Climax Quadrangle Geologic Map, Lake and Park Counties, Colorado

Author's Notes

Includes Description of Map Units, Structural Geology, Geologic Hazards, Mineral Resources, and Ground Water Resources

by

James P. McCalpin, Jay Temple, Karri Sicard, Davis Mendel, Bashir Ahmad

Colorado Geological Survey
Department of Natural Resources
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Panoramic photo of the Climax molybdenum mine (left) and the head of the East Fork Arkansas River (right center), looking southeast and south from Fremont Pass [UTM27 397710, 4357950]

by
James P. McCalpin\textsuperscript{1}, Jay Temple\textsuperscript{2}, Karri Sicard\textsuperscript{3}, David Mendel\textsuperscript{3}, Bashir Ahmad\textsuperscript{4}

1 GEO-HAZ Consulting, Crestone, Colorado
2 Consulting geologist, Woodland Park, Colorado
3 Colorado Geological Survey, Denver, Colorado
3 University of Kashmir, Kashmir, India

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The purpose of Colorado Geological Survey’s (CGS) Climax Quadrangle Geologic Map, Lake and Park Counties, Colorado is to describe the geology, mineral and ground-water resource potential, and geologic hazards of this 7.5-minute quadrangle located northeast of Leadville in central Colorado. Consulting geologists James P. McCalpin and Jay Temple, and field assistants Karri Sicard, David Mendel, and Bashir Ahmad completed the field work on this project during the summer of 2007. Dr. McCalpin and Mr. Temple, the principal mappers and authors, created this report using field maps, photographs, structural measurements, and field notes generated by all three investigators.

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Vince Matthews
State Geologist and Director
Colorado Geological Survey
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We thank local landowners Cecil Clifford (Leadville, CO) and Ben Wright (Denver, CO) for access to their private land and patented mining claims. The Parkville Water District graciously permitted access to its property at the head of Evans Gulch. John Morrissey, District Ranger of the Leadville District, San Isabel National Forest, provided us with aerial photographs of the Forest lands.
INTRODUCTION

The Climax 7.5’ quadrangle is located astride the Mosquito Range of central Colorado, between the towns of Leadville (Lake County) and Alma (Park County) (Fig. 1). The Climax quadrangle is part of the old USGS Leadville 30’ quadrangle (e.g., Capps, 1909; Tweto and Case, 1972), and the SW quarter of the USGS Mount Lincoln 15’ quadrangle (e.g., Tweto, 1974). Parts of the quadrangle had been previously mapped at large scales as part of various mining districts (Table 1), and several adjacent quadrangles have been recently mapped at 1:24,000 scale (Fig. 2).

Table 1. Previously published geologic maps that cover parts of the Climax 7.5’ quadrangle.

<table>
<thead>
<tr>
<th>Part of quadrangle mapped</th>
<th>Scale of Map</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extreme SW corner (Leadville Mining District)</td>
<td>1:9600</td>
<td>Emmons et al., 1927</td>
</tr>
<tr>
<td>SW corner (West Slope of Mosquito range)</td>
<td>1:12,000</td>
<td>Behre, 1953</td>
</tr>
<tr>
<td>NE corner (Climax Mine area)</td>
<td>1:12,000</td>
<td>Butler and Vanderwilt, 1933</td>
</tr>
<tr>
<td>Northern 1/6 (Kokomo-Tenmile Mining District)</td>
<td>1:24,000</td>
<td>Bergendahl and Koschmann, 1971</td>
</tr>
<tr>
<td>Eastern 1/3 (Alma-Horseshoe Mining District)</td>
<td>1:24,000</td>
<td>Singlewald and Butler, 1941</td>
</tr>
<tr>
<td>Western half (Lake County part; compilation)</td>
<td>1:50,000</td>
<td>Cappa and Bartos, 2007</td>
</tr>
<tr>
<td>Entire quadrangle (SW ¼ Mt. Lincoln 15’ quad)</td>
<td>1:62,500</td>
<td>Tweto, 1974</td>
</tr>
</tbody>
</table>

The Climax quadrangle is dominated by the Mosquito Range, a component range of the Southern Rocky Mountains composed mainly of Precambrian crystalline rocks. (Fig. 3). This range probably existed as a topographic high during the Laramide orogeny (late Cretaceous—early Tertiary), based on the presence of reverse faults of that age (London fault). However, the present topography of the range is the result of Neogene uplift along the west-dipping Mosquito and Weston faults on the west side of the range, both normal faults related to the Rio Grande rift. Uplift of 9,000 ft along the Mosquito fault has juxtaposed the Precambrian rocks of the footwall against the Pennsylvanian Minturn Formation, which underlies most of the western half of the Climax quadrangle. Both the Precambrian and Permian rocks are laced by early Tertiary dikes, sills, and stocks, the source of mineralization in the Leadville, Climax, and Alma-Horseshoe mining districts. In the eastern half of the quadrangle (east of the Mosquito fault), most terrain is composed of the Precambrian core of the Mosquito Range. However, in small areas strata of Cambrian through Pennsylvanian age are preserved atop the Precambrian unconformity.
Fig. 1. Shaded relief map of the region surrounding the Climax quadrangle (red outline).
Fig. 2. Location map and index of selected published geologic maps in the vicinity of the Climax quadrangle (yellow).
Fig. 3. Panoramic photograph of the East Fork Arkansas River and the Mosquito Range front. The range front rises steeply above the Mosquito fault (arrows), a Neogene fault with at least 9000 ft of displacement, and is composed predominantly of Precambrian igneous and high-grade metamorphic rocks. View is toward N25E, from the tracks of the Leadville, Colorado & Southern Railroad [UTM27 394160, 4350910]. The tracks of the LC&S railroad can be seen traversing the forested slopes in the middle distance, which lie on the hanging wall of the Mosquito fault and are underlain by the ca. 5000 ft-thick Minturn Formation (Pennsylvanian), intercalated with sills of Tertiary porphyry. Minturn strata are broadly folded in this field of view, with dips to the SW and E-NE. The wide valley of the East Fork Arkansas River was eroded 1000-1400 ft deep into fault hanging wall by a succession of Pleistocene valley glaciers (terminal moraines lie downstream of the Climax quadrangle). This deep incision “daylighted” west-dipping strata, especially on the east valley wall (at center), leading to extensive pre-glacial and post-glacial landsliding. The valley floor was later aggraded by a combination of latest Pleistocene lake sediments and glacial outwash, to form its present wide, flat landform. Photograph taken 06-SEPT-2007.
DESCRIPTION OF MAP UNITS

In the following section we describe the characteristics and spatial distribution of map units depicted on the accompanying geologic map, from youngest to oldest. Major text subdivisions are Quaternary Deposits (surficial deposits) and Bedrock, the latter divided into Tertiary intrusive rocks, Paleozoic sedimentary rocks, Proterozoic intrusive rocks, and Proterozoic metamorphic rocks.

SURFICIAL DEPOSITS

Surficial (Quaternary) deposits are shown on the map if they form a continuous cover over bedrock and are more than 5 ft thick. Quaternary deposits that vary in thickness from zero (exposed bedrock) to >5 ft as a discontinuous cover, are mapped as a “fractional” map unit, shown by a map unit abbreviation that lists the Quaternary deposit in the numerator and the underlying deposit in the denominator (e.g., Qpt/Tp). Areas where Quaternary deposits nowhere exceed 5 ft thick and include many areas of bedrock outcrop are mapped as the bedrock type. We do not map residuum and in-place weathered regolith derived from the underlying bedrock as Quaternary deposits (for example, the thin/discontinuous veneer of frost-wedged rubble above timberline derived from Precambrian bedrock). Although in places such residuum may be thicker than 5 ft, it is only mapped as a Quaternary deposit if it has been transported a significant distance downslope during the Quaternary. Artificial fills of limited extent were not mapped. Contacts between surficial units may be gradational, and mapped units locally include deposits of another type.

The Quaternary deposits of the Climax quadrangle are generally not well exposed, due to the lack of artificial and natural vertical exposures. Therefore, 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).

The terminology used for divisions of late Neogene (Quaternary) time is shown in Fig 4. Numerical ages have not been obtained for any of the surficial units in the Climax quadrangle. The ages assigned to surficial units are estimates based principally on stratigraphic relations, position in the landscape, degree of erosional modification, differences in degree of weathering and soil development, and correlations with deposits elsewhere in the region whose ages have been
determined by numerical-dating methods. For example, the two latest episodes of glaciation are correlated with the Pinedale (15-35 ka) and the Bull Lake (150-170 ka) glacial advances of the Rocky Mountains (Pierce, 2003). For ease of description, deposit localities are described as lying east or west of the range crest of the Mosquito Range that bisects the quadrangle.

