturbation.

Most of the conglomerate contains well-rounded to sub-angular pebble-size clasts in an arkosic sandy matrix. Locally, cobble-size clasts are abundant, particularly within deep (several feet) channels cut into underlying beds. The prevailing clast lithologies, listed in order of abundance, include: granite, quartzite, gneiss, vein quartz, limestone, and sandstone. Gradation is generally a normal fining upwards sequence, although reverse grading was also locally observed. Thickness of the Maroon Formation within the quadrangle is less than 3,000 ft, however, the upper limit of the formation is not exposed on the quadrangle so total thickness cannot be determined.

P₱mu Maroon and Minturn Formations, undivided (Early Permian to Middle Pennsylvanian)—Mapped only on Mount Silverheels. Stratigraphic relations on the south flank of Mount Silverheels suggest that the Minturn/Maroon contact must also cut somewhere across the western and northern flanks of Mount Silverheels. However, faulting and hornfelsing of the rocks in this area has made it nearly impossible to accurately locate the contact. Therefore, the rocks have been mapped as undivided. This unit consists of hornfelsed siltstone, fine-grained micaceous sandstone, and conglomerate. Siltstone horizons have abundant iron oxide-stained interstitial clay and are typically dark-red or multicolored (greenish-gray, bright-green, purple, fleshy-pink, pinkish-gray, and black), (fig. 10). Epidote is prevalent in hornfelsed areas. Sandstone layers are generally dark red. Conglomerate ranges from pinkish-red to pinkish-gray but is locally bleached white.

Figure 10. Multicolored hornfelsed siltstone on the west flank of Mount Silverheels.

IPm Minturn Formation (Middle Pennsylvanian)—Predominantly tan, greenish-gray, or dark purplish-gray arkosic, micaceous pebble- and cobble-conglomerate, sandstone, and shale, interbedded with dark-gray, limestone beds typically less than 30 ft thick. Black shale is most prevalent near the base of the sequence and is interlayered with thinly bedded (platy) dark-purple, gray, or buff micaceous sandstone. This shaly zone may represent the upper part of the Belden Formation, which underlies the Minturn Formation elsewhere in the region, but exposures are too limited to be certain. Above the shaly zone, the lower sequence passes into thick-bedded, medium- to coarse-grained, orange- and red-weathering sandstone interspersed with limestone beds and channel fill conglomerate similar to conglomerates described in the overlying Maroon Formation. Sandstone beds tend to be planar where fine grained and trough cross-stratified where coarser. Coarse-grained sandstone and small-pebble conglomerate in pervasive narrow (less than about 3 meters wide) channels quickly grade upward to medium- and fine-grained sandstone. Conglomerate in broad (a few tens of meters wide) channels as much as 15 meters thick, commonly contains cobble-size clasts, and may exhibit both normal and reverse gradation. Conglomerate is particularly widespread in the southeast quarter of the quadrangle and may indicate a primary or significant tributary paleo-valley. Total thickness of the Minturn Formation in the quadrangle is about 7,000 ft.

IPml **Minturn Formation, limestone beds (Middle Pennsylvanian)—**Unit consists of numerous thin limestone or dolomite beds interspersed throughout the Minturn Formation. Where fresh, limestone is nearly everywhere dark-to medium-gray. However, individual beds have weathered or been altered to gray, black, dark-reddish-gray, tan, and even white. Limestone texture is either micritic or fine grained. A few discontinuous limestone beds near Hoosier Ridge contain numerous bivalve shell fragments up to 2 cm in length. Limestone beds are typically 15 to 20 ft thick or less, although the limestone located northwest of High Park in the central part of the quadrangle may be as much as 40 ft thick. Limestone gives way to limey sandstone near the top of the Minturn Formation (fig. 11).

Figure 11. Limey sandstone in the upper part of the Minturn Formation.

Ml **Leadville Limestone (Mississippian)—**Blue to black, massive-bedded, fine-grained dolomite characterized by local patches of irregular, alternating 1 to 5 mm bands of dark-gray to black dolomite and white, coarse-grained, vuggy dolomite (known as “zebra rock”). This dolomite, particularly its uppermost portion, is intimately associated with most of the orebodies found on Mounts Lincoln and Bross. Throughout much of the quadrangle the dolomite averages about 160 ft thick, but it thins significantly (less than 50 ft) to the north in the area west of Hoosier Pass. This is in accord with mapping by Wallace and others (in press) in the Breckenridge quadrangle to the north, which shows Pennsylvanian rocks (Pm) resting directly on Devonian rocks (Dd) at the south end of that quadrangle.

Dc **Chaffee Formation (Upper Devonian)—**Mapped in areas where Parting Quartzite and Dyer Dolomite Members are poorly exposed or too thin to be mapped separately.

Dd Dyer Dolomite Member**—**Laminated, tan-weathering, fine-grained dolomite. Yellow to brownish-gray on fresh surfaces with wavy microlamination. Throughout the quadrangle, the Dyer Dolomite has a thickness of approximately 75 to 80 ft.

Dp Parting Quartzite Member**—**Purplish, fine- to medium-grained, orthoquartzite with interbeds of dolomitic sandstone. Sandy appearance on weathered surfaces. Visually indistinguishable from the Sawatch Quartzite; identification is based on stratigraphic position. The thickness of the Parting Quartzite is quite variable within the quadrangle, but overall thins to the north, from approximately 55 ft in the Mosquito Gulch area (Singewald and Butler, 1930), to 25 ft in Buckskin Gulch (Corn, 1957), to absent on the summit of Mount Lincoln (Patton and others, 1912). The Parting Quartzite reappears north of the quadrangle on the flanks of Quandary Peak, where it is 20 ft thick (Wallace and others, in press).

O€m Manitou Formation (Ordovician to Upper Cambrian)—Cliff-forming unit composed of light- to dark-gray, thin- to thick-bedded dolomite with rare interbeds of dark gray limestone. Whitish-gray to black laminated chert nodules are characteristic in the upper part of the unit. The lowermost 3 to 10 ft of the Manitou Formation contains 1- to 3-ft-thick beds of whitish dolomite with abundant brick-red ovoid spots. These beds, historically known as the "red-cast beds" (Emmons, 1886), were formerly considered the upper part of the Peerless Formation (Behre, 1953). Myrow and other's (2003) revised stratigraphy now place these beds within the Taylor Pass Member of the (expanded) Manitou Formation (fig. 12). The Manitou Formation appears to thin significantly to the north, from 200 ft at Horseshoe Mountain several miles southwest of the quadrangle (Myrow and others, 2003), to 120 ft in Buckskin Gulch (Corn, 1957) to approximately 65 ft on Mt. Lincoln (Singewald and Butler, 1933).

