Open-File Report 04-4

Geologic Map of the Buena Vista East Quadrangle, Chaffee County, Colorado

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Colorado Geological Survey
Division of Minerals and Geology
Department of Natural Resources
Denver, Colorado

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

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FOREWORD

The purpose of Colorado Geological Survey Open File Report 04-4, *Geologic Map of the Buena Vista East Quadrangle, Chaffee County, Colorado* is to describe the geologic setting, mineral resource potential, and geologic hazards of this 7.5-minute quadrangle located in central Colorado. The principal geologists for the mapping project were John Keller, CGS staff geologist, and Dr. James McCalpin, consulting geologist. Ben Lowry, an undergraduate geology student from The University of Colorado-Boulder, also contributed to the effort.

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

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INTRODUCTION AND LOCATION

The Buena Vista East 7.5-minute quadrangle is located along the Arkansas River in Chaffee County, central Colorado (fig. 1). The eastern part of the town of Buena Vista is in the northwest part of the quadrangle. U.S. Highways 285 and 24 are coincident over most of the quadrangle and transect the quadrangle northeast to southwest. Trout Creek Pass, on the same highway, is located about five miles northeast of the quadrangle. At Johnson Village near the Arkansas River in the map area, the highways split, US Highway 24 going north to Buena Vista and Leadville, U.S. Highway 285 going south to Nathrop and Alamosa.

The majority of the quadrangle is in the southern part of the Mosquito Range (Epis and Chapin, 1975) and is characterized by low, rolling, forested mountains. Limestone Ridge, in the northeastern part of the quadrangle, is the highest point in the map area at 10,132 ft above sea level. The Arkansas River flows south-southeast through the Arkansas Valley in the western one-quarter of the quadrangle. The lowest point in the map area is along the Arkansas River near Ruby Mountain, at about 7,610 ft above sea level. There is 2,522 ft of vertical relief in the Buena Vista East quadrangle.

Most of the mountainous part of the Buena Vista East quadrangle is publicly owned land administered by the U.S. Forest Service (San Isabel National Forest) and the U.S. Bureau of Land Management. A large part of the Fourmile Travel Management Area, a popular system of designated trails and four-wheel-drive roads for off-road vehicles, is on public lands within the quadrangle. The lands in the Arkansas Valley within the quadrangle are mostly privately owned. Much of the land along Trout Creek and in Piles Pasture east of Midland Hill is private as well. The Arkansas River is the most popular whitewater recreation river in the U.S. and dozens of rafts and kayaks float through the Buena Vista East quadrangle every day from late spring through mid-summer.

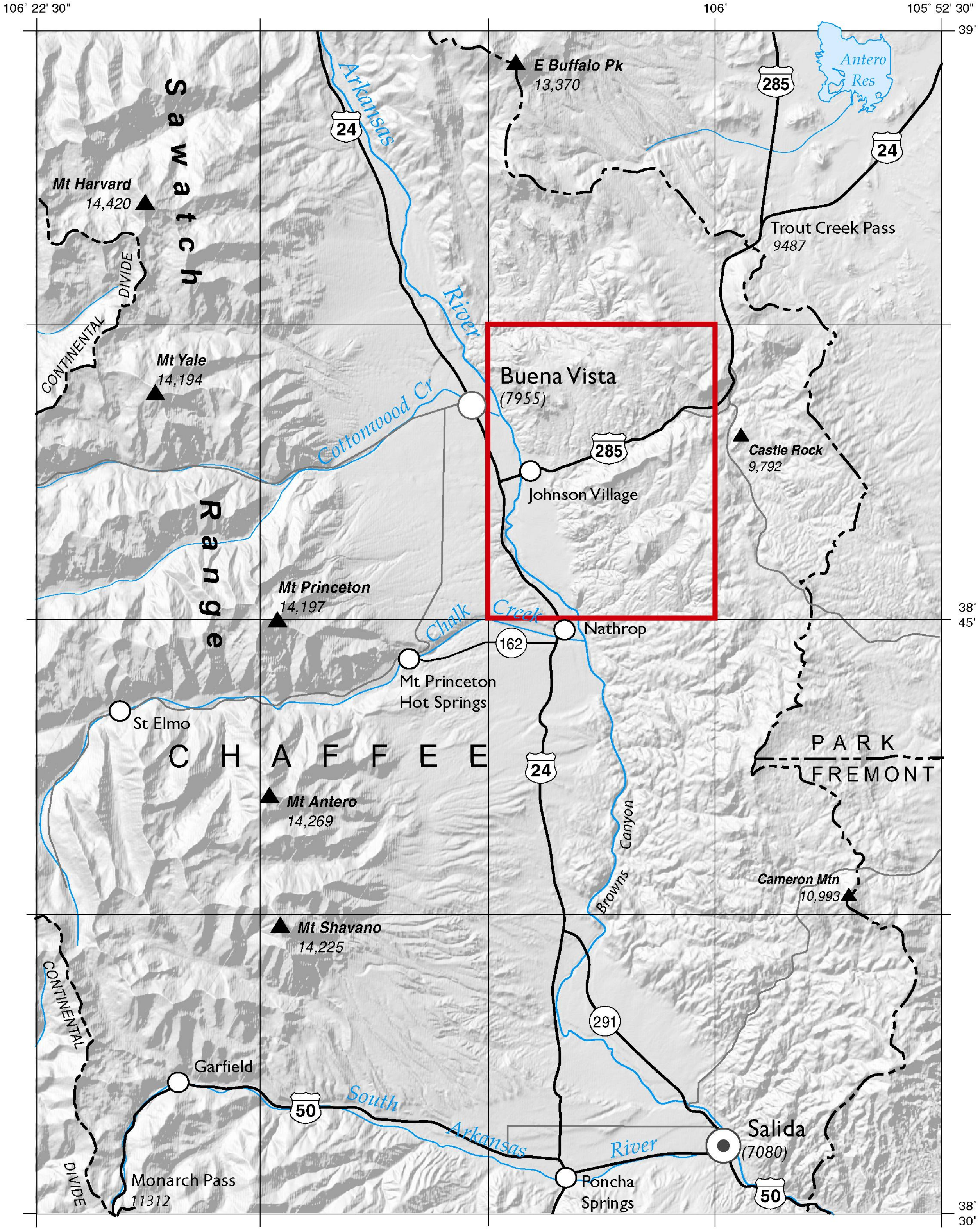


Figure 1. Shaded relief map showing the location of the Buena Vista East 7.5' quadrangle (in red).

GEOLOGIC BACKGROUND

The oldest and most extensive rocks exposed in the quadrangle are Early Proterozoic metamorphic and intrusive igneous rocks. Granodiorite and quartz diorite of Boulder Creek age are part of an irregular batholith that is exposed over a large area of central Colorado (Tweto, 1987). The granodiorite, which is locally gneissic, has been dated at 1672±5 Ma (Bickford and others, 1989) in the Cameron Mountain quadrangle, which adjoins the Buena Vista East quadrangle to the southeast. Small plugs and stocks of granite of Early or Middle (?) Proterozoic age have intruded the older granodiorite at a few places. Pegmatites, some of which have been mined in the past, are spatially and genetically related to these granites.