Fig. 4. Geologic time chart used in this report. Within the Quaternary, we identify glacial deposits as “Pinedale” or “Bull Lake”. Pinedale time is correlative to marine oxygen isotope Stage 2 of the Upper (Late) Pleistocene (from 11.8 ka to 35 ka), and is equivalent to the Latest Glacial Maximum (LGM) of current usage. Bull Lake time is correlative with marine oxygen isotope Stage 6 (ca.150-170 ka) and represents the second-oldest glacial advance commonly interpreted in the Rocky Mountains.
HUMAN-MADE DEPOSITS

af  Artificial fill (latest Holocene) – Unsorted silt, sand, and rock fragments deposited by humans during construction. Mapped only where the Leadville, Colorado and Southern Railroad crosses tributary streams above the East Fork Arkansas River. The average thickness of the unit is less than 30 ft. Artificial fill may be subject to settlement when loaded if not adequately compacted.

mw  Mine waste (latest Holocene) – Unsorted silt, sand, and rock fragments deposited by humans during mining. Includes coarse-grained waste rock (spoil), fine-grained tailings, and areas of graded bedrock veneered with spoil. West of the Range crest, mapped in Evans Gulch and at the Climax Mine. East of the range crest, mapped on Pennsylvania Mountain, the London Mine, South London Mine, and the American Mill. The average thickness of the unit is generally less than 30 ft, except at the Climax Mine. Mine waste may be subject to settlement when loaded if not adequately compacted.

GLACIAL DEPOSITS – Gravel, sand, silt, and clay deposited by ice along glaciated valleys in the Mosquito Range (west of the range crest, East Fork Arkansas River and Evans Gulch; east of the range crest, Mosquito Creek and its forks, Buckskin Creek, headwaters of the South Platte River).

Qnt  Neoglacial till (Holocene) – Heterogeneous deposits of gravel, sand, silt, and clay deposited by ice in small terminal moraines at the base of cirque headwalls. Mapped only below the highest summits in the quadrangle in two locations; north and south of the summit of Mt. Arkansas, and south of Clinton Peak. Deposits are light olive gray, poorly sorted, unstratified or poorly stratified, matrix-supported, boulder, pebble, and cobble gravel in a silty-sand matrix. Clasts are typically angular to subangular and unweathered. Soils comprised of very weak (incipient) A-horizon over unoxidized till. Lack of clast weathering, lack of soil development, and short distance from cirque headwall suggest a Neoglacial age (younger than 5 ka). Maximum thickness is unknown, but height of ridges suggest at least 66 ft in places.

Qty  Pinedale till, younger (late Pleistocene) – Heterogeneous deposits of gravel, sand, silt, and clay deposited by ice in terminal and lateral moraines. May also include localized lenses of material transported by melt-water adjacent to ice. Deposits are poorly sorted, unstratified or poorly stratified, matrix-supported, boulder, pebble, and cobble gravel in a silty-sand matrix. Clasts are typically angular to rounded and unweathered. Small kettle holes and hummocky topography are common. Soils comprised
of moderately well-developed A-horizon and weakly developed C-horizon. Lack of clast weathering, lack of soil development, and very hummocky surface morphology suggest a late Pinedale age (15-22? ka). West of the range rest, mapped only in an unnamed tributary to Birdseye Gulch, and as recessional moraines in the East Fork Arkansas River opposite the mouths of French and Dutch Gulches (Fig. 5). East of the range crest, mapped only south of Kite Lake. Maximum thickness is unknown, but roadcuts along Colorado Highway 91 expose a thickness of at least 33 ft in places.

Fig. 5. Artificial exposure of recessional Pinedale moraine (unit Qpty) on the western side of the East Fork Arkansas River, opposite the mouth of French Gulch.

Qpt Pinedale till, undivided (late Pleistocene) — Heterogeneous deposits of gravel, sand, silt, and clay deposited by ice in terminal, lateral, and ground moraines in all glaciated valleys of the quadrangle. West of the Divide, mapped in the East Fork Arkansas River valley between the cirque and French Gulch, and downstream of Birdseye Gulch. Based on its height above stream level, Nelson et al. (1984) estimated that the Pinedale valley glacier was 785 ft thick. Also mapped in English Gulch, Buckeye Gulch, Birdseye Gulch; in Indiana Gulch and the north side of Prospect Mountain; and Evans Gulch. East of the Divide, mapped in the head of Platte Gulch, Buckskin Gulch-Kite Lake area, and in Mosquito Creek and South Mosquito
Creek. May also include localized lenses of material transported by melt-water adjacent to ice, and post-glacial alluvium in stream courses too small to map. Areas where till is a thin or discontinuous mantle over bedrock, such as upper Birdseye and Indiana Gulches, are mapped as fractional units. Deposits are light olive gray, poorly sorted, unstratified or poorly stratified, matrix-supported, boulder, pebble, and cobble gravel in a silty-sand matrix. Clasts are typically angular to rounded and unweathered. Lithologies in Evans Gulch include light-toned porphyry, pink granite, granitic gneiss, well-stratified sandstone, quartzite, and minor chert. Small kettle holes and hummocky topography are common. Soils comprised of moderately well-developed A-horizon and weakly developed C-horizon. Lack of clast weathering, limited soil development, and hummocky surface morphology suggest a late Pleistocene age (Pinedale equivalent, 15-35 ka). Maximum thickness is unknown.

Mapped as a thin/discontinuous covering over bedrock (fractional map unit) on the west side of Fremont Pass; in upper East Fork Arkansas River; in lower Birdseye Gulch; lower Buckeye Gulch; upper and lower Evans Gulch; and in American Flats above South Mosquito Creek. Where mapped on the south side of Evans Gulch, prospect pits show that thickness decreases to less than 5 ft in places.

Qbt **Bull Lake till (late middle Pleistocene)** — Heterogeneous deposits of gravel, sand, silt, and clay deposited by ice in terminal and lateral moraines. Mapped only west of the range crest, at English Gulch, unnamed tributary to Birdseye Gulch, and Evans Gulch (lateral moraines). Deposits are brown to reddish-brown, poorly sorted, unstratified or poorly stratified, matrix-supported, boulder, pebble, and cobble gravel in a silty-sand matrix (Fig. 6). Most clasts are angular to subangular and little weathered, but Precambrian schist clasts rich in biotite are rounded and partly disintegrated. Generally, exposed boulders are half buried below surface of moraine. Moraine is only slightly hummocky and crest is rounded. Soils are moderately developed and have a weakly developed argillic B-horizon. Degree of clast weathering, soil development, and surface morphology suggest a late middle Pleistocene (Bull Lake, 150-170 ka) age for these deposits. Maximum thickness is unknown, but may be as much as 66 ft (20 m). Mapped as a fractional unit on south side of Evans Gulch, where prospect pits show that thickness decreases to less than 5 ft in places.
Fig. 6. Artificial exposure of Bull Lake till (unit Qbt) along the Leadville, Colorado & Southern Railroad where it crosses Indiana Gulch.

**Qto**  
**Pre-Bull Lake till (early to middle Pleistocene)**—Heterogeneous deposits of gravel, sand, silt, and clay deposited by ice in terminal and lateral moraines. Mapped only at the northern map boundary, on the Continental Divide west of Chalk Creek. The bouldery deposit here lies on the interfluve above the limit of Pinedale and Bull lake moraines to the west. Deposits are poorly exposed except in jeep roads, where they are brown to reddish-brown, poorly sorted, boulder, pebble, and cobble gravel in a silty-sand matrix. Generally, exposed boulders are half or more buried below surface of moraine. The deposit surface lacks morainal morphology. Degree of clast weathering and surface morphology suggest an early to middle Pleistocene (pre-Bull Lake) age for these deposits. Maximum thickness is unknown.
PERIGLACIAL DEPOSITS – Deposits formed in cold environments by freeze-thaw action, solifluction, and nivation. Includes talus deposited by gravity processes (rockfall, creep) and talus fans deposited by both gravity and debris-flow processes.

**Qrg**  **Rock glacier deposits, undivided (Holocene)**—Poorly sorted, angular to sub-angular boulders, cobbles, gravel, and sandy silt. Mapped in most of the cirques in the quadrangle as smaller rock glacier deposits and lobes. Composed almost exclusively of the hardest, well-jointed rocks exposed on cirque headwalls, such as Precambrian crystalline rocks and Tertiary porphyries. The surface of the rock glacier is typically clast-supported, matrix-free, and composed of angular to subangular, predominantly boulder-sized rock fragments (Fig. 7). The interior of the deposit contains more matrix, but is rarely exposed. Downslope movement is the result of slow creep of interstitial ice or an ice core. Rock glaciers commonly have a lobate or tongue-like morphology and form in cirque basins where sediment supply is abundant. Includes rock glaciers that are generally inactive, but may contain some small areas of later Holocene reactivation too small to map. Maximum thickness about 60 ft.

**Qrgo**  **Rock glacier deposits, older (early to middle Holocene)**—same as map unit Qrg, but lacking any evidence of recent movement (e.g., unvegetated, angle-of-repose slopes). Morphology is more subdued and surface is more heavily vegetated than map unit Qrg. Boulders on top, sides, and front are covered with lichen and/or trees, so deposits are inferred to be stationary. Often covered with younger talus and colluvium on edges. Maximum thickness about 66 ft.