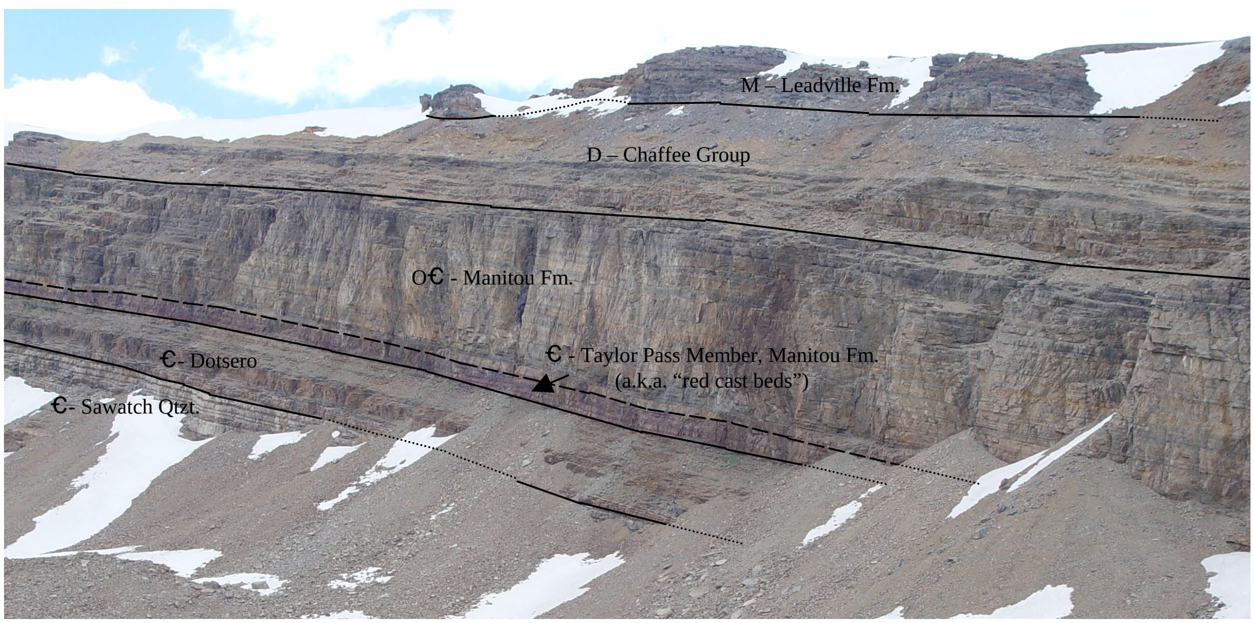

Figure 12. View looking southwest at Horseshoe Cirque (southwest of Alma quadrangle). This site was one of many sections measured and used by Myrow and others (1995, 1999, 2003) to redefine the lowermost Paleozoic succession of Colorado. Note that the Cambrian-Ordovician boundary occurs within the Manitou Formation at the top of the Taylor Pass Member. The Taylor Pass Member is about 50 ft thick at this location. € – Cambrian, O – Ordovician, D – Devonian, M – Mississippian.

Ꞓd **Dotsero Formation (formerly Peerless Formation) (Late Cambrian)—**Poorly exposed unit composed of basal medium to fine grained, locally glauconitic, purple quartzitic sandstone overlain by dolomite-cemented sandstone and thin, sandy to silty dolomite beds. Within the quadrangle, the Dotsero Formation weathers recessively, typically yielding a rusty colored soil horizon. Where exposed, the unit weathers a distinctly brown color that contrasts with the whitish rocks of the underlying Sawatch Quartzite. Thickness of the unit is about 50 ft.

Ꞓs **Sawatch Quartzite (Late Cambrian)—**White, thick-bedded, medium-grained, well-cemented quartzitic sandstone. Typically outcrops as light colored or whitish cliffs composed of 2- to 10-ft-thick beds. The lower contact is a nonconformity with an overlying basal pebble conglomerate 7 to 12 inches thick, composed of well-rounded quartz pebbles in a medium to coarse sandstone matrix. Overall, the Sawatch Quartzite is a medium grained, moderately to well sorted, sub to well rounded, orthoquartzitic sandstone. Overall detrital feldspar content tends to diminish upward in the unit. Thickness of the Sawatch Quartzite within the quadrangle increases northward and varies from approximately 115 to 150 ft.

PROTEROZOIC INTRUSIVE ROCKS

Proterozoic intrusive rocks in the Alma quadrangle belong to the Berthoud (1,400 Ma) and Routt (1,700 Ma) plutonic suites. The largest of these bodies are located in the Platte River valley north and northwest of Mount Lincoln and on the west flank of Mount Bross. Smaller plugs and dikes are common throughout the western part of the quadrangle. Descriptions of the rock units are primarily on the basis of hand sample petrography and limited thin section analysis.

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. The rock has a seriate porphyritic texture defined by alignment of tabular microcline phenocrysts, many of which exhibit Carlsbad twinning. Some euhedral laths of microcline exceed 1 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 miles 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 inches 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, fine-grained, massive to weakly foliated lamprophyre dikes comprised primarily of hornblende and/or biotite, plagioclase and/or potassium feldspar, epidote, and chlorite. Locally, other constituents include pyroxene, quartz, staurolite, magnetite and other opaque minerals, and traces of apatite. The dikes commonly exhibit small dark or light blebs consisting of fine-grained aggregates of hornblende or potassium feldspar (fig. 13).

Figure 13. Precambrian mafic dike. Dark blebs are fine-grained aggregates of hornblende.

Xgg Granitic gneiss (Early Proterozoic)—Light-gray, medium- to coarse-grained, massive to moderately foliated monzogranite composed of microcline, plagioclase, quartz, and biotite, and hornblende (fig. 14). Garnet, muscovite, sphene, zircon, and apatite are minor constituents. Quartz commonly forms recrystallized polygonal ribbons with sutured boundaries, undulatory extinction, and triple point junctions. A poikilitic texture prevails within larger microcline grains. The rock has a hypidiomorphic to xenomorphic texture and commonly exhibits short, thin biotite-rich aggregates parallel to foliation. Similar rocks in the Frisco quadrangle to the north were assigned to the Routt plutonic suite by Kellogg and others (2002).