Paleozoic sedimentary rocks unconformably overlie the Proterozoic basement on Limestone Ridge, and in a small area on an unnamed ridge along the eastern boundary of the map area. The Cambrian Sawatch Quartzite is the oldest of these. The Sawatch is about 10 ft thick at the northern margin of the Buena Vista East quadrangle. The sandstone pinches out to the south along Limestone Ridge, and is absent from the section at the road cut on Highway 285/24 in Castle Rock Gulch quadrangle directly east of the map area. The Leadville Limestone is of very high purity on Limestone Ridge and has been mined in the past at the Newett Quarries, which are mainly located just east of the map area. The Belden Shale is the youngest Paleozoic unit exposed in the map area. It underlies the gentle, treeless topography of Chubb Park in the extreme northeast corner of the Buena Vista East quadrangle.

Volcanic rocks were extruded during late Eocene time (37.5-36.1 Ma) and during middle Oligocene time (30.1 to 30.4 Ma) and overlie Proterozoic rocks and Paleozoic rocks. These volcanic rocks are erosional remnants of the extensive central Colorado volcanic field (McIntosh and Chapin, 2004). The volcanics rest on a late Eocene erosion surface that has been documented over a large area of central and southern Colorado (Epis and Chapin, 1975). In the Buena Vista East quadrangle, late Eocene volcanic rocks on Triad Ridge (fig. 2) help to define the Trout Creek paleovalley (Scott, 1975) and at least one other paleodrainage. The Tallahassee Creek Conglomerate is also preserved at places in paleovalleys within the quadrangle.

Rhyolitic rocks of the Nathrop Volcanics (Van Alstine, 1969) were extruded during Oligocene time in the southwestern part of the map area. McIntosh and Chapin (2004) have dated the Nathrop Volcanics at 30.1 to 30.4 Ma. Ruby Mountain, Sugarloaf Mountain, Bald Mountain, and Dorothy Hill are erosional remnants of this alkali rhyolite volcanism. Fine specimens of spessartine garnet (ruby red color), topaz, and "apache tears" of obsidian are found at Ruby Mountain and it is a well-known mineral collecting locality (Voynick, 1994). The extrusion of the Nathrop Volcanics is roughly coincident with the onset of Rio Grande rift extensional tectonics (Chapin and Cather, 1994).

The Dry Union Formation of Miocene and Pliocene age is exposed west of the Arkansas River in the southwest part of the quadrangle. The Dry Union Formation consists of arkosic, partly volcaniclastic floodplain and alluvial fan sediments (Van Alstine, 1969). The Dry Union Formation is probably partially equivalent to the lithologically similar Wagontongue Formation and Trump Formation (De Voto, 1971) in South Park. Clasts of the Nathrop Volcanics have been identified in the Wagontongue Formation in South Park (Scott, 1975). This indicates that the paleovalleys described above continued to transport sediment eastward until sometime after ~29 Ma (Tweto, 1978).

Surficial Quaternary deposits cover the floor of the Arkansas Valley and include large glacial outwash deposits from several glacial episodes, modern stream alluvium, and alluvial fan deposits. In the mountainous part of the quadrangle, landslide deposits of Quaternary age are common.

The Buena Vista East quadrangle lies within the area of intersection of three major tectonic and tectono-stratigraphic features of regional to continental scale: the Rio Grande rift (Chapin, 1971; Chapin and Cather, 1994); the Colorado mineral belt (Tweto and Sims, 1963; CD-Rom Working Group, 2002); and the Central Colorado trough (De Voto, 1972; 1980). Rocks within the quadrangle have undergone structural deformation repeatedly through geologic time. Notable deformation events occurred in central Colorado during the Proterozoic (Tweto, 1980a; Reed and others, 1987; Shaw and others, 2001); the Pennsylvanian (De Voto, 1972); the Laramide Orogeny of Late Cretaceous and early Tertiary time (Tweto and Sims, 1963; Tweto, 1980b); and during middle and late Tertiary (Epis and others, 1980). Perhaps the most striking structural feature in the region of the Buena Vista East quadrangle is the Rio Grande rift, a major continental rift zone that has been tectonically active from Oligocene time to the present. The upper Arkansas Basin is one of the axial basins of the rift (Chapin, 1971; Chapin and Cather, 1994). Evidence for strong earthquake activity during the Quaternary was observed at one location in the southwestern part of the quadrangle.

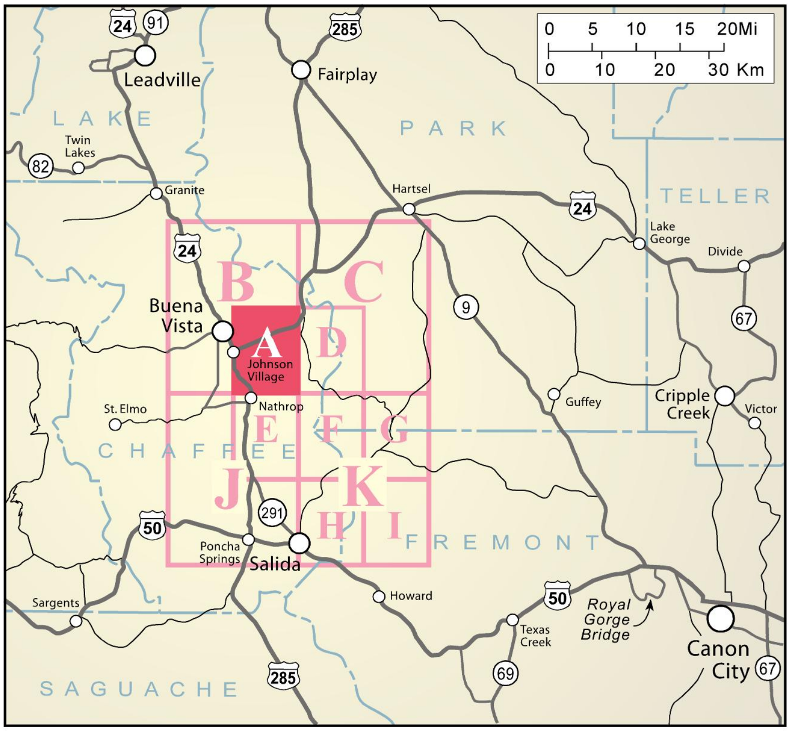
Figure 2. View to the west down Trout Creek, parallel to the axis of the Trout Creek paleovalley of Eocene age. Triad Ridge is at left; US Highway 285/24 is at center; Sawatch Range is in the far distance. At far right is McGee Gulch, the site of a northwest-trending fault.

PREVIOUS STUDIES

Numerous geologic studies have established the regional geologic framework in the southern Mosquito Range and Arkansas Valley areas. Barker and Brock (1965), Reed and others (1987), Tweto (1987), and Bickford and others (1989), reported on the regional geology and geochronology of the Proterozoic intrusive and metamorphic rocks that comprise the majority of the bedrock in the Buena Vista East quadrangle. Reports on regional stratigraphy of lower and middle Paleozoic rocks by Campbell (1972), Conley (1972), Gerhard (1972), Nadeau (1972), Ross and Tweto (1980) and Myrow and others (2003) established the regional stratigraphic sequence and lithofacies relations. De Voto (1971, 1972, 1980), and De Voto and Peel (1972) established the stratigraphic framework for upper Paleozoic rocks in the southern Mosquito Range. Chapin and Lowell (1979), Epis and Chapin (1974, 1975), and McIntosh and Chapin (2004) developed regional correlations of ash-flow tuff deposits and determined isotopic ages for volcanic rock units. In a comprehensive study, McIntosh and Chapin (2004) developed a time-stratigraphic framework for the central Colorado volcanic field, of which the intermediate volcanic rocks in the Trout Creek paleovalley and the silicic Nathrop Volcanics are erosional remnants. The Nathrop Volcanics were formally named and described in detail by Van Alstine (1969), who also mapped the geology of what is now the Nathrop 7.5-minute quadrangle, which lies directly south of the Buena Vista East quadrangle. In an unpublished M.S. thesis, Limbach

(1975) mapped and described the geology of both sides of the Arkansas Valley as well as the valley floor.