**Qrgl**  **Rock glacier-landslide deposits (Holocene)**—Poorly sorted, angular to sub-angular boulders, cobbles, gravel, and sandy silt. Mapped west of the range crest in three places: (1) cirque headwall of Indiana Gulch, (2) on the south valley wall of East Fork Arkansas River near the western map boundary, (3) west valley wall of the upper East Fork Arkansas River, 2 km south of the Climax Mine; and east of the range crest in the western cirque headwall of Mosquito Creek.
Fig. 7. Photograph of rock glacier deposits (lower) and talus deposits (upslope of them) in the cirque of the East Fork Arkansas River, looking south. Both deposits are derived from cliffs of Precambrian migmatite (unit Xm).

Composed of meter-plus-size blocks of the hardest, well-jointed rocks exposed on the cirque headwall above. The surface of the rock glacier is typically clast-supported, matrix-free, and composed of angular to subangular, predominantly boulder-sized rock fragments. These deposits are distinguished from other rock glaciers by: (1) the presence of landslide headscarp scars above them, (2) the abnormally large clast size, and (3) in some cases (south of Climax Mine) a clear rockslide/rockfall source area scar of unique lithology that matches the boulder lithology. Although the deposits now possess rock glacier morphology and pressure ridges, they are inferred to have originally formed as rockslide or rockfall avalanche deposits in one or more catastrophic failure events. Because the rubble was deposited at high elevations subject to periglacial climate, it formed interstitial ice after deposition, and began to creep as a rock glacier. May be covered with younger talus and colluvium on edges. Maximum thickness about 66 ft.

Qta  Talus deposits, active (late Holocene to historic) – Angular, cobbly and bouldery rubble as much as 6 ft in diameter. Mapped at the base of oversteepened glacial valley sidewalls in all cirques, and along the range-
front escarpment formed by the Mosquito Fault. Deposits are derived from bedrock that was transported downslope by gravity principally as rockfalls, rock avalanches, rock topples, and rockslides. Downslope movement may have been locally aided by water and freeze-thaw action. This unit typically lacks matrix material near the surface, but dissected talus reveals significant matrix at depth. No surface vegetation, indicating that rubble deposition is continuing in modern times. Thickness of the deposits is probably less than 33 ft. Talus areas are subject to rockfall, rock-topple, and rockslide hazards.

**Qti**  
**Talus deposits, inactive (Holocene)** – Angular, cobbly and bouldery rubble as much as 6 ft in diameter. Deposits are derived from bedrock that was transported downslope by gravity principally as rockfalls, rock avalanches, rock topples, and rockslides. Downslope movement may have been locally aided by water and freeze-thaw action. This unit typically lacks matrix material near the surface, but dissected talus reveal significant matrix at depth. This unit is distinguished from active talus by the presence of some surface vegetation, indicating that rubble deposition is no longer continuing in modern times. Includes a protalus rampart deposit in the cirque of the unnamed tributary valley north of Delmonica Gulch. Thickness of the deposits is probably less than 33 ft. May be subject to rockfall, rock-topple, and rockslide hazards in extreme events (storms, earthquakes).

**Qtf**  
**Talus fan deposits (Holocene)** – Angular, cobbly and bouldery rubble as much as 6 ft in diameter deposited in steep cones marked by a prominent axial gully. Mapped only in cirques east of the Mosquito Fault, where cirques expose steep headwalls in Precambrian rocks. Deposits are derived from bedrock that was transported downslope by both rockfalls and debris flows. Axial gully is typically flanked by prominent debris-flow levees. This unit typically lacks matrix material near the surface, but dissected talus reveal significant matrix at depth. Surface is unvegetated, indicating that it has received recent active deposition. Thickness of the deposits is probably less than 15 ft. Talus fan areas are subject to rockfall and debris flows.

**Qs**  
**Solifluction deposits (Holocene to late Pleistocene)** – Angular to subrounded pebbles, cobbles, and large boulders in a chiefly sandy matrix deposited in alpine and sub-alpine basins. Mapped only on unforested slopes above the Pinedale glacial limit. Solifluction deposits result from the slow downslope flowage of surficial deposits that are water saturated and subject to seasonal freezing. Frost creep and melt-water transport are also important factors in the formation of these deposits. This type of slope movement, involves a slow, plastic deformation of the soil and surficial deposits. Solifluction areas are characterized
by hummocky terrain, ground cracks and fissures up to several inches wide, and numerous seeps and
springs. On open hillslopes solifluction may also produce lobes, terracettes (small ledges or benches up to
about 5 ft high), or stone stripes trending downslope, through differential movement of surficial material.
Average thickness of these deposits is typically less than about 16 ft. These deposits may be susceptible
to future downslope movement and shallow groundwater.

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

Qal Stream-channel and flood-plain alluvium (late Holocene) – Deposits are mostly clast-supported, pebble,
cobble, and locally boulder gravel in a sandy silt matrix. The deposits are locally interbedded with and
commonly overlain by sandy silt and silty sand. Clasts are subangular to well rounded, and their varied
lithology reflects the diverse types of bedrock within their provenance. This unit includes modern stream-
channel deposits of all perennial streams, adjacent flood-plain deposits, and low-terrace alluvium that lie
a maximum of 10 ft above modern stream level. The largest mapped areas are in the channels and
floodplains of perennial streams (East Fork Arkansas River, Evans Gulch), where channel facies is small
pebble gravel and floodplain facies is medium to coarse sand. Smaller areas lie in the channels of
intermittent streams. Deposits may be interbedded with colluvium or debris-fan deposits where the distal
ends of fans extend into modern river channels and flood plains. Maximum thickness normally about 33
ft, but may overlie thicker (100 ft?) Pinedale-age lake beds and older alluvium in the East Fork Arkansas
River. Areas mapped as alluvium may be prone to flooding and sediment deposition. The unit is typically
a good source of sand and gravel.

Qat Low stream terrace alluvium (Holocene) – Deposits are mostly clast-supported, pebble, cobble, and
locally boulder gravel in a sandy silt matrix. This unit includes alluvium of low terraces above the modern
floodplain, most of which is inferred to be early to middle Holocene in age, but some may have been
deposited as latest Pinedale glacial outwash. Mapped on the floor of the East Fork Arkansas River
downstream from English Gulch. The deposits are locally interbedded with and commonly overlain by
sandy silt and silty sand. Clasts are subangular to well rounded, and their varied lithology reflects the
diverse types of bedrock within their provenance. Maximum thickness probably less than 20 ft.
Qao  **Alluvium, older (late to middle Pleistocene)** – Deposits are mostly clast-supported, pebble, cobble, and locally boulder gravel in a sandy silt matrix. Mapped only in Chalk Creek. Maximum thickness probably less than 20 ft.

**COLLUVIAL DEPOSITS** – Silt, sand, and gravel on valley sides and floors. Material mobilized, transported, and deposited primarily by gravity, but commonly assisted by sheetwash, rillwash, freeze-thaw action, and debris flows too small to map.

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

Qco  **Colluvium, older (late to middle Pleistocene)** – Includes weathered bedrock fragments that have been transported downslope primarily by gravity. Mapped only on the south flank of prospect Mountain, above the Bull Lake lateral moraine. Deposit there may have been deposited with an unsorted to poorly sorted texture, similar to map unit Qc. However, most of deposit has now been churned and segregated into fine (matrix-supported) and coarse (talus) facies by subsequent frost wedging, cryoturbation, and solifluction. Maximum thickness is estimated as 33 ft.
Landslide deposits, undivided (Holocene to late Pleistocene) — Chaotically arranged debris ranging from clay to boulder size (diamicton). Mapped throughout the quadrangle. West of the Mosquito fault, where landslides were derived from the failure of Minturn Formation and Tertiary porphyry, deposits have a higher silt and clay component. East of the Mosquito fault, where landslides are generally derived from failure of altered Precambrian crystalline rocks, deposit texture tends to be coarser. Surface of deposits commonly hummocky, and source area of landsliding is generally identifiable (top of scarp area indicated by thick dashed lines with ticks in direction of sliding). Larger landslide deposits may be more than 50 ft thick.

Landslide deposits, younger (mid-late Holocene) — Chaotically arranged debris ranging from clay to boulder size (diamicton), associated with slumps and slides of weak bedrock or till on steep slopes. Mapped only west of the Mosquito fault, in terrain underlain by the Minturn Formation. Surface of deposit is hummocky, and source area of landsliding is easily identifiable (top of scarp area indicated by thick dashed lines with ticks in direction of sliding). May be more than 33 ft thick.

Landslide deposits, intermediate age (early Holocene to late Pleistocene) — Chaotically arranged debris ranging from clay to boulder size (diamicton). Mapped only west of the Mosquito fault, in terrain underlain by the Minturn Formation, where these deposits can be differentiated (based on freshness of landslide morphology) from younger (Qlsy) or older (Qlso) landslides. Surface of deposit is hummocky, and source area of landsliding is generally identifiable (top of scarp area indicated by thick dashed lines with ticks in direction of sliding). May be more than 33 ft thick.