Figure 14. Granitic gneiss with thin biotite-rich aggregates parallel to foliation.

Xgp Porphyritic granodiorite (Early Proterozoic)—Medium- to dark-gray, well foliated to massive, commonly migmatitic, porphyritic granodiorite consisting of a medium- to coarse-grained groundmass of oligoclase, potassium feldspar, quartz, and biotite and porphyroblasts of potassium feldspar up to 1 inch long (fig. 15). Potassium feldspar crystals exhibit microcline grid-twinning and Carlsbad twins and locally, make up as much as 50 percent of the rock. Accessory minerals include magnetite, ilmenite, pyrite, apatite, sphene, zircon, and muscovite. 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. Sparse, angular fragments of biotite gneiss within the granodiorite indicate a probable igneous origin for granodiorite. This unit crops out only in the northwestern part of the quadrangle and correlates with porphyritic granodiorite described in the Copper Mountain quadrangle by Widmann and others (in press), porphyroblastic migmatite described in the Breckenridge quadrangle by (Bergendahl (1963), and possibly with a border phase of the Cross Creek Granite in the Minturn 15-minute quadrangle to the northwest, which has been correlated to the Boulder Creek batholith of the Front Range (U-Pb age of 1,714.4 ± 4.6 Ma; Premo and Fanning, 2000) by Tweto and others, 1970).

Figure 15. Porphyritic granodiorite with porphyroblasts of potassium feldspar (white).

PROTEROZOIC METAMORPHIC ROCKS

Includes metasedimentary and metavolcanic rocks of the Proterozoic gneiss complex of Tweto (1987). Biotite gneiss, which underlies the majority of the Mosquito Range in the western part of the quadrangle, is the most common of the metamorphic rocks. Rocks generally north and northwest of Mount Lincoln tend to be migmatitic. 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, medium-grained gneiss characterized by the intimate layering of locally schistose, dark-colored laminae containing biotite, hornblende, plagioclase, and quartz and light-gray, medium-grained to pegmatitic material composed primarily of quartz, plagioclase, and microcline. 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. Locally, this unit grades to or includes layers of porphyritic granodiorite. Migmatite gneiss is similar in lithology and mineralogy to biotite gneiss but has a higher percentage of felsic material (greater than about 20%) and is more strongly contorted (fig. 16). The contacts between migmatite, biotite gneiss, and porphyritic granodiorite are everywhere gradational, and a given type of gneiss is frequently found within the overall boundaries of another.

Figure 16. Migmatite. Note higher percentage of felsic material and greater degree of deformation than in biotite gneiss.

Xb Biotite gneiss (Early Proterozoic)—Medium- to dark-gray, medium-grained, well foliated gneiss composed primarily of quartz, plagioclase, and biotite, with accessory magnetite, sillimanite, garnet, and/or cordierite (fig. 17). This gneiss is similar in lithology and mineralogy to migmatite but has less felsic material and exhibits a lesser degree of deformation. The contact between the two units is everywhere gradational, and one type of gneiss is frequently found within the overall boundaries of the other. Locally, biotite gneiss contains layers or zones of augen or "bright-eye" gneiss, particularly in the northwestern part of the quadrangle. The augen "eyes" are light in color and are characterized by a rim of plagioclase enclosing magnetite. Individual augen are generally less than 1 inch long and 0.5 inches wide, but may be up to 1.5 inches long in maximum direction (fig. 18).

Figure 17. Biotite gneiss is commonly thinly laminated and is not as severely deformed as migmatite.

Figure 18. Zone of augen, or "bright-eye" gneiss within an overall package of biotite gneiss. Outer white rim is plagioclase, reddish center is plagioclase stained by alteration of magnetite; the magnetite is not generally visible in hand specimen.

Xph Layered plagioclase and hornblende gneiss (Early Proterozoic)—Mapped only at one locality on the northeast side of Buckskin Gulch. This package of rocks appears to have been caught up in and highly altered (sericitized) by the Buckskin Gulch intrusives (Td). The unit consists of light-gray, fine-grained quartz-microcline-plagioclase or quartz-plagioclase gneiss interlayered with greenish-gray to greenish-black, fine-grained amphibolite to hornblende-plagioclase gneiss. Individual layers are typically on the order of a few centimeters, but may range up to about one meter in thickness.

STRUCTURAL GEOLOGY

The geology of the Alma quadrangle generally defines a north-northeast-striking, eastward-dipping (approximately 15 to 25 degrees) homoclinal sequence of Paleozoic strata overlying an east-tilted block of Precambrian crystalline rocks in the Mosquito Range. In general, the

Precambrian and lower Paleozoic rocks crop out in the western half of the quadrangle, whereas Pennsylvanian-Permian sedimentary rocks are found in the eastern half of the quadrangle. The entire section has been intruded by numerous and varied Tertiary igneous rocks as sills, dikes, and small stocks. Paleomagnetic work (Oppenheimer and Geissman, 1988) suggests that the Mosquito Range was tilted prior to magmatic emplacement sometime during the Laramide orogeny. The actual duration of orogenesis within the quadrangle appears to have been quite short – on the order of 5 to 10 million years (Oppenheimer and Geissman, 1988). Following tilting (and possibly associated reverse faults), there was a prolonged series of igneous intrusions of various compositions lasting from approximately 65 Ma to 25 Ma. The latest of these igneous intrusions were the high silica rhyolite bodies at Climax, northwest of the quadrangle, which host world-class molybdenum deposits.

The Climax orebody has been rotated approximately 20 degrees to the southwest (Wallace and others, 1968, White and others, 1981). This implies another much younger tilting event (post-25 Ma) than the earlier event affecting the Mosquito Range, which tilted rocks to the east. It is not clear if this latest tilting event is expressed within the Alma quadrangle. On the basis of paleomagnetic data, (Oppenheimer and Geissman, 1988) stated that the post-25 Ma tilting event only involved local deformation related to extension and drag along the Mosquito fault, which bounds the western margin of the Mosquito Range. This localized deformation would therefore not likely be expressed within the Alma quadrangle, which is on the opposite side of the Mosquito Range. In contrast, Bookstrom (1989) believes that the general flattening of dips in Paleozoic rocks at the top of the Mosquito Range (particularly evident near Mount Cameron) indicates that the entire Mosquito Range was tilted approximately 9 degrees to the east following the southwest tilting event expressed at Climax.