A series of 15-minute geologic maps by the U.S. Geological Survey (Scott, 1975; Wrucke and Dings, 1979) described geologic relations in the southern Mosquito Range. In particular, Scott's (1975) reconnaissance geologic map of the Buena Vista 15-minute quadrangle served as a guide for much of our mapping. De Voto (1971) published the Antero Reservoir 15-minute quadrangle, which lies directly east of the Buena Vista East quadrangle. The Colorado Geological Survey published a series of geologic maps at 1:24,000-scale in the southern Mosquito Range (Wallace and others, 1997; Wallace and Lawson, 1998; Wallace and others, 1999, 2000; Wallace and Keller, 2003); Buena Vista East is the sixth map in that series. Previous geologic mapping at scales of 1:62,500 and 1:24,000 are shown in figure 3, below. The geology of the Buena Vista East quadrangle is shown in a generalized form in the eastern part of the Montrose 1° X 2° quadrangle (Tweto and others, 1976).



A. Buena Vista East 1:24,000 geologic map (present study), CGS

B. Buena Vista 1:62,500 geologic map (Scott, 1975), USGS

C. Antero Reservoir 1:62,500 geologic map (De Voto, 1971), Colo. Sch. Mines

D. Castle Rock Gulch 1:24,000 geologic map, (Wallace and Keller, 2003) CGS

E. Poncha Springs NE (Nathrop) 1:24,000 geologic map (Van Alstine, 1969), USGS

F. Cameron Mountain 1:24,000 geologic map (Wallace and Lawson, 1998), CGS

G Gribbles Park 1:24,000 geologic map (Wallace and others, 1999), CGS

H Salida East 1:24,000 geologic map (Wallace and others, 1997), CGS

I. Jack Hall Mountain 1:24,000 geologic map (Wallace and others, 2000), CGS

J. Poncha Springs 1:62,500 geologic map (Scott, VanAlstine and Sharp, 1975), USGS

K. Cameron Mountain 1:62,500 geologic map (Wrucke and Dings, 1979), USGS

Figure 3. Location of the Buena Vista East 7.5-minute quadrangle and index of previously completed 1:24,000- and 1:62,500-scale geologic mapping in the area.

PRESENT STUDY

The present study focuses on geologic mapping in the Buena Vista East 7.5-minute quadrangle at a scale of 1:24,000. Geologic mapping was completed during July to October, 2003. John Keller and Ben Lowry mapped and described the bedrock geology. Dr. James McCalpin mapped the surficial Quaternary deposits throughout the map area, and mapped exposures of the Neogene Dry Union Formation in the southwest part of the map area. Keller and McCalpin described the structural geology of the quadrangle. McCalpin completed the geologic hazards analysis and the description of water resources. Keller compiled and assembled the map and text from information provided by all authors, and completed the description of mineral resources in the quadrangle. Lowry cut thin sections of samples of Tertiary dikes and Proterozoic rocks.

Field data for bedrock were plotted on color aerial photographs taken by the U.S. Forest Service in 1997 at a nominal scale of 1:24,000. The annotated photos were scanned and imported into ERDAS Imagine Stereo Analyst where they were photogrammetrically corrected and rendered in 3-D. Line work and point data was digitized directly from ERDAS Imagine Stereo Analyst and exported as ESRI shapefiles. Surficial Quaternary units were mapped directly onto a U.S. Geological Survey 1:24,000-scale topographic map of the Buena Vista East quadrangle and subsequently digitized in ESRI ArcView. Geological editing and final map production was completed using ESRI ArcGIS software.

DESCRIPTION OF MAP UNITS

QUATERNARY DEPOSITS

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

HUMAN-MADE DEPOSITS

af **Artificial fill (latest Holocene) –** Unsorted silt, sand, and rock fragments deposited by humans during construction of U.S. Highways 24 and 285 and earthfill beneath the runway of the Chaffee County Regional Airport. The average thickness of the unit is less than 30 ft. Artificial fill may be subject to settlement when loaded if not adequately compacted.

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

Qaly **Younger stream-channel, flood-plain, and low-terrace alluvium (Holocene) –** Deposits are mostly matrix-supported gravelly sand. The deposits are locally interbedded with thin gravel lenses. This unit includes modern stream-channel deposits of the tributaries to Trout Creek, which are graded to a level about 10 ft above the modern stream level of Trout Creek. Deposits are interbedded with colluvium at the heads of the tributaries. Thickness about 10 ft. Areas mapped as alluvium may be prone to flooding and sediment deposition. The unit is typically a good source of sand.

Qal **Stream-channel, flood-plain, and low-terrace alluvium (Holocene) –** Deposits are mostly clast-supported, pebble, cobble, and locally boulder gravel in a sandy silt matrix. The deposits are locally interbedded with and commonly overlain by sandy silt and silty sand. Clasts are subangular to well rounded, and their varied lithology reflects the diverse types of bedrock within their provenance. This unit includes modern stream-channel deposits of the Arkansas River, Trout Creek, and their tributaries, adjacent flood-plain deposits, and low-terrace alluvium up to 10 ft above modern stream level. Deposits may be interbedded with colluvium or debris-fan deposits where the distal ends of fans extend into modern river channels and flood plains. Overlies buried older gravel along the Arkansas River. Thickness about 10 ft. Areas mapped as alluvium may be prone to flooding and sediment deposition. The unit is typically a good source of sand and gravel.

Qat **Younger terrace alluvium (Holocene) –** Consists of poorly sorted, clast-supported, cobble, pebble, and locally boulder gravel in a silty, sandy matrix underlying terraces 10 to 15 ft above modern stream channels. Fine-grained overbank deposits may be present locally. Deposits underlie alluvial terraces in Trout Creek and its larger tributaries. Clasts are generally unweathered and abundant on the surface. Soil development on terrace surfaces is weak. Generally post-dates the Pinedale glaciation, so is considered early to middle Holocene in age. Maximum exposed thickness is 15 ft. The unit may be a good source of sand and gravel.

Qpoy **Pinedale outwash deposits, younger (latest Pleistocene) –** Yellowish-gray, crudely stratified alluvium containing well-rounded to subrounded boulders, cobbles, pebbles, and sand. Composed principally of Tertiary igneous rocks and Precambrian metamorphic and igneous rocks. Soil at top is weakly developed. Forms a terrace about 30 ft above Arkansas River. Upper parts of outwash contain huge boulders emplaced by two catastrophic floods from breakouts of glacier dams at Pine Creek north of the map area (Scott, 1975). Average size of boulders is about 4 to 6 ft, but the largest boulder recognized is 65 ft in diameter. In places, Pinedale outwash can be subdivided into three terraces, from oldest to youngest, $Qpoy_1$, $Qpoy_2$, and $Qpoy_3$. The unit is a commercial source of gravel. Thickness probably 10-30 ft.