Landslide deposits, older (late to middle? Pleistocene) — Chaotically arranged debris ranging from clay to boulder size (diamicton). Mapped only west of the Mosquito fault, in terrain underlain by the Minturn Formation. Distinguished from younger landslide deposits by its subdued surface topography, and difficulty in distinguishing the headscarp, toe bulge, and margins from other non-landslide landforms. May be more than 66 ft thick.

Landslide complex deposits, undivided (Holocene to late Pleistocene) — Chaotically arranged debris ranging from clay to boulder size (diamicton), but mostly angular blocks and mega-blocks of quasi-intact Minturn Fm and Tertiary porphyry (Fig. 8). Includes rockslides and blockslides of various ages and sizes, and large pieces of local bedrock that have detached from slopes above and slid a short distance, but not far enough to totally disaggregate. Mapped only on the south valley wall of the East Fork Arkansas River,
near the western map boundary. Surface of deposit is hummocky and contains springs, and source area of landsliding is easily identifiable (linear pull-away scarps indicated by thick dashed lines with ticks in direction of sliding). Based on thickness estimated from railroad cuts, deposit may be thicker than 66 ft.

Fig. 8. Photograph of a railroad cut into the landslide complex deposit (unit Qlsc) near the western map boundary, on the south wall of the East Fork Arkansas River. Note large intact blocks of Tertiary porphyry floating in a crushed matrix of porphyry and Minturn Formation. Height of cut shown is approximately 26 ft.

Qlsw  **Landslide deposits, deposited into standing water (late Pleistocene)** —Chaotically arranged debris ranging from clay to boulder size (diamicton), but dominated by large angular blocks of Minturn Formation from 1.5 to 16 ft in diameter. Derived from catastrophic rockslide avalanches that fell from oversteepened glaciated valley walls, into temporary lakes in the valley of the East Fork Arkansas River, during the Pinedale deglaciation. Surface of deposit is extremely hummocky and blocky, and source area of landsliding is easily identifiable (top of scarp area indicated by thick dashed lines with ticks in direction of sliding). Deposit is at least 16 ft thick.
Earthflow deposits, undivided (Holocene to late Pleistocene) — Chaotically arranged debris ranging from clay to boulder size (diamicton), but mostly silt and clay. Mainly derived from weathering of Minturn Formation. Mapped only south of the Climax Mine, on the south valley wall of the East Fork Arkansas River, directly west of unit Qefy. Surface of deposit is hummocky, contains springs, and source area of landsliding is easily identifiable (top of scarp area indicated by thick dashed lines with ticks in direction of sliding). Based on thickness estimated for unit Qefy, deposit is at least 33 ft thick.

Earthflow deposits, younger (mid-late Holocene) — Chaotically arranged debris ranging from clay to boulder size (diamicton), but mostly silt and clay derived from weathering of the Minturn Formation. Mapped only on the northern flank of Mount Arkansas, where an earthflow descends to the hairpin curve in US Highway 91 south of Climax. Surface of deposit is very hummocky, contains many ponds and springs, and source area of landsliding is easily identifiable (top of scarp area indicated by thick dashed lines with ticks in direction of sliding). Based on the Highway 91 roadcut into its toe south of Climax, deposit is at least 33 ft thick.

Earthflow deposits, intermediate age (early Holocene to late Pleistocene) — Chaotically arranged debris ranging from clay to boulder size (diamicton), but mostly silt and clay. Mapped only on northern flank of Mount Arkansas, where it lies directly upslope of unit Qefy. Surface of deposit is hummocky, contains springs, and source area of landsliding is easily identifiable (top of scarp area indicated by thick dashed lines with ticks in direction of sliding). Based on thickness estimated for unit Qefy, deposit is at least 33 ft thick.

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

Alluvium and colluvium, undivided (Holocene to late Pleistocene) — Unit primarily consists of a mixture of alluvial deposits of ephemeral, intermittent, and small perennial streams, and of colluvial deposits deposited from valley sides. Interfingers with and is gradational with stream alluvium (Qal), alluvial-fan deposits (Qf), and colluvium (Qc). Alluvium is typically composed of poorly to well sorted, stratified, interbedded, pebbly sand, sandy silt, and sandy gravel. Colluvium may range from unsorted, clast-supported, pebble to boulder gravel in a sandy silt matrix to relatively well-sorted sand composed of
disintegrated granitic rocks (grus). Clast lithologies vary and are dependent upon the bedrock or surficial unit from which the deposit was derived. Maximum thickness of the unit is approximately 20 ft.

**Qf Alluvial-fan deposits, undivided (Holocene to late Pleistocene)** – Moderately sorted sand- to boulder-size gravel in undissected, fan-shaped deposits from tributary streams. Mapped where narrow, steep, intermittent and ephemeral tributaries debouch into wider, lower-gradient master stream valleys. This undivided unit is mapped where deposition has occurred over a long time period, beginning (in places) as early as early- to middle-Pleistocene time and continuing into the Holocene. Deposits typically composed of both matrix-supported beds (debris flow facies) and clast-supported beds (streamflow facies), often interbedded. Clasts are mostly angular to subrounded with varied lithologies dependant upon local source rock. Sediments are deposited by debris flows, hyperconcentrated flows, streams, and sheetwash. Debris-fan deposits commonly grade from boulder- and cobble-size fragments at the head of the fan to sandier deposits near the fan terminus. The maximum estimated thickness is less than 33 ft. Extreme precipitation events may trigger future deposition on alluvial fans. Debris-fan deposits may be prone to collapse when wetted or loaded.

**Qfp Alluvial-fan deposits, older (late to middle Pleistocene)** – Moderately sorted sand- to boulder-size gravel in dissected, fan-shaped deposits from tributary streams. Deposits typically composed of both matrix-supported beds (debris flow facies) and clast-supported beds (streamflow facies), often interbedded. Clasts are mostly angular to subangular. Deposits are inferred to be contemporaneous with the Pinedale glaciation, from their relationship with end moraines. The maximum thickness is at least 16 ft.

**BEDROCK UNITS**

**TERTIARY INTRUSIVE ROCKS**

Within the quadrangle, at least 8 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 Montgomery Gulch-Mount Silverheels area located in the northeastern part of the Alma 7.5’ quadrangle, which was heavily intruded by monzonites and rocks ranging from diorites to quartz monzonites, roughly 42 to 43 Ma; the Mount Lincoln and Bross area located in the northwestern part of the Alma
quadrangle, which is the type locality for the Lincoln porphyry, approximately 65 Ma (although, as indicated below, this date is controversial); and the Buckskin Gulch area located in the west-central part of the Alma quadrangle and the east-central part of the Climax quadrangle, which is characterized by episodic monzonitic to granodioritic intrusions 72 to 42 Ma (Widmann and others, 2004b). The petrogenesis of the Buckskin Gulch intrusive complex and the abundance and complexity of dikes in this area (not all shown on our map) is discussed in detail by Kuntz (1968). Descriptions of the rock units are primarily on the basis of hand sample analysis by the authors and limited thin section petrography by Steve Quane of Colorado College. A more detailed but proprietary map by Bookstrom (1983) was generated for the Climax Molybdenum Company (cited by Widmann and others, 2004b). That map and report evidently define up to 19 separate Tertiary porphyries. In this report we define eight Tertiary intrusive units, by combining the subdivision of dikes in the Alma-Horseshoe mining district (Singewald and Butler, 1941, Plate 1), from which we compiled much of our dike mapping, with the subdivision used by Widmann and others (2004b) in the Alma quadrangle.

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 a few inches to 300 ft thick or more, and have strike lengths that can exceed 1 mile. Dikes tend to be much narrower, generally less than about 20 ft. There appears to be a gross spatial association between quartz monzonite porphyries and significant mine workings. Whether this association is genetic (as the authors suspect), is impossible to definitively tell at this time.

**Climax late dikes (Oligocene)**—Mapped only in the Climax Mine mineralization area between the Mosquito fault and Clinton Peak. Composed of light-gray rhyolite porphyry containing 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 (our unit Tlw; 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). These dikes cut the major ore bodies and were dated at 25.5 Ma (Bookstrom, 1989). 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.
Tc  **Chalk Mountain rhyolite (Oligocene)**—Chalk Mountain forms a prominent ridge along the range crest in the northern part of the quadrangle and is underlain by a large mass of white rhyolite porphyry. The rock is bright white and contains abundant co-equal amounts of sanidine, plagioclase, and quartz phenocrysts up to 2 inches in length within a white microcrystalline groundmass of plagioclase and quartz. The quartz phenocrysts are generally smoky. The Chalk Mountain rhyolite has been dated at 29 Ma by the K-Ar method (V.E. Surface, Climax Molybdenum Company, 1970, written communication in Tweto, 1974a). This unit is believed to be associated with the igneous events responsible for the formation of the Climax ore body (White and others, 1981). The mode of emplacement of the Chalk Mountain rhyolite was suggested by Emmons 1886 to be an intrusive sill. Field observations of undifferentiated Cambrian through Mississippian units on top of Chalk Mountain support this interpretation.