The broad, glacial valley containing the Middle Fork of the South Platte River is generally considered the eastern boundary of the Mosquito Range. Various authors consider this valley to be underlain by a structural break that forms a half-graben, similar to what has been proposed for the Blue River north of Breckenridge (see Kellogg, 1999). Authors such as Singewald (1951) and Taranik (1974) have projected the Blue River fault (also known as the Frontal fault) southward from Breckenridge to beyond Alma. However, our mapping negates the idea that this valley is formed along a major north-south fault zone. Although there is evidence for faulting adjacent to Highway 9 north of Hoosier Pass, the structure there does not appear to be a major through-going fault, nor do cross sections indicate significant offset within the Paleozoic rocks at this locality or farther south on either side of the valley (see cross section A-A'). Work by Wallace and others (in press) in the Breckenridge quadrangle to the north indicates that whereas there is significant offset in the Blue River valley near Breckenridge in the northern part of the quadrangle, there is minimal to no offset within the Blue River valley at Quandary Peak at the southern edge of the quadrangle (compare section A-A' to B-B' in Wallace and others, in press).

A network of numerous variably oriented faults, some with significant displacement, cross cut the Alma quadrangle. Although local relations are variable, the general timing relations of faults from oldest to youngest are as follows: east-west, north-northeast, northeast, north-northwest, northwest, east-northeast and lastly, north-south. Northeast- and northwest-trending faults are roughly contemporaneous with igneous activity, which suggests an Eocene age for most of the faulting. The north-south faults by analogy beyond the quadrangle (Kellog and others, 2002, Wallace and others, in press) are probably related to extension and may well postdate 25 Ma. Northeast and north-northeast faults typically have minor displacement and offset but are the most predominant in the area and appear to define the dominant structural grain, particularly in the western part of the quadrangle. In contrast, the area centered on Mount Bross is a zone of wedge-shaped fault slivers, many with horst and graben features, northeast or northwest strikes and significant displacement.

One of the more significant faults in the quadrangle is the Cooper Gulch fault, which is located in the southwestern part of the quadrangle. The Cooper Gulch fault is a complex, northwest-trending (N5° to 40°W; average is N30°W) reverse fault with a total strike length on the order of 4 miles. The axis of an overturned, asymmetric fold is associated with and parallel to the fault. Timing relations established by Patton and others (1912) suggest that the fold was created first and then later faulted along its axis, probably during the Laramide orogeny. The Cooper Gulch fault dips 15° to 25° east in Paleozoic rocks, but is much steeper (nearly vertical) in the underlying Precambrian rocks (Patton and others, 1912).

A nested dome complex, termed the inner and outer Alma domes, has been proposed by Bookstrom (1989) for much of the area within the quadrangle. The domes, which are centered on Mount Bross, were defined by near-radial drainages such as the Monte Cristo Gulch to the north, and the Mosquito Gulch drainage to the south for the outer Alma dome, and the Platte (north) and Buckskin Gulch (south) drainages for the inner Alma dome. The eastern boundary of both domes was defined as the Middle Fork of the South Platte River valley; the western boundaries could not be well defined. Bookstrom and others (1988) and Bookstrom (1989) related the doming to a non-exposed, granitic batholith intruded about 35 Ma. This batholith would be the source of the late white porphyry dikes (Tlw). In addition, the slightly later Climax intrusions were proposed as emanating from a separate apotheosis off this batholith. However, the Mt. Bross area has been tectonically active since at least the Paleozoic and intermittent uplift on individual fault blocks is believed a more likely explanation for the so-called Alma domes. For example, whereas the Cambrian Dotsero Formation maintained a constant thickness throughout the quadrangle and throughout the region (Myrow and others, 2003), the overlying unit, the Manitou Formation is significantly reduced in thickness in the vicinity of Mounts Lincoln and Bross. Stratigraphic studies have not been sufficient to determine whether the Manitou Formation was reduced by subsequent erosion (as is suspected) or by non-deposition. The unit overlying the Manitou Formation, the Parting Sandstone, is completely absent on Mount Lincoln. Singewald (1931) suggested that the Parting Sandstone was simply not deposited. The Mount Lincoln area is therefore inferred to be a paleohigh in Devonian time. The thickness of the Dyer Dolomite, the next unit upwards in the section, is relatively constant throughout the quadrangle, suggesting tectonic quiescence at this time. However, the overlying Leadville Limestone thins dramatically from as much as 200 ft in the southern part of the quadrangle to less than 50 ft to the north, which indicates that the Mount Lincoln block was again uplifted. The Leadville Limestone has indications of karsting (an important ore control in the district), but the karst soil horizon (Molas Formation) is absent in the quadrangle. Farther upwards in the section, the stratigraphy of the Minturn Formation has been inadequately resolved to determine whether there has been Pennsylvanian–Permian uplift in the area, but the absence of the Belden Formation within the quadrangle certainly suggests continued uplift during this time. Regardless, the observed changes in formation thickness and absence of some formations locally point to the fact that individual fault blocks were periodically uplifted through time. Whether the last uplift event was caused by the emplacement of a batholith is uncertain. Paleomagnetic data suggests that tilting of the Paleozoic rocks preceded Tertiary uplift (Oppenheimer and Geissman, 1988); and thus the idea of inflation related to intrusion would appear to be negated. There probably exists a batholith at depth under the quadrangle as proposed by Bookstrom (1989); however, its overlying structural expression (if any) would likely have been through activation of individual fault blocks in a piston-like manner as opposed to range-wide inflation.

ECONOMIC GEOLOGY

METALLIC MINERALS

Mining has been an important component of the Alma quadrangle's history; it continues to this day. There are a multitude of mineral deposits and mineral deposit types within the quadrangle and portions of three mining districts (fig. 19): the Alma district (western side of the quadrangle, extending south from Mt. Lincoln, fig. 20); the upper reaches of the Tarryall district (northeast corner of the quadrangle, includes the small placers on Beaver Creek south of Mt. Silverheels); and a small portion of the Upper Blue River district (far north central portion of the quadrangle). The age of the deposits and igneous associations are different within each district.