Qpoo **Pinedale outwash deposits, older (late Pleistocene) –** Yellowish-gray crudely stratified alluvium containing well-rounded to subrounded boulders, cobbles, pebbles, and sand. Composed principally of Tertiary igneous rocks and Precambrian metamorphic and igneous rocks. Soil at top is weakly developed. Forms most of the valley floor in the vicinity of the Arkansas River, in a terrace about 65 ft above the river. Upper parts of outwash contain huge boulders emplaced by two catastrophic floods from breakouts of glacier dams at Pine Creek north of the map area (Scott, 1975). The unit is a commercial source of gravel. Thickness probably 10-30 ft.

Qboy **Bull Lake outwash deposits, younger (late Pleistocene)**-- brownish gray to light gray sandy bouldery alluvium. In terrace 80 ft above Arkansas River. Boulders average about 10 inches in diameter, but some are larger than 4 ft, and are well rounded to subround, fairly well sorted, and fairly well stratified. Composed principally of Tertiary igneous and Precambrian metamorphic and igneous rocks. Some pieces of Mount Princeton Quartz Monzonite are disintegrated; other rock types are only slightly weathered. Soil at top is moderately well developed. The unit is a commercial source of gravel. Thickness probably about 20 ft.

Qao **Old alluvium (early to middle Pleistocene) –** Moderately sorted and stratified, locally-derived stream deposits. The deposits are texturally and depositionally similar to terrace alluvium (Qat), but clasts are moderately to highly weathered and not as abundant on terrace surfaces. Soil horizons are moderately well developed. Maximum thickness probably less than 16 ft. Mapped at only two places in the far western part of the quadrangle. The unit is a potential source of sand and gravel.

Qaof **Old alluvium, fine-grained (early to middle Pleistocene) –** Well-sorted and stratified, sandy to clayey stream and marsh deposits. Mapped only in the southwestern corner of the quadrangle, west of the down-to-the-west normal fault. Represents deposits of east-flowing streams (Dry Creek) and marshes partially dammed by the west-facing fault scarp. Post-dates map unit Qna (early Pleistocene), and may be in part as young as late Pleistocene. Contains soft-sediment deformation possibly related to earthquake-induced liquefaction. New radiocarbon dates for two samples (BVE-C5 and BVE-C6) of carbon-rich sediment from above and below the soft-sediment deformation interval bracket the timing of the possible earthquake between 3,140 -3,600 cal yr BP (calibrated years before present) and 14,100-15,350 cal yr BP. Maximum thickness of unit probably less than 16 ft.

Qk **Kansan (?) alluvium (middle Pleistocene)**— Yellowish gray to yellowish orange, fairly well-stratified alluvium containing well-rounded to subrounded fragments of igneous and metamorphic rocks. Overlain by fine-grained colluvial or overbank deposits that, 5-6 miles north of Buena Vista, contain type-O Pearlette ash, a marker volcanic bed with origin in Yellowstone National Park (Scott, 1975). Soil at top is very strongly developed. Deposit is part pediment cover and part terrace gravel; possibly includes some till or outwash from pre-Bull Lake glaciers. Deposits are about 160-200 ft above the Arkansas River. Part of deposit resulted from catastrophic flood that emplaced 20-ft-diameter boulders in S ½ sec. 11, T. 13 S., R. 79 W. Equivalent to unit Qg_3 of Van Alstine (1969) on the Nathrop quadrangle. Thickness probably more than 20 ft.

Qna **Nebraskan (?) alluvium (early Pleistocene)**—Light brown to gray, poorly sorted, poorly stratified, deeply weathered, sandy and bouldery deposit on pediments, and bouldery alluvium along the Arkansas River. Possibly includes some till or outwash from pre-Bull Lake glaciers. Lower part of deposit resulted from catastrophic flood that emplaced 18 ft-diameter boulders in abandoned Arkansas River channel in sec. 31, T. 13 S., R. 78 W. and sec. 6, T.14 S., R. 78 W. Soil at top is very strongly developed. Thickness possibly as much as 80 ft.

Qn **Nussbaum (?) Alluvium (early Pleistocene)—**Brownish-gray to pale-brown bouldery alluvium, crudely stratified, poorly sorted. Composition varies widely depending on source. Deposits are deeply weathered; soil at top is very strongly developed. Deposits are 260-270 ft above Arkansas River. Equivalent to unit Qg1 of Van Alstine (1969) on the Nathrop quadrangle. Thickness probably as much as 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, freeze-thaw action, and water-saturated conditions that affect pore pressure.

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

Qt **Talus deposits (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. Mapped only on the slopes of Triad Ridge, Sugarloaf Mountain, and Bald Mountain, where talus is derived from jointed Tertiary volcanic rocks. Thickness of the deposits is probably less than 15 ft. Talus areas are subject to rockfall, rock-topple, and rockslide hazards.

Qls **Landslide deposits, undifferentiated (middle? Pleistocene to Holocene) –** Mapped in areas where the relative age of a landslide is difficult to ascertain because many of the more common diagnostic features used to establish relative age have been altered by human activities. Composed of chaotically arranged debris ranging from clay to boulder size (diamicton). Surface of deposits commonly hummocky, and source area of landsliding is generally identifiable (top of scarp area indicated by thick dashed lines with ticks in direction of sliding). Larger landslide deposits may be more than 100 ft thick.

Qlsy **Younger landslide deposits (late Pleistocene to Holocene) –** Similar to map unit Qls, but younger than or coeval with the Pinedale glaciation (15-23 ka).

Qlso **Older landslide deposits (middle to late Pleistocene) –** Similar to map unit Qls, but older than Pinedale glaciation (15-23 ka). Mapped on the north slope of Triad Ridge and the east slope of Bald Mountain.

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

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

Qaco **Alluvium and colluvium, older (Pleistocene) –** Unit primarily consists of stream deposits of ephemeral, intermittent, and small perennial streams and colluvium deposits along valley sides. Alluvium is typically composed of poorly to well-sorted, stratified, interbedded, pebbly sand, sandy silt, and sandy gravel. Colluvium may range from unsorted, clast-supported, pebble to boulder gravel in a sandy silt matrix to matrix-supported, gravelly, clayey, sandy silt. Clast lithologies vary and are dependent upon the bedrock or surficial unit from which the deposit was derived. Maximum thickness of the unit is approximately 20 ft.

Qf **Alluvial-fan deposits, undifferentiated (Holocene and late Pleistocene) –** Moderately sorted sand- to boulder-size gravel in fan-shaped deposits from tributary streams of Trout Creek, and from smaller side streams in those tributaries. Deposits typically composed of both matrix-supported beds 3-5 ft thick (debris flow facies) and clast-supported beds 1-2.6 ft thick (streamflow facies), often interbedded. Clasts are mostly angular to subround with varied lithologies dependant upon local source rock. Sediments are deposited by debris flows, hyperconcentrated flows, streams, and sheetwash. Fan-shaped deposits form where tributary drainages with steep gradients join lower gradient streams. Debris-fan deposits commonly grade from boulder- and cobble-size fragments at the head of the fan to silty sand near the fan terminus. The maximum estimated thickness for debris fans along Trout Creek may exceed 30 ft. Elsewhere, the deposit is typically less than 10 ft thick. Extraordinary precipitation events may trigger future deposition in areas mapped as debris-fan deposits. Debris-fan deposits may be prone to collapse when wetted or loaded.