Tca  **Alicante Stock (Oligocene)**—mapped only in the center of the Climax Mine mineralization area (Wallace, 1968). Composed of subhedral phenocrysts of quartz and orthoclase averaging 2 to 3 mm across set in a fine-grained matrix of the same minerals. In places, the porphyry contains numerous ragged crystals of primary biotite, which along with its alteration product, sericite, defines a flow foliation near contacts. On the Phillipson Level of the Climax Mine, the Alicante stock is 1,800 ft by 1,100 ft. Below the Phillipson Level, it plunges northward in contact with the Bartlett stock. The Ceresco Ore Body lies well outside the Alicante stock, and the porphyry is not affected by the mineralization. Dikes that extend from the Alicante stock into the ore body are well mineralized. Three main ore bodies were formed by the multiple intrusions of the Climax Stock: the Upper Ore Body, the Lower Ore Body, and the Ceresco Ore Body. The Ceresco Ore Body is related to the emplacement of the Alicante stock, the earliest porphyry intrusion.

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 in the east central part 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 on the Alma quadrangle to the east of the Climax quadrangle.

Tqpm Quartz monzonite porphyry – megacrystic variety (Eocene)—Light-gray to light-bluish-gray quartz monzonite porphyry that contains prominent large phenocrysts (megacrysts) of orthoclase 0.5 to 2 inches long, and in many places, rounded bipyramids of quartz up to 0.5 inches in diameter. These phenocrysts are set in a porphyritic matrix composed of anhedral grains of plagioclase, quartz, orthoclase, and abundant biotite, set in a bluish-gray aphanitic matrix (Fig. 9). Along Highway 91 between Birdseye and French Gulches, the porphyry is exposed in a north-south outcrop for several miles. This intrusive appears to closely follow the lower contact of the Minturn Formation, suggestive of emplacement as a sill. 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, 2005; Widmann and others, 2004a) 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 in the east central part of the quadrangle; this locale has been interpreted as the possible feeder for the laterally extensive laccolithic arms structurally above it on Mts. Bross and Lincoln in the Alma quadrangle (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.
Fig. 9. Megacrystic variety of the quartz monzonite porphyry (Tqpm).

**Tqp** *Quartz monzonite porphyry (Eocene)*—Grayish-tan- to light-brown- to purple weathering porphyritic quartz monzonite comprised primarily of quartz, plagioclase, orthoclase, biotite, and hornblende (Fig. 10). 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).

**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. 11). Quartz is generally absent. The monzodiorite porphyry is typically unaltered and forms sills and minor dikes in the southern part of the quadrangle where it is exposed along the footwall of the Mosquito fault. 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.
Fig. 10. Quartz monzonite porphyry (Tqp). Resistant quartz phenocrysts (white) stand out against a weathered fine-grained matrix (dark purple).

Fig. 11. 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.
Diorite rocks of Buckskin Gulch (Eocene and Paleocene)—Includes stocks and dikes ranging in composition from monzonite to granodiorite near the head of Buckskin Gulch (Sec. 29, T8S, R78W). These rocks are typically medium- to light-gray in color and range from fine to coarse grained (Fig. 12). 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 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 magma 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.

Fig. 12. Hand specimen of the Buckskin diorite (Td). Sample is about 12 cm across.
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, Belden Formation, and Maroon Formation, were not found to crop out within the Climax quadrangle. The oldest sedimentary stratigraphic unit, the Sawatch Quartzite, rests nonconformably on the Proterozoic basement rocks that form the core of the Mosquito Range.

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.

Pm  Minturn Formation (Middle Pennsylvanian)—Predominantly white, 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 wide) channels quickly grade upward to medium- and fine-grained sandstone. Conglomerate in broad (a few tens of wide) channels as much as 15 thick, commonly contains cobble-size clasts, and may exhibit both normal and reverse gradation. Clasts are primarily composed of quartz and chert. Along Chalk Creek in the northwest part of the quadrangle, clasts composed of granite and gneiss were observed and may be indicative of the upper Minturn (Houck, 2007, oral communication). Numerous thin limestone or dolomite beds are interspersed throughout the Minturn Formation. Fresh exposures of the limestone are generally dark-to medium-gray. Weathered beds may be altered to black, dark-reddish-gray, tan, and even white. Limestone texture is either micritic or fine grained. Limestone beds are typically 15 to 20 ft thick. Total thickness of the Minturn Formation in the quadrangle is estimated to be over 5,000 ft however, the upper part of the section and contact with the Maroon Formation is not observed. The formation is over 7,000 ft thick in the Alma quadrangle (Widmann and others, 2004).

MI 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 ore bodies found in the areas between London Mountain and Mosquito Peak in the central part of the quadrangle and on Mounts Lincoln and Bross in the Alma quadrangle. Throughout much of the quadrangle the dolomite averages about 160 ft thick, but it thins significantly (less than 50 ft) to the northeast in the area west of Hoosier Pass. This is in accord with mapping by Wallace and others (2005) in the Breckenridge quadrangle to the northeast, 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 the Parting Quartzite and Dyer Dolomite Members are poorly exposed or too thin to be mapped separately.

Dd Dyer Dolomite Member of the Chaffee Formation (Upper Devonian)— 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.
Parting Quartzite Member of the Chaffee Formation (Upper Devonian)—

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 estimated to be approximately 55 ft where exposed along Loveland Mountain in the east central part of the quadrangle.

Manitou Formation (Ordovician to Upper Cambrian)—Cliff-forming unit especially along the top of Loveland Mountain composed of light- to dark-gray, thin- to thick-bedded dolomite with occasional interbeds of dark gray limestone (Fig. 13). 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 stains. 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. The Manitou Formation appears to thin significantly to the north, from 200 ft at Horseshoe Mountain several miles south 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).

Fig. 13. Manitou Formation outcrop on southwest side of Loveland Mountain showing beds of light tan to pink dolomitic limestone interbedded with thin, dark gray to black, fissile limestone (UTM83 402338, 4349640).
**Cd** Dotsero Formation (formerly Peerless Formation) (Upper 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. The Dotsero Formation crops out only around the periphery of Loveland Mountain within the quadrangle. The unit weathers to a distinctively brown color that contrasts with the whitish rocks of the underlying Sawatch Quartzite. Thickness of the unit is about 50 ft.

**Cs** Sawatch Quartzite (Upper Cambrian)—White, thick-bedded, medium-grained, well-cemented quartz sandstone. Typically outcrops as light colored or whitish cliffs composed of 2- to 10-ft-thick beds. A basal pebble conglomerate 7 to 12 inches thick, composed of well-rounded quartz pebbles in a medium to coarse sandstone matrix, is in nonconformable contact with the underlying Proterozoic rocks. Overall, the Sawatch Quartzite is a medium grained, moderately to well sorted, sub to well rounded, quartz sandstone. The 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 Climax quadrangle belong to the Berthoud (1,400 Ma) and Routt (1,700 Ma) plutonic suites. The largest of these bodies is 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 eastern part of the quadrangle. Descriptions of the rock units are primarily on the basis of hand sample analysis and limited thin section petrography.

**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 30 miles
northeast of the quadrangle, this granite yielded a uranium-lead zircon age of 1,422 ± 2 Ma (Graubard and Mattison, 1990).

**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).

![Fig. 14. Granitic gneiss with thin biotite-rich aggregates parallel to foliation.](image)

**PROTEROZOIC METAMORPHIC ROCKS**

Description 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 eastern part of the
quadrangle, is the most common of the metamorphic rocks. 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, 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. 15). The contacts between migmatite, biotite gneiss, and porphyritic granodiorite are everywhere gradational, and a composition of one type is frequently found within the overall boundaries of another.

![Fig. 15. Migmatite. Note higher percentage of felsic material and greater degree of deformation than in biotite gneiss.](image)

**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. 16). 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. 16).

Fig. 16. Biotite gneiss is commonly thinly laminated and is not as severely deformed as migmatite.

**STRUCTURAL GEOLOGY**

The rocks observed in the Climax quadrangle show structural features representative of multiple periods of tectonic activity. Many of the Proterozoic rocks are metamorphosed, complexly folded and faulted, and overlain by faulted Paleozoic sedimentary strata. Tertiary intrusive rocks form dikes most likely through pre-existing Laramide fractures in the Proterozoic rocks as suggested by Kuntz (1968), but are primarily emplaced as sills at various scales through many exposures of the Paleozoic strata. Late Tertiary and Quaternary landslides, rock glaciers, and solifluction movements punctuate the deformational history. The faults mapped in the quadrangle are all high-angle normal and reverse faults and can be grouped into several systems. Throughout the length of the central part of the quadrangle the Mosquito fault strikes N to N 10 degrees E. This fault separates the quadrangle into two distinct blocks: the Mosquito Range fault block to the east which is
comprised mainly of Proterozoic rocks, and the western fault block comprised mainly of Paleozoic sedimentary rocks. In the southeastern part of the quadrangle the London fault and several subsidiary faults strike northwest to southeast. Northeast to southwest striking faults are more numerous in the western part of the quadrangle.