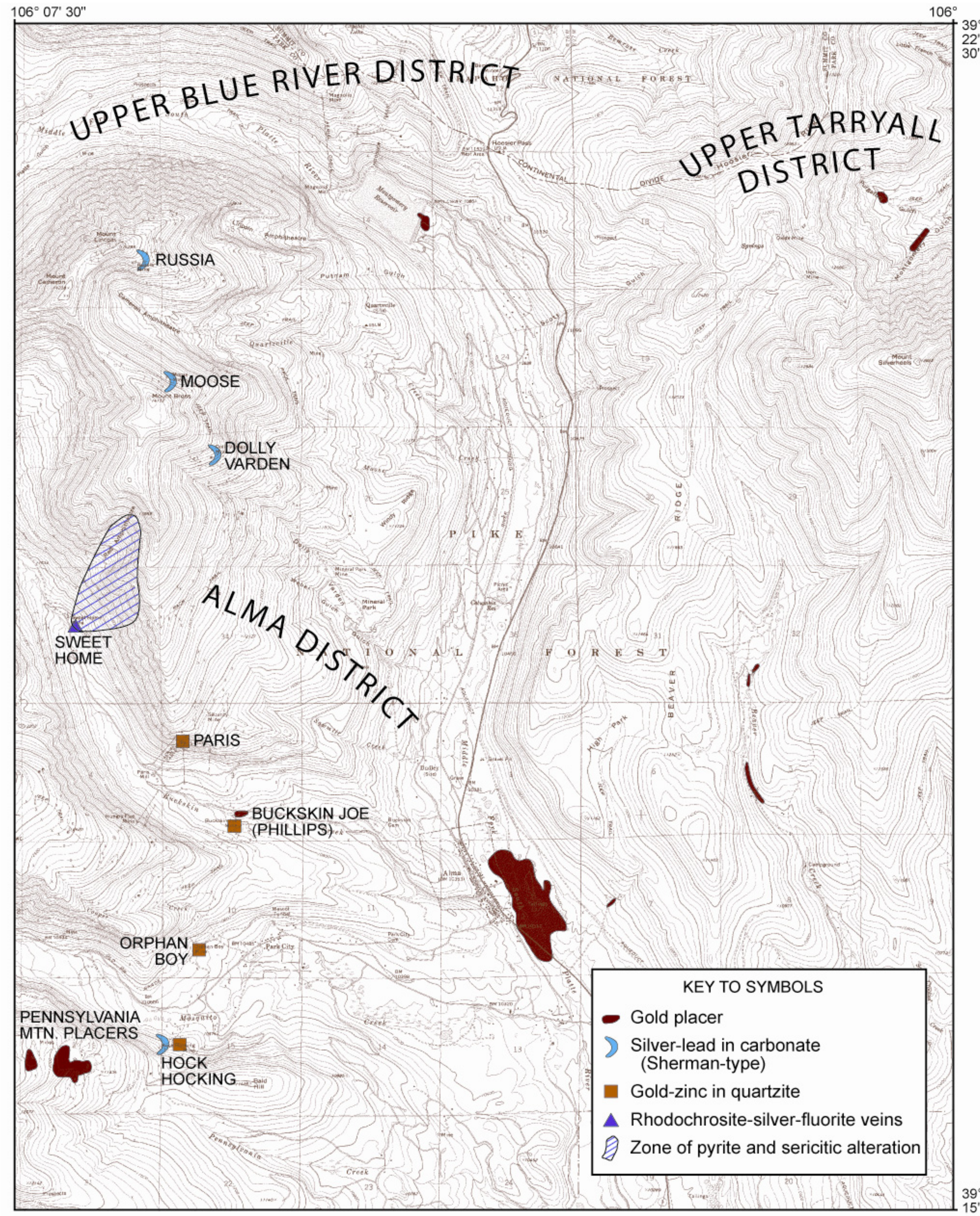

Figure 19. Generalized metallogenic map showing major mines and mining districts of the Alma quadrangle.

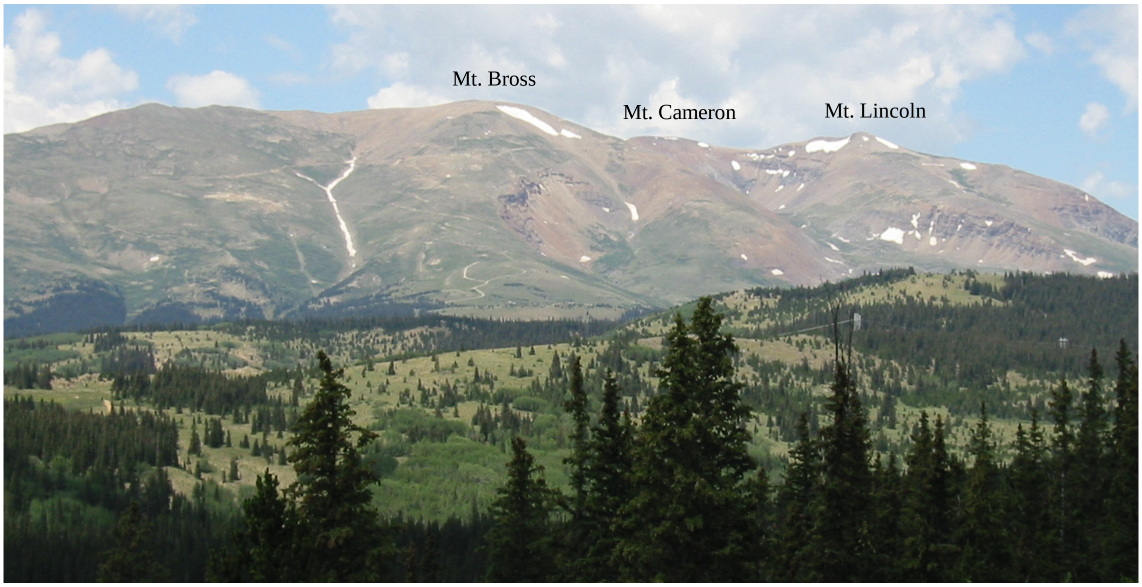

Figure 20. View looking west at the Alma mining district, which extends southward from Mount Lincoln.

MINING HISTORY

Placer gold was discovered in South Park in 1859; first on Tarryall Creek, then somewhat later on the South Platte River near Alma. Placer mining has continued up to the present day; peak production was from 1935 to 1942 (Parker, 1974). Hard-rock mining in the quadrangle started in 1860 with the discovery of the Phillips lode (also known as the Buckskin Joe mine). On the surface, this deposit consisted of a gossan in quartzite and shale with gold-bearing pyrite. Similar deposits such as the Paris (1861) and Orphan Boy (1862) were soon discovered nearby. These early ores were oxidized and worked by sluicing or grinding in arrastras followed by amalgamation; the remains of one such arrastra can still be seen in Buckskin Creek near the Paris mill. Operations ceased when the miners encountered unworkable primary sulfides, and the area was mostly deserted by 1867 (Shawe, 1990). In 1871, silver was discovered high on the peaks of Mounts Bross and Lincoln. These were the first silver mines in the state. Major mines were the Moose, Dolly Varden and the Russia. Accompanying the silver mining was the construction of smelters (principally in and near the town of Alma); this allowed reopening of the previously discovered gold deposits. Silver ores were principally worked from 1871 to 1893, when the

Silver Crash (a reduction in silver prices by approximately 50%) occurred. During this period, approximately 200,000 tons of high-grade silver ore were mined; this yielded 9 million ounces of silver (Johansing and Thompson, 1990). Significant mining of the gold lodes and placers continued up until World War II; the 1930s were a particularly active period for placer operations.