Qfy **Alluvial-fan deposits, younger (Holocene) –** Moderately sorted, sand- to boulder-size gravel in fan-shaped deposits from tributary streams. Deposits typically composed of both matrix-supported beds 3-5 ft thick (debris flow facies) and clast-supported beds 1-2.6 ft thick (streamflow facies), often interbedded. Clasts are mostly angular to subround with varied lithologies dependant upon local source rock. Sediments are deposited by debris flows, hyperconcentrated flows, streams, and sheetwash. Fan-shaped deposits form where tributary drainages with steep gradients join lower gradient streams. Deposit overlies and thus post-dates Pinedale outwash deposits in many places. The maximum estimated thickness for fan deposits along lower Trout Creek may exceed 16 ft. Extraordinary precipitation events may trigger future deposition in areas mapped as alluvial-fan deposits. Debris-fan deposits may be prone to collapse when wetted or loaded.

Qfi **Alluvial-fan deposits, intermediate age (latest Pleistocene to Holocene) –** Moderately sorted sand- to boulder-size gravel in fan-shaped deposits from tributary streams, mainly in intermittent tributary streams north of Trout Creek. Deposits typically composed of matrix-supported sandy alluvium locally derived from decomposed granite. Clasts are mostly angular to subangular. Deposit forms incised alluvial fans and small terraces 10 to 16 ft above modern stream level. The maximum thickness is at least 10 ft.

Qfo **Alluvial-fan deposits, older (late Pleistocene) –** Moderately sorted sand- to boulder-size gravel in fan-shaped deposits from tributary streams on the eastern (unglaciated) side of the upper Arkansas Valley. Deposits typically composed of both matrix-supported beds 3-5 ft thick (debris flow facies) and clast-supported beds 1-2.6 ft thick (streamflow facies), often interbedded. Clasts are mostly angular to subround with varied lithologies dependant upon local source rock. Sediments are deposited by the Arkansas River and by tributary fans. Deposit forms erosional remnants 16-33 ft above Pinedale outwash terraces on the eastern side of the upper Arkansas Valley. May correlate in part with map unit Qbf mapped on the western (glaciated) side of the valley. The maximum thickness is at least 16 ft.

Qbf **Alluvial-fan deposits, Bull Lake outwash deposits, younger (late Pleistocene)-- –** Moderately sorted sand- to boulder-size gravel in terrace deposits from tributary streams on the western side of the upper Arkansas Valley. Deposits typically composed of both matrix-supported beds 3-5 ft thick (debris flow facies) and clast-supported beds 1-2.6 ft thick (streamflow facies), often interbedded. Clasts are mostly angular to subround and derived from crystalline rocks of the Sawatch Range, or recycled from erosion of the Dry Union Formation. Sediments were deposited mainly by west-side tributaries to the Arkansas River, although some main-stream gravel facies may be interbedded. Deposit forms a large erosional remnant 16-33 ft above Pinedale outwash terraces (unit Qpoo) on the western side of the upper Arkansas Valley, and is probably correlative with Bull Lake outwash deposits (unit Qboy) deposited by glaciated tributaries to the Arkansas River. The maximum thickness is at least 16 ft.

TERTIARY ROCKS AND DEPOSITS

Td **Dry Union Formation (Pliocene and Miocene)—**Gray, yellowish gray, reddish gray, or greenish gray layers of clay, silt, sand, and gravel composed mainly of fragments of Tertiary volcanic rocks, but also containing Precambrian igneous and metamorphic rocks and Lower Paleozoic sedimentary rocks. Contains white to gray volcanic ash beds. Lower part contains fragments of Wall Mountain Tuff, ash-flow tuff from a caldera near Mount Aetna, Badger Creek Tuff, Tuff of Triad Ridge, Mount Antero Granite, Nathrop Volcanics, and Paleozoic chert and quartzite. Some layers are cemented by calcium carbonate. Sand and gravel layers are cross-stratified. Material deposited by streams and in ponds. Locally layers are tilted and faulted. On the Buena Vista East quadrangle, the Dry Union Formation is mostly buried by Quaternary deposits. Thickness is probably more than 2,000 ft in the extreme southwestern part of the quadrangle. Scott and others (1975) estimate that the Dry Union Formation is more than 5,000 ft thick on the western side of the Arkansas Valley graben.

NATHROP VOLCANICS - The 30 Ma Nathrop Volcanics are topaz-bearing, alkaline rhyolitic rocks that form Ruby Mountain, Sugarloaf Mountain, the upper part of Bald Mountain, and Dorothy Hill in the southern part of the Buena Vista East quadrangle and the northern part of the Nathrop quadrangle. Van Alstine (1969) formally named the Nathrop Volcanics based on his geologic mapping in the Nathrop quadrangle. Honea (1955) described the volcanic geology of the Ruby Mountain area and provided whole-rock geochemical analyses for eight samples from the Nathrop Volcanics (Table 1). Shannon (1988) presented strong evidence supporting a genetic relationship between the topaz-bearing Nathrop Volcanics and the chemically evolved, A-type hypabyssal granites of the Mount Antero area, 7 mi to the west-southwest on the west side of the Arkansas Valley graben. As part of that study, whole-rock and trace-element geochemical data, and lead, strontium, and neodymium isotope data, were presented.

Honea (1955) proposed a very young age (Pleistocene) for the volcanics and suggested that Bald Mountain is a symmetrical, composite volcanic cone with a crater-like "vent" at the top and has been little affected by erosion. Subsequent workers have shown that the Nathrop Volcanics are much older (Oligocene). The most recent ^{40}Ar/^{39}Ar radiometric age dates place the Nathrop Volcanics at 30.08 to 30.35 ±0.08 Ma (McIntosh and Chapin, 2004). The Nathrop Volcanics and the hypabyssal, A-type granites in the Mount Antero area were emplaced during or shortly before the earliest stages of the Rio Grande rift extensional tectonic event (Shannon, 1988). The topographical similarity of Bald Mountain to a symmetrical volcanic cone is probably only coincidental, given that no volcanic activity has occurred in the area for over 30 million years, during which time the area has been undergoing rapid erosion. Rhyolite fragments derived from the Nathrop Volcanics represent a significant percentage of the voluminous Dry Union Formation of Miocene and Pliocene age in the Arkansas Valley near Salida (Van Alstine, 1969). Fragments of the flow-banded rhyolite from the Nathrop Volcanics have also been found in the Miocene Wagontongue Formation in southwestern South Park (Stark and others, 1949). Thus, the direction of erosional transport from the Nathrop Volcanic area was both southward and northeastward.

Honea (1955) and Scott (1975) interpreted that a vent source for the Nathrop Volcanics exists near the top of Bald Mountain. Our mapping does not confirm that Bald Mountain was an extrusive vent for the Nathrop Volcanics. Although it remains possible that a vent exists on Bald Mountain, herein we present an alternative interpretation: the rhyolite at Bald Mountain was deposited as a thick flow accumulation within an east-northeast-trending paleovalley that also contains erosional remnants of Wall Mountain Tuff (Twm) and Tallahassee Creek Conglomerate (Ttc). During the Oligocene and into the Miocene, paleovalleys transported erosional debris from west to east across this region, as evidenced by fragments of Nathrop Volcanics in the Wagontongue Formation in South Park (Stark and others, 1949; Scott, 1975). Highly alkaline, topaz-bearing rhyolitic lava generally has lower viscosity than other types of rhyolitic lava and in some cases can flow for several miles away from a source vent (J. Price, written communication, 2004). Van Alstine (1969) mapped a small area of Nathrop Volcanics 2.75 mi southeast of Ruby Mountain on the Nathrop quadrangle. We mapped a similarly small "scab" of rhyolite 0.6 mi west of Bald Mountain between Tie Gulch and Arnold Gulch. Other possible source vent locations for the Nathrop Volcanics are: (1) at the north end of Sugarloaf Mountain where the contact between Nathrop rhyolite and Proterozoic granodiorite is steep and flow layering in the rhyolite dips very steeply and is highly contorted (Van Alstine, 1969), or (2) buried beneath Quaternary gravels west of the Sugarloaf/Ruby area.