**MOSQUITO FAULT**

The Mosquito fault transects the entire central part of the quadrangle from north to south and places Proterozoic rocks in the east half next to Paleozoic sedimentary rocks in the west half (Fig. 3). This fault is traceable along the west flanks of the Mosquito and Tenmile Ranges for at least 33 miles and is considered to be one of the major faults in Colorado (Behre, 1953). Wallace and others (1968) estimated approximately 1500 ft of left-lateral, strike-slip motion and approximately 9,000 ft of displacement on the Mosquito fault in post Oligocene time in the Climax area. This estimate is based on the offset of the Climax ore body discovered in deep drilling and is supported by stratigraphic reconstructions made by Bergandahl and Koschmann (1971).

In the Climax pit, the Mosquito fault is a normal fault with a 71 to 80 degree westward dip (Koschmann and Wells, 1946). Approximately 13 miles south of the Climax mine in the Mount Sherman quadrangle; Behre (1953) reported a 75 to 80 degree east dip of the fault suggesting reverse movement. Tweto and Sims (1963) have speculated on a Precambrian origin for the Mosquito fault noting that in many places the present trace of the fault is superimposed on a Precambrian shear zone. However, a key age constraint is that the Mosquito fault truncates the Climax ore body, which indicates the most recent movement on the fault is younger than the 24 to 33 Ma intrusive (Bookstrom and others, 1987).

The Mosquito fault is well exposed in the north wall of the Climax pit (Fig. 17). Here it dips steeply to the west and is approximately 50 ft wide. Widmann and others, (2004a) describe the eastern margin of the fault zone as a 1 to 1.5 foot wide zone of light-gray to white, clayey fault gouge, probably derived from crushing and pulverizing of the Precambrian granite (map unit YXg) in the footwall block. These authors also report that the footwall block has been altered to a jasperoid mass of rock for a distance of at least 50 ft from the fault and other parts of the fault zone incorporate several 3-6 foot wide slivers of Minturn Formation. The report continues to describe these slivers as lens shaped, elongated parallel to the fault zone, and appear to have tapered ends that dovetail into each other.

According to the Quaternary Fault & Fold Database of Colorado (Widmann et al., 1998) the Mosquito fault has experienced movement as young as late Quaternary (<130 ka), citing Kirkham and Rogers (1981). Kirkham and Rogers, in turn, cite the existence of “several distinctive scarps as much as 12 m high on glacial moraine and landslide deposits”, apparently following remarks of Tweto (1978, p. 18). However, we examined Tweto’s
localities and found no evidence for Quaternary faulting of either moraines or landslides. The only young-looking landforms along the Mosquito fault are a series of antislope scarps at the base of the Mosquito Range front between French and English Gulches (Fig. 18). These antislope scarps all lie upslope of the fault trace, and only exist in one small reach of the fault that lies directly upslope of the French-English Gulch low-angle slide block. Accordingly, we interpret the scarps to represent gravitational spreading due to toe debutressing, and not any tectonic offset. In our opinion, there is no evidence for late Quaternary movement on the Mosquito fault within the Climax quadrangle.

Fig. 17. The Mosquito fault is well exposed on the north wall and floor of the Climax pit, and juxtaposes the darker Pennsylvanian Minturn Formation (left) against lighter Precambrian granite and Tertiary porphyry (right). Photo by V. Matthews.
Fig. 18. Unannotated and annotated telephoto views of antislip scarps above the Mosquito fault trace between French and English Gulches. Further details are given in the Geologic Hazards section.

LONDON FAULT
The London fault is a major northwest-southeast striking, high-angle reverse fault that transects the southeastern part of the Climax quadrangle and appears to terminate against the Mosquito fault near the quadrangle’s center. The London fault is best exposed on the north side of Pennsylvania Mountain (Fig. 19) and on the south and north sides of London Mountain. On the north sides of Pennsylvania Mountain and London Mountain, the fault is responsible for east to northeasterly dipping overturned beds of the Minturn Formation in its footwall block. On the south side of London Mountain, the beds of the Minturn Formation in the footwall
block show an extreme zone of brecciation about 30 ft wide and dip normally to the southwest. Northwest of London Mountain and on the north side of Mosquito Peak (Fig. 20), highly fractured and brecciated rocks of the Leadville Limestone are exposed in the footwall block. The hanging wall block is composed of the Proterozoic biotite gneiss (Xb) and quartz monzonite (Yqm) with the exception of the top of Pennsylvania Mountain where exposures of Sawatch quartzite, Manitou Formation, and Tertiary intrusives were observed. Average dip on the fault is about 70 degrees to the northeast (Singewald and Butler, 1941). At the London Mountain mine, Berry (1990) describes the fault as a zone of fracturing, breccia, and gouge ranging up to 70 ft in width and estimates the vertical throw on the fault at 3,300 ft. To the southeast, the London fault is described by Widmann and others (2006) in the Fairplay West quadrangle as generally striking north-south and dipping from 51 to 90 degrees east, where exposed in the northwest part of the quadrangle. These authors also describe a relatively tight, anticline-syncline pair associated with the fault, which was not observed in the Climax quadrangle. Further south in the Fairplay West quadrangle, the fault is concealed by Quaternary deposits but Stark and others (1949) showed the fault as continuing as far southeast as Antero Reservoir. This gives the overall traceable length of the London fault at just under 25 miles. The high-angle reverse nature of the London fault and the associated overturned beds in the footwall block are deformational styles suggestive of Laramide age movement.

Fig. 19. View of the north face of Pennsylvania Mountain. Dark gray rocks on the right are southeasterly dipping beds of the Minturn Formation in the footwall of the London fault. Rocks on the left are Proterozoic biotite gneiss. Fault is in the center of the photo and is partially obscured by landslide deposits. Note the dark red to rust colored overturned beds of the Minturn Formation near the fault along the ridgeline (UTM83 400612, 4347766). Photo by V. Matthews.
Fig. 20. Panoramic view of the London fault and American Flats basin, looking northwest from the summit of Pennsylvania Mountain. To the left (SW) of the fault, east-dipping Minturn Formation and interbedded Tertiary sills underlie American Flats, and the eastern slope of the Mosquito Range between Mt. Evans and Mosquito Peak. The east-dipping beds have failed in numerous small to large dipslope rockslides, one of which is outlined in yellow dots; landslide headscarsps are shown by yellow dashes. To the right (NE) of the fault, London Mountain and the glaciated valley of upper Mosquito Creek are underlain by Precambrian biotite gneiss (Xb) and quartz monzonite (Yqm). The summit of Loveland Mountain at far right is underlain by the a thin sequence of Paleozoic sedimentary rocks ranging from the Sawatch Quartzite (Cambrian) to the Manitou Formation (Ordovician).
NORTHEAST-SOUTHWEST STRIKING FAULTS

In the western part of the quadrangle, the Minturn Formation is cut by numerous northeast-southwest striking high-angle faults. The faults are difficult to recognize in the field due to poor exposure and were approximately mapped based on changes in attitudes in the Minturn Formation outcrops and lineation features visible on air photographs. These faults are probably a continuation of a zone of similar faults mapped by Tweto (1949, 1956) in the Pando and Tennessee Pass areas northwest of the Climax quadrangle. Tweto suggests the concentration of these faults defines a structural corridor in the overlying sedimentary rocks that reflects an underlying Precambrian shear zone which was reactivated in Laramide time. Individual faults do not appear to exceed a few miles in length and are thought to be less than a few hundred ft in vertical throw, although difficult to ascertain since offset is within the Minturn Formation. Bergendahl and Koschmann (1971) report considerable strike-slip components along similar faults north of the Climax quadrangle and describe the faults as serving as ore controls in the Kokomo district, channeling hydrothermal fluids to favorable carbonate beds which were later replaced by sulfides.

FAULTS MAPPED FROM PREVIOUS REPORTS

Numerous faults mapped in the southwestern part of the Climax quadrangle from south Prospect Mountain through Evans Gulch were not observed during this investigation. This area has been highly reworked by state and federal land reclamation agencies where extensive open-pit mining occurred during the late nineteenth and early twentieth centuries. Early maps of this region by Emmons and others (1927) and Behre (1939) show a number of faults throughout this area that were probably revealed in mine workings available to them during that time. These faults are probably small in displacement but still give important information on the nature of movement and degree of fracturing in the area.