Small and sporadic mining has taken place in the area since World War II. Placer deposits at Alma, Buckskin Joe, and Pennsylvanian Mountain were active in the 1980s (A. Bookstrom, 1983, private Climax report) with activity on the Pennsylvania Mountain placers continuing almost to the present day. The Sweet Home mine has been mining beautiful gem-quality specimens of rhodochrosite for the last thirteen years; this remains the last active hard rock mine in the area. Although mining has virtually ceased within the quadrangle, mineral exploration has been quite active up until recent times. During the 1980s, the area was extensively explored by many mining companies. Many of the old mines such as the Morning Star, Hock Hocking, Russia and Moose were reopened, explored, and/or mined on a small scale; there was drilling for porphyry molybdenum deposits in Buckskin Gulch as well as possible bulk tonnage gold deposits in the Tarryall district. Total production for the quadrangle is estimated to be on the order of $17 million.

ALMA DISTRICT

The most widely distributed mineral deposits within the quadrangle (excluding placers) are carbonate-hosted silver-lead-zinc sulfide deposits. Ore bodies typically are found in the upper part of the Leadville Formation as blanket-like replacement bodies in and near faults and fractures. Individual ore bodies are typically meters to 100 meters long and form a series of pods aligned along faults that shattered and slightly displaced the limestone. This produced an overall orebody configuration similar to that of karst caves. In fact, Tschauder and others, 1990) proposed that some of the largest mines in the area (Russia, Moose, Dolly Varden) were paleo-cave systems.

Silver ore grades were as much as 700 oz/ton Ag, but typically less than 100 oz/ton Ag. The higher grades were commonly the result of supergene enrichment. Hypogene ore grades were considerably lower. For example, ore mined from the Russia mine in 1922 averaged 0.05 oz/ton Au and 14-18 oz/ton Ag (U.S. Bureau of Mines, 1943 reported in Shawe, 1990), whereas the Moose mine, located 1 mile southeast of the Russia mine, had ore that in 1942 assayed 5.2 oz/ton Ag, 0.6% lead, 28.3% zinc, and 1.5% iron (U.S. Bureau of Mines, 1943 reported in Shawe, 1990). Hypogene ore typically consisted of yellow to light olive green sphalerite, galena and pyrite in a gangue consisting of abundant ankerite, ferroan dolomite, and barite. Silver occurred in tetrahedrite. Common secondary minerals are cerussite, anglesite, smithsonite, hemimorphite, malachite, covellite, chalcocite, jarosite and native silver. Among the sulfides, pyrite was deposited firest, followed by sphalerite, tetrahedrite, chalcopyrite and galena. Typically the sulfides occurred as small clusters through the carbonate and barite gangue (Singewald and Butler, 1931). These deposits strongly resemble the paleokarst-hosted sulfide deposits found on Mount Sherman to the south (Behre, 1953; Landis and Tschauder, 1990).

There is considerable debate in the literature regarding these “Sherman-type" deposits. Tschauder and others (1990) and Landis and Tschauder (1990) argued for a late Mississippian to Early Pennsylvanian formation age and a formation mechanism similar to Mississippi Valley type lead-zinc deposits, which were formed by deeply circulating regional brines derived from evaporated seawater. In contrast, Johansing and Thompson (1990) argued that although the Alma deposits are hosted by pre-Pennsylvanian karst breccia, crosscutting relations and geologic setting constrains the age of mineralization to the Tertiary. These authors proposed a model of the Paleogene batholith acting as a heat source and drawing basinal brines updip from the South Park basin to the east. In support of Johansing and Thompson (1990) is the close spatial association of deposits to igneous intrusions, particularly dikes of quartz monzonite. The debate is complex but hinges in part on whether barite-sphalerite-galena-quartz veinlets cutting altered megacrystic (Tqpm) porphyry capping orebodies at the Russia and Moose mines (Johansing and Thompson, 1990, p.383) are synchronous with deposition or represent mobilization of earlier mineralization, or possibly another mineralizing event. Locally, on the east slope of Mount Bross, early yellow to olive-green sphalerite is rimmed and partially replaced by later, dark-brown sphalerite (Brookstrom, 1990). This supports two episodes of sphalerite deposition but not necessarily two separate mineralizing events. The two episodes could have been part of one chemically evolving event.

In addition to the Sherman-type deposits, there are silver-gold bearing mantos (strata-bound orebodies) in the lower Paleozoic carbonates containing dark-brown sphalerite, pyrite, galena, dolomite, barite, and minor chalcopyrite, as seen at the Hock Hocking mine (Machado, 1967), as well as gold-bearing pyritic deposits in dolomitic shales and quartzites of the Dotsero and Sawatch Formations (Orphan Boy, Phillips, Paris, and Atlantic and Pacific).

Typically mineralization in these deposits is in beds adjacent to minor, steeply-dipping, northeast-trending faults, or within the faults themselves, particularly where the faults pass from one rock type to another and change strike and dip (Machado, 1967). Replacement apparently was favored in beds that contained calcareous cement. There was considerable variation in gold and silver grade, although overall gold content was significant. For example a 1.5-ft-wide vein in the Orphan Boy mine in 1942 averaged 0.3 oz/ton Au, 10 oz/ton Ag, 10 % lead, and 35 % zinc, whereas one replacement body in the same mine averaged 0.05 oz/ton Au, 6 oz/ton Ag, and 3% zinc and another replacement layer assayed 0.15 oz/ton Au, 6 oz/ton Ag, 5 % lead, and 17 % Zn (U.S. Bureau of Mines, 1943 reported in Shawe, 1990). Overall, these deposits strongly resemble the deposits at Gilman where gold-bearing pyritic veins underlie dark brown sphalerite-pyrite-galena mantos. Thus, there appears a suggestion of a stratigraphic control on the style of mineralization. Alternatively, the Sherman-type mantos may represent cooler, more dilute hydrothermal fluids deposited higher in the section and more distal form the fluid/heat source.