Figure 4. Looking south toward Ruby Mountain and the Arkansas River from Sugarloaf Mountain, Buena Vista East quadrangle.

Table 1. Whole-rock geochemical analyses of samples from the Nathrop Volcanics (modified from Honea, 1955).

SAMPLE ID	SiO2	TiO2	Al2O3	Fe2O3	FeO	CaO	MgO	Na2O	K2O	H20	MnO	CO2	Total
1 (perlite, Ruby Mt)	73.77	0.11	12.82	0.85	0.25	0.57	0.1	4.17	5.08	2.86	0.001	0	100.58
2 (pitchstone, Ruby Mt)	71.25	0.09	13.77	0.69	0.19	0.95	0.13	3.41	4.12	5.14	0.001	0.45	100.19
4 (rhyolite, Ruby Mt)	76.37	0.09	13.1	0.58	0.21	0.71	0.15	4.82	4.53	0.05	0.06	0	100.67
5 (rhyolite, Ruby Mt)	75.05	0.1	13.53	0.99	0.14	0.5	0.08	4.99	4.78	0.34	0.02	0	100.52
6 (rhyolite, Dorothy Hill)	75.9	0.1	13.77	0.57	0.19	0.37	0.06	4.76	4.62	0.06	0.02	0	100.42
7 (rhyolite, Sugarloaf)	74.84	0.09	13.65	0.61	0.42	0.83	0.14	5.32	4.56	0.06	0.03	0	100.55
8 (tuff, Ruby Mt)	73.79	0.11	13.6	0.82	0.27	0.57	0.2	4.35	4.42	2.42	0.02	0	100.57
9 (rhyolite, Bald)	76.05	0.08	13.15	0.98	0.23	0.44	0.25	4.74	4.49	0.06	0.03	0	100.50

For this mapping project, we have subdivided the Nathrop Volcanics into three separate rock units that correspond to those mapped by Van Alstine (1969): (1) rhyolite flow (Tnr), (2) vitrophyre (Tnv), and (3) tuff and tuffaceous breccia (Tnt).

Tnr **Rhyolite of the Nathrop Volcanics (middle Oligocene) -** Alkaline rhyolite forms the crests and west faces of Ruby Mountain and Sugarloaf Mountain, and the upper part of Bald Mountain. Rhyolite also forms Dorothy Hill, the low, flat-topped mesa-like feature on the west bank of the Arkansas River, just north of Nathrop. A small, thin patch of rhyolite is present is present between Arnold Gulch and Tie Gulch west of Bald Mountain. Rhyolite was deposited as one or more lava flows on an uneven erosional surface. ^{40}Ar/^{39}Ar age dates of rhyolite are provided by McIntosh and Chapin (2004). Sanidine from a rhyolite sample from Bald Mountain is dated at 30.35 ±0.08 Ma. Sanidine from a rhyolite sample from Sugarloaf Mountain is dated at 30.08 ±0.08 Ma. A third age date, derived from anorthoclase from a sample of Bald Mountain rhyolite, was dated at 28.88 ±0.21 Ma. The rhyolites from both localities are chemically and petrographically very similar (Honea, 1955; Bade, 1989). On Bald Mountain, the rhyolite flow is estimated to be about 500 ft thick (cross section B-B'), and was deposited within a paleovalley that also contains erosional remnants of Wall Mountain Tuff (Twm) and Tallahassee Creek Conglomerate (Ttc). The moderate- and steeply-dipping rhyolite at Sugarloaf Mountain (fig. 5) and Ruby Mountain may be 1,000 ft. thick or more. The western extent of the rhyolite in that area is obscured by Quaternary alluvium of the

Arkansas Valley, so precise estimates of the true thickness are indeterminate. The rhyolite is very light-gray, light pinkish-gray, and purplish-gray. It is conspicuously flow-layered with thin, wavy, alternating layers of lighter and darker material. The rhyolite is often platy-weathering because of the flow layering. Rhyolite flow layering dips moderately to steeply to the west on both Ruby Mountain and Sugarloaf Mountain. Exposures of solid, in-place bedrock are rare on Bald Mountain. Two good exposures on the west side of Bald Mountain show flow layering dipping gently to the east. Petrographically, the rhyolite consists of small and sparse phenocrysts of smoky quartz, sanidine, plagioclase, and rare biotite in a dense microcrystalline groundmass. Accessory minerals include apatite, zircon, magnetite, garnet, and topaz. Whole-rock geochemical analyses of rhyolite samples from Bald Mountain, Ruby Mountain, Sugarloaf Mountain, and Dorothy Hill show that the composition is remarkably similar in all areas (Honea, 1955). Table 1 shows the results of these whole-rock analyses. Near the base of the rhyolite and above the vitrophyre (Tnv), the rhyolite commonly has a spherulitic texture. Spherulites range from about 0.1 to 3 inches in diameter. Flow-breccia is also present in the rhyolite at some places, particularly on Bald Mountain. Lithophysal cavities and vesicles are locally abundant in the rhyolite, particularly on Ruby Mountain (Honea, 1955). Lithophysae are up to 2 inches in diameter, and the roughly elliptical vesicles are generally less than 1 inch in the longest dimension (Van Alstine, 1969). Lithophysae and vesicles sometimes contain well-formed crystals of deep-red spessartine garnet and topaz. Topaz is less common than garnet and is "wine-yellow" when a cavity is first opened, but upon exposure to sunlight fades to pale blue or colorless (Honea, 1955). Both garnet and topaz crystals are generally less than 0.25 inch in diameter, but a few specimens measure up to 0.5 inch in diameter (Voynick, 1994). Some specimens are of gem-quality and have been cut into gemstones. Other more common minerals such as sanidine, quartz, magnetite, and hematite are also found in the lithophysal cavities.

Figure 5. Rhyolite of the Nathrop Volcanics (Tnr) at the top of Sugarloaf Mountain. Note the steep, westerly dip of the volcanic flow layering.

Tnv **Vitrophyre of the Nathrop Volcanics (middle Oligocene) -** Rhyolitic vitrophyre lays directly below the rhyolite (Tnr) on the eastern sides of Ruby Mountain and Sugarloaf Mountain, and on the northern side of Bald Mountain. The vitrophyre is the glassy, hydrous, chilled base of the rhyolite flow. The vitrophyre is composed predominantly of perlite, with lesser pitchstone. The vitrophyre unit varies greatly in thickness. It is up to 100 ft thick on Ruby Mountain, but is completely absent from parts of Sugarloaf Mountain. It is thickest on Ruby Mountain. The perlite is glassy, light- to dark-gray, brownish-gray, and black. It usually displays classic "shelly" or "onion-skin" perlitic structure. Toward the top of the vitrophyre, near the gradational contact with rhyolite, vitrophyre often displays spherulitic structure. The perlite contains sparse phenocrysts of quartz, sanidine, and plagioclase (Van Alstine, 1969). Light-gray perlite commonly contains obsidian nodules (marekanites) up to 0.5 inch in diameter. Obsidian nodules are commonly known to collectors as "Apache tears". Pitchstone is black with reddish mottling and consists of hydrated glass, pumice, and ash. On Ruby Mountain, pitchstone lies stratigraphically below perlite (Nickel, 1987). Honea (1955) presented whole-rock analyses for perlite and pitchstone (Table 1). Nickel (1987) presented numerous trace element analyses and detailed petrographic data for perlite, pitchstone, and obsidian nodules from Ruby Mountain.