FOLDS IN PROTEROZOIC ROCKS

Proterozoic metamorphic rocks in the quadrangle show structures and textures representative of ductile deformation resulting from multiple periods of crustal instability and the high temperatures and high pressures of deep burial. Small folds are observed throughout the migmatite as either contorted layering or ptygmatic folds. Multiple fold lineations were observed and measured, however
limited data showed no preferred directions. The rocks show strong foliation, primarily in the form of preferred mineral orientation, which probably is concordant with the original bedding of the rocks (Fig. 14). No large folds were observed although they may be present but unrecognizable in the thick, discontinuous units of the Proterozoic metamorphic rocks.

GEOLOGIC HAZARDS

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

LANDSLIDES

Landslide deposits are relatively abundant west of the range crest, due to the widespread presence of the relatively weak Minturn Formation (unit Pm), and the existence of steep slopes eroded by late Pleistocene valley glaciers. Most landslides occur where beds in the Minturn Formation dip in the same direction as the slope. This condition is widespread between the Mosquito fault and the East Fork Arkansas River, and landslides are particularly abundant on the steep eastern valley wall of the East Fork Arkansas River, where beds daylight (Fig. 21). A similar situation exists on the eastern side of the summit ridge of the Mosquito Range, including American Flats, where east-dipping beds of Minturn Formation and interbedded porphyry sills have slid. Some of the landslide blocks have been smoothed by overriding glacial ice, so presumably predate the Pinedale glaciation.

In contrast, there are fewer landslides in the Precambrian terrane east of the Mosquito and/or London faults. Generally in Colorado, landslides in Precambrian crystalline rocks are rare except where past faulting, shearing, and alteration have induced low rock mass strength. In such areas, the rock mass strength is low enough to permit slope failure of fractured and/or altered rock on steep slopes during times of either elevated water table, strong earthquake shaking, or both. In the Climax quadrangle, two landslides lie astride the Mosquito fault (see Fig. 18). Another two landslides lie along the London fault, on either flank of Pennsylvania Mountain (see Fig. 19).
Fig. 21a. View looking east, of a post-glacial landslide on the eastern wall of East Fork Arkansas River, north of the mouth of French Gulch (just off photo to right). Highway 91 in foreground. Cuts of the LC&S railroad are visible at the head of the slide. The bouldery, hummocky toe is separated from the slide body by a low trough, and has a much lower slope angle. We infer that this toe may have been deposited in standing water in a marsh or shallow lake on the valley floor.

Fig. 21b. Annotated Google Earth view of the French-English Gulch low-angle landslide block (at center; younger part outlined in red, older part in yellow). View is to the east; the glaciated valley of the East Fork Arkansas River is in foreground. Dotted blue line shows the Pinedale glacial limit. The toe of the younger landslide block is composed of blocks of Tertiary intrusive that were clearly overridden by Pinedale ice, thus this block moved pre-Pinedale. The upper slide block extends all the way to the Mosquito fault, and based on morphology, is older than the lower landslide block. Note that the antislope scarps (orange arrows) along the Mosquito Fault escarpment exist only above the head of the low-angle slide block.
In addition to landslide deposits, the geologic map shows areas where large intact masses of bedrock have detached from mountain ridges, but have not slid far enough downslope to disaggregate into an unconsolidated deposit. These areas form one end of a spectrum of slope failures, which ranges from incipient gravitational spreading (sackung) marked by antislip scarp, to bulging of slopes due to rock mass creep into steep valley walls, to mappable landslide complexes that are a mixture of intact bedrock blocks and crushed matrix material (such as unit Qlsc). The Qlsc deposit on the western map boundary coincides with a stretch of deformed track on the Leadville & Southern Railroad, suggesting ongoing historic movement.

**FLOODS AND DEBRIS FLOWS**

Intense summer rainstorms or rapid melting of deep snowpack during unusually warm spring thaws may cause localized flooding and debris-flow activity. For example, most of the area mapped as Holocene alluvium (Qal) in the quadrangle lies on modern floodplains and is potentially subject to flooding. A related hazard is that of sheetwash and sheetfloods at the heads of small drainages, debris flows in ephemeral and intermittent streams, and resulting deposition on alluvial fans. Such areas are generally mapped herein as alluvium/colluvium (Qac). All undissected Holocene alluvial fans (Qf) and talus fans (Qtf) are potentially subject to debris-flow deposition over most of their surfaces (Fig. 22).

**ABANDONED MINES**

Collapse of abandoned mine shafts, tunnels, and excavated highwalls pose a potential hazard in the Climax quadrangle. The hazard potential is greatest in heavily-mined districts such as the Leadville Mining District in the southwestern corner of the quadrangle, and the Alma-Horseshoe Mining District in the eastern quarter of the quadrangle. Numerous shallow prospect pits are also present in the quadrangle, but most of these are partly filled with local slopewash and do not present a collapse hazard.

**SEISMICITY AND ACTIVE FAULTING**

The Climax quadrangle lies in the Rio Grande rift, an active zone of crustal extension. The level of historic seismicity is low in the Colorado portion of this rift. A search of the USGS/NEIC Internet catalog of earthquakes "Preliminary Determination of Epicenters" (1973-2003 A.D.) reveals only one instrumental earthquake within a 10 km (6 mile) radius of the center of the quadrangle (Table 2).
Fig. 22. Photograph of recent debris flow deposits on a talus fan (Qtf) in the cirque of the East Fork Arkansas River. This deposit probably resulted from the storm of July 28, 1999 (Godt and Coe, 2003).

Table 2. Summary of instrumental earthquakes within a 10 km radius of the center of the Climax quadrangle. Source: USGS website, http://neic.usgs.gov/neis/epic/epic_circ.html; Catalog= PDE; Circle Search, centered on Latitude=38.562N Longitude=106.062W Radius: 10.000 km; Data Selection: Historical & Preliminary Data

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Previous work suggested that the Mosquito fault may have been active in late Quaternary time (see previous section on Structural Geology). For example, the Quaternary Fault and Fold Database maintained by the Colorado Geological Survey (http://geosurveymaps.state.co.us/cgs_faults/) lists the Mosquito fault as a definite Quaternary fault exhibiting latest displacement in late Quaternary time (past 130 ka). This assessment stems mainly from reconnaissance observations by Tweto (1978, p. 18), who stated that “high lateral moraines are faulted” by the fault in a saddle north of the summit of Mount Arkansas. These
observations were repeated by Kirkham and Rogers (1981, p. 41), who concluded, however, that “the nature of the anomalous features that occur along the fault trace in the moraine can only be ascertained through detailed studies which would probably have to include trenching.”

According to our mapping and interpretation, all the scarps in the vicinity of the Mosquito fault are related to landsliding or deep-seated gravitational spreading, rather than to coseismic surface faulting in the Quaternary. The largest anomalous landform along the Mosquito fault is the prominent bench and antislope scarp at the toe of the range front escarpment between English and French Gulches (Fig. 23).

![Fig. 23. Photograph of the most prominent antislope scarp and trough between English and French Gulches. Active, unvegetated talus at center has been beheaded from its source at right, by the development of a fresh tension fissure. The trace of the Mosquito fault is located about 50 m downslope (to the left). Person for scale is 6 ft 2 inches tall.](image)

This linear landform lies roughly 50 m upslope from the trace of the Mosquito fault. The most prominent part of this antislope scarp occurs on the upslope end of the ridge that separates French Gulch and Little English Gulch (French-Little English Ridge). The trough behind that scarp exhibits a sharp fissure in active talus that may be as young as historic.
This anomalous series of three antislope scarps on the French-English Ridge is inferred to reflect gravitational spreading and westward toppling of the (altered) fault footwall rocks and overlying range-front colluvium, rather than tectonic faulting, for several reasons: (1) the antislope scarps only exist at the range front, directly upslope of the large French Gulch-English Gulch low-angle slide block, (2) there are no antislope scarps, or valley-facing scarps, elsewhere along the mapped trace of the Mosquito fault in the Climax quadrangle, and (3) the young fissure shown in Fig. 20 cannot be coseismic, because there have been no late Holocene or historic earthquakes on the Mosquito fault. The driving force for the inferred gravitational toppling is the debuttressing effect from a large, low-angle slide block directly downslope, a slide block which contains all of the French-Little English Ridge. The toe of this ridge-slide block protrudes 500-600 ft into the glaciated valley of the East Fork, but was overridden by Pinedale ice; thus it probably last had major movement between the Pinedale and Bull Lake glaciations. However, the very fresh appearance of the trough fissure implies that stress adjustments may still be continuing.

MINERAL RESOURCES

METALLIC MINERALS

Three important mining districts are located within the quadrangle; the Climax district is in the northern part, the Leadville district is in the southwestern part, and the London district is in the southeastern part. Each deposit has a distinct geology and origin and will be discussed separately.

CLIMAX MINING DISTRICT

The Climax mining district contains the world’s largest molybdenum deposit, with an initial geologic reserve estimated at 1 billion tons averaging 0.24 percent Mo (Carten and others, 1993). The main producing mine, the Climax Mine (Fig. 24), has been on standby status since 1995, and in 2009 was being prepared to re-open, before those plans too were put on hold.
Fig. 24. Panoramic photograph of the Climax Mine, looking east from the west side of Highway 91, at the summit of Fremont Pass.