The Sweet Home mine, located in the upper portion of Buckskin Gulch, is a vuggy quartz-fluorite-tetrahedrite-fluorite vein in Precambrian rocks (Kosnar, 1979; Moore and others, 1998). Historically, it was a small-scale silver mine, yielding a total production on the order of $200,000 (Voynick, 1978). However, associated with the silver mineralization are bright ruby-red, gem-quality crystals of rhodochrosite. These rhodochrosite crystals are among the world's best; the Sweet Home mine is renowned among mineral collectors. The Colorado legislature in 2002 declared rhodochrosite to be the state mineral; this in large part reflects the fame generated by Sweet Home specimens. Since 1990, the Sweet Home mine has been operated as a mineral specimen mine. Approximately 20,000 tons have been mined (Bryan Lees, 2003, personal communication); cumulative value of rhodochrosite specimens mined up to 1998 was estimated by Voynick (1998, p.20) as exceeding $5 million.

The Sweet Home hydrothermal system, including the broadly sericitized and iron-stained (after disseminated pyrite) rocks in Red Amphitheater above the Sweet Home mine as well as the quartz-molybdenite veins to the north at Kite Lake, is believed to represent a failed porphyry molybdenite system of the Climax type. Supporting evidence for this interpretation include age dates of alteration and early vein fillings of 27 to 31 Ma (the same as Climax); the presence of a pebble dike close to Sweet Home; abundant fluorite, huebnerite and topaz (the F, W, Mo geochemical signature of Climax deposits); pervasive sericitic and greisen alteration; local Mo-bearing pegmatites, and isotopic evidence showing a magmatic component to the rhodochrosite deposition (Misantoni and others, 1990). Climax Molybdenum Company drilled three holes in this area from 1978 to 1980. Weak chloritic, phyllic, propylitic and potassic alteration was encountered. Pyrite, sphalerite-galena ± chalcopyrite, and fluorite-molybdenite ± rhodochrosite veinlets were widely and sparsely scattered throughout the drill holes, but no significant molybdenite mineralization was encountered (Bookstrom, 1983, private Climax report).

UPPER BLUE RIVER DISTRICT

Within the Precambrian rocks in the far northern part of the quadrangle are a series of small gold and silver base metal veins typically bearing dark-brown sphalerite, pyrite, quartz, and locally, minor molybdenite and huebernite (Singewald, 1951). Alteration haloes associated with these veins are superimposed on White porphyry dikes and nowhere do these dikes cut the veins (Bookstrom, 1989). The veins are thus younger than the 35 Ma dikes; mineralization here is believed associated with the early stages of Climax-style mineralization (Bookstrom, 1989).

TARRYALL DISTRICT

There has been limited placering from Purgatory Gulch and the upper reaches of Montgomery Gulch; this constitutes the far western end of the Tarryall district. Overall, the Tarryall district yielded on the order of $1.5 million in gold (this at times when the price per ounce ranged from $20 to $36 {Parker, 1974}); however, very little of this production is believed to have originated from within the Alma quadrangle. There is a large monzonite porphyry stock north of Montgomery Gulch immediately east of the quadrangle; this stock and associated dikes and sills have contact metamorphosed the surrounding Minturn and Maroon Formations to an epidote-chlorite hornfels. This hornfels is locally cut by numerous small pyrite-quartz veinlets; gold appears associated with these veinlets as well with small pods of magnetite-garnet. The district has been explored and drilled by Homestake for bulk tonnage gold deposits; results of this work are unknown.

PLACERS

All told, approximately $900,000 in gold at then current prices has been mined from placers within the quadrangle (Parker, 1974). Of this amount, the vast majority ($850,000) came from the placer immediately east of the town of Alma (fig. xx). Gold in the placer deposits doubtless was derived from erosion of lodes in the Alma district as well as from the quartz-pyrite veinlets in the hornfels surrounding Mt. Silverheels. Distribution of the placer gold has been largely controlled by glacial processes (Singewald, 1942).

Of particular interest are the placers located high on the flanks of Pennsylvania Mountain in the extreme southwestern corner of the quadrangle. The gold from this placer is commonly extremely coarse, angular and nuggety. An 11.95 oz nugget was recorded from this placer in 1937 (Parker, 1974), and an 8 oz nugget found in 1990 from this locale is currently on display at the Denver Museum of Science and Nature. A nearby source is suggested. The placer deposit is composed of colluvial glacial gravels filling a small trough on the hillside. The Cooper Gulch fault is on the eastern boundary of the placer ground; it seems likely that gold in the placer was derived from the nearby erosion of orebodies hosted within splays of the Cooper Gulch fault.

INDUSTRIAL MINERALS

The Alma region is host to relatively abundant industrial mineral (or construction material) resources. **Sand and gravel** is the most widely mined of the industrial minerals in the area as evidenced by the numerous historic sand and gravel operations throughout the Alma quadrangle. Additionally, sand and gravel is currently mined at the Alma Placer pit near the town of Alma. Sand and gravel resources are typically associated with stream alluvium (Qa) and till (Qt1, Qt2), both of which are extensive along the Platte River valley. These deposits may be used to serve a variety of aggregate needs such as road base and ingredients in asphalt and concrete.

Rocks similar to the Proterozoic rocks underlying much of the Mosquito Range have been used throughout Colorado as a source of **crushed stone**, which may be used for riprap, road base, decorative landscaping, and numerous other aggregate needs. Additionally, the Sawatch Quartzite (Ꞓs) may be a good source of crushed stone.

Limestone and dolomite (Ml, OꞒm) have a wide variety of applications such as dimension or crushed stone; ingredients in cement and concrete; coal mine dusting to prevent coal fires; soil conditioning, and metallurgical and chemical processes. Historically, the Leadville Limestone (Ml) was used to make fluxing agents for local smelters. Thin limestone beds in the Minturn Formation (ℙm) may be of sufficient quality for industrial uses, but their limited and discontinuous nature generally makes them economically undesirable.

Several **peat** mining operations are or have been active in Park County, and peat was mined as recently as the early 1990s at Branaman Pond just south of the quadrangle. In the Alma quadrangle, peat resources are associated with surficial unit Qao. Peat is primarily used in potting soil mixtures and as a soil conditioner.