Tnt **Tuff and tuffaceous breccia of the Nathrop Volcanics (middle Oligocene)** - Rhyolitic, pumiceous tuff and tuffaceous breccia of the Nathrop Volcanics is exposed on the lower, eastern sides of Sugarloaf Mountain and Ruby Mountain in the southwestern part of the quadrangle. The unit is light pink, light tan, and white, and is moderately consolidated. Angular clasts up to 12 inches in diameter composed of pumice, rhyolite, vitrophyre, and rarely Proterozoic rock, are present within the unit. Van Alstine (1969) reports blocks of pumice up to 4 ft in diameter. The matrix is composed of devitrified glass shards and pumice. Some of the glass fragments are partly devitrified to feldspar and cristobalite and further altered to a clay mineral (Van Alstine, 1969). The unit is crudely bedded, and local unconformities (erosional channels) are present within the unit. Tuff and tuffaceous breccia underlies the vitrophyre of the Nathrop Volcanics (Tnv) and the rhyolite of the Nathrop Volcanic (Tnr). Scott (1975) described the unit as a pumiceous volcanic mudflow. Two small exposures of poorly consolidated ashy breccia that are too small to map at 1:24,000 scale were observed on Bald Mountain, directly beneath the base of the rhyolite.

Tsb **Slide block (late Eocene or Oligocene[?])** – Landslide block consisting of a semi-cohesive mass of Manitou Limestone, Harding Quartzite, and Fremont Limestone that rests on Proterozoic granodiorite (Xgd) in sec. 21, T. 14 S., R. 77 W. The slide block appears to have originated from the ridge to the east and southeast where Lower Paleozoic strata are locally exposed beneath tuff of Triad Ridge. However, directly uphill from the mapped slide block, Paleozoic strata is not exposed (Ttr). The presence of tuff of Triad Ridge and Tallahassee Creek Conglomerate in the vicinity of the slide block indicates that the block was deposited within a paleovalley. The slide block here is similar to a slide block on the Castle Rock Gulch quadrangle to the east that appears to rest on the Tallahassee Creek Conglomerate (Wallace and Keller, 2003). That slide block, also located in a paleovalley, is not near enough to any exposures of in-place Paleozoic bedrock that could have provided material for the deposit during the Quaternary. Both blocks have localized orange-brown and dark brown jasperoidal silica deposits near their lower contacts. The jasperoid occurs as highly fractured, locally brecciated masses that have replaced irregularly shaped zones of Manitou Limestone (Om) or Fremont Dolomite (Of). Archaeologists have shown that silicified material from a small quarry site in the slide block on the Buena Vista East quadrangle was traded across long distances by native people. Known as the "Trout Creek chert quarry", the site was a significant toolstone source that shows utilization from 8,000 B.C. to early historic times. The material was traded throughout the Rocky Mountain region (T. McMahon, written communication, 2003).

Ttc **Tallahassee Creek Conglomerate (late Eocene and early Oligocene) -** Tallahassee Creek Conglomerate (Ttc) is exposed as isolated remnants spatially associated with Tertiary volcanic rocks within paleovalleys, mainly in the eastern part of the quadrangle. Epis and Chapin (1974) formally named the Tallahassee Creek Conglomerate and noted its presence in paleovalleys that drained eastward from the Sawatch Range into South Park. De Voto (1971) previously gave this unit the informal name “lower volcanic conglomerate”. Field relationships are often ambiguous because the unit is poorly exposed, it is not resistant to erosion, and it was deposited in paleovalleys. As defined by Epis and Chapin (1974) and mapped by Scott (1975), the Tallahassee Creek Conglomerate is younger than the Wall Mountain Tuff. The unit may have been deposited as large volcanic mudflows that originated from volcanoes in the Sawatch Range during the late Eocene (J. Shannon, personal communication, 2004).

The Tallahassee Creek Conglomerate is a polymict cobble- and boulder-conglomerate in a tuffaceous matrix. Boulders and cobbles are often prominent at the surface and represent a residual lag deposit that has remained after finer grained material had been removed by erosion (DeVoto, 1971; Wallace and Keller, 2003). Silicified fossil wood fragments (chalcedonic, opaline, and crystalline silica) are locally abundant in the Tallahassee Creek Conglomerate, which is a distinguishing feature that separates the

Tallahassee Creek Conglomerate from most Quaternary terrace and pediment deposits. In the Buena Vista East quadrangle the Tallahassee Creek Conglomerate consists of subangular, subrounded, rounded, and well-rounded clasts of Middle Proterozoic granodiorite (Xgd), andesite, Wall Mountain Tuff (Twm), Tertiary porphyritic intrusive rock , Lower Paleozoic quartzite and carbonate, and, rarely, tuff of Triad Ridge (Ttr). Boulders of Proterozoic granodiorite up to 12 ft in diameter were observed; clasts of other lithologies are smaller. The lithology of the clasts varies greatly over relatively short distances. At some locations, the cobbles and boulders are nearly all Wall Mountain Tuff, whereas a short distance away the clasts are dominantly granodiorite or Paleozoic rocks. Clasts occur in a matrix of light-gray to light pinkish-tan, water-laid and air-fall tuff, grayish-white and yellowish-white slightly welded tuff, and tuffaceous sand and silt. At most localities where the Tallahassee Creek Conglomerate is preserved, boulders occur in silt and clay-rich soil that contains angular feldspar and quartz pebbles derived from Middle Proterozoic granodiorite. Tuffaceous and volcaniclastic layers within the Tallahassee Creek Conglomerate are seldom exposed below the weathered, bouldery residuum. As in the Castle Rock Gulch quadrangle (Wallace and Keller, 2003) phenocrysts of feldspar are prominent in the tuffaceous matrix and biotite crystals, though prominent due to their dark color, are less common than feldspar. Fragments of light-grayish-white and light-pink pumice occur in the slightly welded tuff, and dark-red and reddish-gray fragments of aphanitic volcanic rocks are a common lithic component. The thickness of the Tallahassee Creek Conglomerate is highly variable because it was deposited on an uneven, eroded surface in Tertiary paleovalleys and it has been differentially eroded since its deposition. It is estimated to have a maximum thickness of between 30 and 50 ft in the Buena Vista East quadrangle.

Tan **Andesite (late Eocene) -** Andesitic lava forms a narrow deposit that is exposed along the crest of Triad Ridge. The andesite flow filled a steep-sided paleovalley that was incised into the softer tuff of Triad Ridge during the late Eocene. Limbach (1975) correlated this andesite to the upper part of the Buffalo Peaks Andesite based on mineralogy. The type locality of Buffalo Peaks Andesite is at Buffalo Peaks, 12 mi north of Triad Ridge. Two samples of the andesite from atop Triad Ridge were analyzed for whole rock geochemistry (samples Tan-K334 and Tan-K510, Table 2). The two samples plot near the boundary between the andesite and trachyandesite fields on a total alkali vs. silica diagram (Le Bas and others, 1986). McIntosh and Chapin (2004) refer to this andesite as 'dacite of Triad Ridge' and provide an $^{40}Ar/^{39}Ar$ age date from sanidine of 36.14 ±0.10 Ma.