Mineralization at Climax is spatially, temporally, and genetically related to a series of porphyritic granite intrusions into Precambrian granitic rocks (Wallace et al., 1968; White et al., 1981). The ore body consists of three separate shells of quartz-molybdenite mineralization; a highly silicified core, a moderately silicified zone, and a slightly silicified outer zone (Butler and Vanderwilt, 1933). Each ore shell is associated with the intrusion of separate granite porphyries, which collectively formed a composite stock. The outer slightly silicified zone, and a small portion of the moderately silicified zone, cropped out and were mined at the surface. The moderately silicified zone formed the bulk of the open pit mining at Climax, whereas the highly silicified core was mined underground (Wallace and others, 1968). The mineralized pipe or stock containing these zones is roughly circular, except where it is cut off by the Mosquito fault, and is approximately one mile in diameter. Mineralization is typically contained within thin (less than a quarter of an inch), closely spaced, quartz-molybdenite veinlets that cut the rock in every direction. Toward the central core the replacement veins become larger and more coarsely crystalline. Both veins and wall rock contain more quartz and less orthoclase and pyrite. The molybdenite content decreases to a level below that desired for ore, but small occurrences of ore are present within the core.

The magmatic intrusions responsible for the Climax mineralization occurred over an 11 million year period, between 24 and 33 Ma (White and others, 1981). The chemistry of these magmas is distinctly different from the calc-alkaline igneous rocks that are present in the rest of the quadrangle with one exception; the Chalk Mountain rhyolite is believed to be associated with the Climax intrusions (White and others, 1981).
LEADVILLE MINING DISTRICT

The Leadville district was inactive and all mines were inaccessible when this report was written. Most of the following data were taken from Emmons and others, 1927, and Bergendahl and Koschmann, 1971. The ore bodies in the Leadville district are classified according to form into veins, stockworks closely related to veins, replacement deposits, and placers. The first two classes are found primarily in the siliceous rocks of the Minturn Formation and the Proterozoic crystalline rocks. The third class is found in the carbonate rocks of the Leadville Limestone, the Manitou Formation, and in the limestone members of the Minturn Formation. The placers are only incidentally considered and are mentioned mainly for historic interest.

The ore bodies of the first group are generally found in contact with sills of porphyry which were consolidated and fractured prior to deposition of the ore. This group is the least important commercially. Most of the important veins of the district were discovered by underground development. The scarcity of outcrops is due to the rapid erosion of the vein material, extensive glacial deposits and disintegrated rock, and the failure of most veins to reach the surface of the bedrock. The greatest production has come from veins with northward trends. The veins of the second group have been worked since 1868, but have also been of minor economic importance. Only a few stockworks have been found and they may be regarded as variations of the veins.

The replacement deposits of the third group consist of large masses of sulfide minerals that were formed primarily in the Leadville Limestone, with secondary deposits found in the Manitou Formation (referred to as the “White Limestone” by Emmons and others, 1927). The replacement bodies commonly occur at certain horizons, locally called “contacts”, where structural conditions have controlled the mineralizing solutions and consequently, the concentration of the ore. The number of “contacts” varies with the number of porphyry sills and shale beds that act as impermeable boundaries to the ore bodies. In some places, ore has been mined at as many as ten or eleven “contacts”.

The ores are believed to have been deposited by high to moderate temperature magmatic waters during the multiple porphyry intrusive stages during the Tertiary. Large quantities of ore-bearing solutions accumulated in the magma reservoirs and rose upwards as faulting and fracturing allowed. Several periods of ore-solution activity are suggested by moderate temperature sulfide veins crosscutting higher temperature deposits. Differences in mineral composition of the deposits were determined largely by the types of rocks which the solutions passed and by the temperature at which reaction with the rocks took place.
LONDON MINING DISTRICT

All of the mines along the London fault in the quadrangle from Pennsylvania Mountain to London Mountain to Mosquito Peak were inaccessible during the mapping and report preparation. The following data and descriptions are primarily from Singewald and Butler (1941).

The ore deposits along the London fault constitute a large group in the Mosquito Range and have regional relations to the ores of the Alma District to the east. The mines of both of these districts are within a few hundred ft of the London fault or several thousand ft of the Cooper Gulch fault in the western part of the Alma quadrangle. Their distribution along these two major reverse faults is not uniform; they are localized near the centers of mineralization. The principal types of ores are; (1) gold-bearing quartz-sulfide veins in or adjoining porphyry sills close to the base of the Minturn Formation, (2) replacement deposits of silver-lead ores within the limestones, primarily the Leadville limestone, and (3) gold deposits in the quartzites of the Sawatch Formation. Individual ore bodies are localized along minor faults. Gold deposits of each type are flanked by small silver-lead deposits, but the large silver-lead deposits appear to be grouped near an independent, local center of mineralization.

The age relations of the ores with respect to the Tertiary intrusives and the faults suggest only one period of deposition. The ores formed from hydrothermal solutions from the porphyry magma reservoirs which propagated upwards along the fault planes and associated fractures. The London vein system, worked primarily in the London Mine, has supplied most of the ore from the London fault zone. The veins occur in fractures that strike essentially parallel to the London fault but dip to the southwest. At least 90 percent of the production has come from veins where they are in or adjoining contiguous sills of White porphyry or quartz monzonite porphyry that are close to the base of the Minturn Formation. The remainder has come from the upper beds of the Leadville Limestone. The veins are barren in the rocks above the tops of these sills.

INDUSTRIAL MINERALS

Two active industrial mineral permits exist within the Climax quadrangle. The largest is a gravel pit located just south of Fremont Pass along the upper Arkansas River in the northern part of the quadrangle. The second is a small gravel pit located in the west central part of the quadrangle, also along the Arkansas River. Each of these pits is a source of sand and gravel sourced from stream deposits and glacial alluvium.
Precambrian migmatite and granite are abundantly exposed in the eastern half of the quadrangle and can be used for rip-rap and crushed rock aggregate. However, access to these potential deposits is currently limited due to poor roads and steep topography.

Numerous beds of limestone are found within the Minturn Formation but are discontinuous and generally less than 15 ft in thickness. The Leadville Limestone is a thicker more continuous unit, but crops out east of the Mosquito fault in the higher, more inaccessible areas of the quadrangle. Currently, these limestone units are not considered a significant resource.

**GROUND-WATER RESOURCES**

According to the Colorado Division of Water Resources, there are 63 water wells in the Climax quadrangle, of which 38 have information on well depth. More than half of the wells (34 of 63) are clustered in a residential subdivision between Buckeye Gulch and the western map boundary, on the north side of Highway 91. Another 7 wells lie nearby on the valley floor of the East Fork Arkansas River, opposite the mouth of Birdseye Gulch. The remaining wells are scattered about the quadrangle.

Wells range from 3-700 ft deep, but 29 of the 38 wells with known depths are less than 100 ft deep. Of the remaining 9 wells >100 ft deep, 3 are from 100-200 ft deep, 3 are from 200-300 ft deep, and 3 are from 500-700 ft deep. All 3 of the deepest wells are located on the lip of the glacial U-shaped valley of South Mosquito Creek near the London Extension and American mines. These wells lie about 520 ft above the valley floor, thus their bottoms are 50-180 ft below the elevation of the valley floor.

Of the 38 wells with depth information, 31 have measured static water levels. These levels range from 2-326 ft below surface. Generally, the deeper wells have deeper water levels (Table 3), but water yield is not a simple function of depth. The highest yields (325-326 gpm) come from the deepest wells (569-655 ft) that produce from bedrock aquifers. However, in the shallower wells, well yield is moderate from 0-50 ft, higher from 50-100 ft, then decreases from 100-300 ft. The decreased yield of wells deeper than 100 ft probably results from their all being completed in relatively impermeable (“tight”) bedrock, whereas most of the wells shallower than 100 ft are completed in more permeable surficial deposits (alluvium, glacial till).
Table 3. Summary of water well data in the Climax quadrangle.

<table>
<thead>
<tr>
<th>Well Depth (ft)</th>
<th>Water Level (ft below ground surface)</th>
<th>Yield (gpm)</th>
<th>Average Yield (gpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-50</td>
<td>10-35</td>
<td>3-20</td>
<td>12.6</td>
</tr>
<tr>
<td>50-100</td>
<td>14-40</td>
<td>8-30</td>
<td>16.0</td>
</tr>
<tr>
<td>100-200</td>
<td>29-40</td>
<td>10-12</td>
<td>11.0</td>
</tr>
<tr>
<td>200-300</td>
<td>90-150</td>
<td>6</td>
<td>6.0</td>
</tr>
<tr>
<td>500-700</td>
<td>325-326</td>
<td>347</td>
<td>347.0</td>
</tr>
</tbody>
</table>

REFERENCES CITED


Behre, C.H., Jr., 1939, Preliminary geologic map of the West Slope of the Mosquito Range in the vicinity of Leadville, Colorado: U.S. Geological Survey, scale 1: 12,000