GEOLOGIC HAZARDS

Floods, debris flows, and landslides are the principal geologic hazards in the Alma quadrangle. Also, rock glaciers, although far from populated areas, may be hazardous to power lines, pipelines, and towers for communication systems. The area of flood hazard is much smaller than that of debris flows and potential landsliding. However, flooding is more predictable and frequent than landsliding, and risk tends to be higher. Risk as used here refers to the potential for loss of life and property should floods, debris flows, or landslides occur. Obviously, risk is higher in populated areas than in unpopulated areas simply because there is more at stake.

FLOODING

In the Alma quadrangle, the overall flood hazard along streams is low because peak flows of streams at this altitude are related to snowmelt runoff rather than to rainstorms (Jarrett, 1993; Andrews, 1984). Peak flows from snowmelt runoff are predictable in timing and magnitude, and are relatively similar from year to year. The 100-yr flood (i.e., flood magnitude that has 1% chance of occurring in any given year) tends to be only a few percent larger than the mean annual flood (Pitlick, 1993). Consequently, flood plains in the Alma quadrangle are not much wider than the streams that formed them. As used here, the term flood plain applies to the flat area adjacent to a stream channel that (1) was formed by the stream under the present climate and (2) is flooded frequently (Dunne and Leopold, 1978). According to this definition, areas that are flooded only by rare events such as the 50-, 100-, or 500-yr floods are not part of the flood plain. The flood plains of the Alma quadrangle and the low terraces (1 to 5 ft high) that flank them generally are wetlands. As such, they are much less desirable for home sites than most other terrain in the area. Thus, along most streams, the primary flood risk is to the bridges and culverts through which streams flow.

Damaging floods are more likely to be caused by the failure of small, low (and thus unregulated) earthen dams and unplanned impoundments dammed by mine waste than by stream flow. Also, the risk of flood damage on some deposits of Qdf is higher than on unit Qa. The recurrence interval of intense thunderstorms in the small drainage basins that were the sources of Qdf is long, and thus, the evidence of the floods and debris flows that formed them is obscure. Consequently, residences have been constructed on them in places.

DEBRIS FLOWS

Debris flows (Qf) are dense mixtures of sand, silt, clay, rock debris, and lesser amounts of water and air that move as a fluid mass. Debris flows commonly resemble wet concrete that varies in degree of fluidity depending on the proportions of debris and water present. The amount of debris (material larger than 2 mm) in debris flows may range from as little as 20 percent to as much as 80 percent (Cruden and Varnes, 1996). Flows in which less than 20 percent of the material is debris are called mudflows in some mass-movement classifications (Selby, 1993).

Most debris flows in the Alma quadrangle originate in the upper reaches of gullies and small valleys that drain steep, sparsely vegetated slopes. Debris-flow deposits are major constituents of fan-shaped masses that accumulate where large gullies and tributary valleys join the main valleys of the area. Debris-fan deposits and, in places, much of the colluvium in Qac consist of debris-flow deposits. The recurrence interval of debris flows depends primarily on the frequency of intense rain or heavy snowmelt and the time required to replenish the supply of debris swept away by the previous debris flow.

LANDSLIDES

Landslide classifications include most forms of mass movement, and, thus, the term landslide is applied to all but the slowest forms of mass movement regardless of whether movement was by fall, flow, or slide. In this discussion, debris flows and landslides are treated separately, except where they are components of complex mass movements as defined by Cruden and Varnes (1996). Many slopes in the Alma quadrangle are susceptible to failure for a variety of reasons, including weak rocks, high relief, steep slopes, and locally abundant moisture. Much of the Minturn and Maroon Formations consist of materials that are fine grained and weakly cemented. Oversteepened slopes caused by erosion-resistant strata within and overlying these formations also contribute to landsliding. Furthermore, some of the strata in these formations may contain expansive clay minerals, which can reduce rock strength and slope stability.

Many landslide deposits (Qls) in the quadrangle probably are relicts of the Pleistocene (in other words, they formed under different conditions of climate and vegetation than exist today), and are stable under present conditions. However, stable slopes, whether underlain by surficial deposits or bedrock, can be destabilized by human activities that replicate the wetter conditions that prevailed at times during the Pleistocene. Examples of such activities include irrigation, installation of septic systems, and diversion of surface runoff by roads, ditches, and various other land-surface modifications.

Landslides that occurred in the past century provide clues as to where landsliding is apt to occur in the future. In addition, the nature and distribution of landslide deposits in general, regardless of age, offer insights into the probable causes of slope failure. The natural events that trigger landslides are well known. The principal natural triggering events worldwide include intense rainfall, rapid snowmelt, water-level changes, and strong ground shaking during earthquakes (Wieczorek, 1996). In addition, human activities commonly trigger landslides.

Unfortunately, humans continue to trigger landslides by neglecting simple fundamentals that have been well understood for decades (Brunsden, 1993). Erly and Kockelman (1981) discussed some of these triggering activities, including (1) the use of earth fills for construction, (2) construction of buildings, roads, and other structures, (3) use of septic systems, and (4) landscaping activities, such as watering lawns, excavating, or cutting benches into hillsides. Most of the activities either add weight to the natural slope, which increases the shear stress in the area where the weight was added, or they remove support by excavating material, which reduces shear strength (the force that resists downslope movement of material). Excavations in footslope areas or at the toe of a slope are particularly troublesome. The weight of earth material commonly is overlooked when material is being rearranged by excavation and filling during construction. A layer of earth fill one-foot thick is equivalent in weight to that of a single-story home of equal area (Erly and Kockelman, 1981). Also, activities that cause water, either from ground-water or surface-water sources, to be concentrated in localities that had not been heavily soaked before can cause slopes to fail. The added weight of the water increases shear stress and increased pore-water pressure reduces shear strength.

ROCK GLACIERS

Rock glaciers (Qrgw, Qrgf) are hazardous to any structure placed on or in them because (1) they are moving and (2) disturbance invariably leads to melting of the frozen substrate and subsequent differential settling or collapse. Towers for communication systems or the transmission of electricity should not be located on rock glaciers. Likewise, it is best if water-supply lines, gas pipelines, and tunnels not cross rock glaciers. Roads in ski areas or those constructed to service mines, power lines, and pipelines also should avoid penetrating or crossing rock glaciers, and care should be taken not to allow incidental or deliberate ponding of surface water against rock glaciers. Structures placed near rock glaciers also may be at risk from the slow but progressive advance of the rock glacier itself or from materials that slough from it (Giardino and Vick, 1987).

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