Andesite is dark-gray on fresh surfaces, medium- to dark reddish-brown, reddish-gray, and orange-brown on weathered surfaces. It is porphyritic, and phenocrysts comprise 40 percent of the rock mass. Most of the phenocrysts are euhedral plagioclase. Other phenocrysts include hypersthene, augite, and minor biotite (Limbach, 1975). The dark-gray groundmass consists of plagioclase and pyroxene microlites (Scott, 1975). Columnar cooling joints are well developed and their orientations show that the unit was deposited in a steep-walled valley or canyon cut into the underlying rock. The maximum estimated thickness of the andesite is about 200 ft (cross section A-A').

Table 2. Whole-rock analyses of samples from the Buena Vista East 7.5' quadrangle, Chaffee County, Colorado. Sample locations are shown on the geologic map. Analyzed by X-ray fluorescence [analyses by ALS-Chemex, Sparks, Nevada; report no. RE04009460. LOI, loss on ignition; NA, not analyzed; <, less than]

SAMPLE ID	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	Cr_2O_3	TiO_2	MnO	P_2O_5	SrO	BaO	LOI	Total
Tad-K352	59.44	17.8	6.4	3.72	1.78	3.25	2.76	0.01	0.7	0.11	0.42	0.05	0.09	3.09	99.61
Tan-K334	60.5	16.78	6.35	4.46	2.31	2.98	3.7	<0.01	0.81	0.09	0.32	0.07	0.11	1.2	99.68
Tan-K510	59.08	16.68	6.23	4.46	2.25	3.03	3.55	0.01	0.81	0.27	0.32	0.08	0.12	1.31	98.2
Tdd-K129	65.3	16.24	4.16	3.25	0.99	3.06	2.85	0.01	0.46	0.08	0.23	0.07	0.14	1.87	98.7
Tdd-K166	65.25	16.04	3.95	2.99	0.86	3.3	3.1	<0.01	0.45	0.06	0.23	0.07	0.11	2.08	98.5
Tdd-K185	66.7	16.55	3.75	2.78	0.76	3.6	2.54	<0.01	0.39	0.04	0.21	0.06	0.09	2.33	99.8
Tdd-K350	65.75	16.44	4.39	3.1	1.16	3.09	3.14	0.01	0.49	0.09	0.22	0.07	0.18	1.61	99.74
Tdd-K548	67.05	16.97	3.65	3.62	0.71	3.36	2.52	0.03	0.32	0.05	0.16	0.07	0.11	1.1	99.71
Tdd-L261	65	16.08	3.91	3.57	1.07	3.54	2.8	0.02	0.39	0.06	0.2	0.09	0.15	1.47	98.36
Tdd-L462	68.4	16.59	3.61	0.81	0.84	2.97	3.22	0.01	0.35	0.08	0.18	0.05	0.08	2.34	99.53
Xqd-K001	55.33	15.44	10.13	5.25	3.69	3	2.54	0.03	1.54	0.12	0.63	0.07	0.15	0.9	98.83
Xqd-K674	55.5	15.5	10.22	5.3	3.5	2.95	2.53	0.03	1.57	0.14	0.6	0.05	0.12	0.99	99
YXd-K538	51.4	16.96	11.29	6.05	5.12	2.84	1.91	<0.01	1.44	0.15	0.26	0.03	0.07	2.37	99.88
YXm-K637	50.23	13.5	10.22	7.34	7.66	2.8	1.89	0.06	1.1	0.16	0.56	0.1	0.08	3.22	98.92
YXm-K745	46.37	13.91	12.31	8.79	9.35	1.94	2.4	0.06	0.95	0.21	0.32	0.06	0.04	2.74	99.45

Twm Wall Mountain Tuff (late Eocene) - The Wall Mountain Tuff is exposed as erosional remnants in the eastern part of the quadrangle. The Wall Mountain Tuff, formally named by Epis and Chapin (1974) is a rhyolitic, moderate to densely welded ash-flow tuff that was deposited as a major ignimbrite that filled steep-sided paleovalleys that were incised into the previously erupted tuff of Triad Ridge (Ttr) or into older Proterozoic and Paleozoic rocks. The Wall Mountain Tuff has played an important role in the reconstruction of paleovalleys and the extent of the late Eocene erosion surface in central Colorado (Epis and Chapin, 1975). Based on five ^{40}Ar/^{39}Ar sanidine age dates (McIntosh and Chapin, 2004) the Wall Mountain Tuff is 36.7 Ma.

The Wall Mountain Tuff is a multiple-flow, simple cooling unit and commonly displays prominent eutaxitic texture. The basal 8 to 12 ft of the tuff consists of black, glassy vitrophyre that contains crystals of quartz and sanidine. The main body of the welded tuff is mostly light-gray, moderate-gray, light-brownish-gray, and grayish-red rhyolite that contains prominent sanidine and plagioclase phenocrysts (Epis and Chapin, 1974). Biotite is sparse. Bold and somewhat rounded outcrops typically weather to light orange-brown, reddish-brown, or buff color. Widely spaced columnar jointing is sometimes prominent near the base. Laminar flow foliation is prominent locally. Chapin and Lowell (1979) described primary and secondary deformation structures from the Wall Mountain Tuff in the Gribbles Run paleovalley where this glassy tuff formed a single cooling unit that slid and folded into the paleovalley as the plastic and mobile tuff degassed and compacted. Exposures of the Wall Mountain Tuff show similar plastic deformation features at Castle Rock, less than 1 mi east of the Buena Vista East quadrangle in the Castle Rock Gulch quadrangle, where prominent foliation dips at steep angles parallel to basal contacts that define pre-existing drainageways (Wallace and Keller, 2003). The maximum thickness of Wall Mountain Tuff in the Buena Vista East quadrangle is approximately 200 ft.

Tva **Volcaniclastic sediments and ash (middle to early Eocene) -** Poorly to moderately consolidated, medium- and fine-grained, light-gray to green, silty and sandy volcaniclastic sediments and local ashy layers. Thin bedding is visible at places where the material is slightly consolidated. Biotite and feldspar grains are abundant in sandy layers. Nonresistant and poorly exposed. Contains well-rounded to subrounded pebbles, cobbles, and small boulders of Lower Paleozoic quartzite and Proterozoic granitic rocks that form a thin lag deposit at the surface. Underlies the Wall Mountain Tuff (Twm) in sec. 33, T. 14 S., R. 77 W., and sec. 4, T. 15 S., R. 77 W., the near the eastern margin of the quadrangle. The unit is similar in character to the Tallahassee Creek Conglomerate, and unless field relationships are very clear, the two units can easily be confused for one another. Volcaniclastic sediments and ash may have been deposited as a volcanic mudflow that originated from one of the volcanoes that existed in the Sawatch Range during the Eocene (J. Shannon, personal communication, 2004). Maximum thickness is about 100 ft. May be correlative with rhyodacitic ash mapped by Van Alstine (1969) in the Nathrop quadrangle.

Ttr **Tuff of Triad Ridge (late Eocene) -** The dacitic tuff of Triad Ridge forms the large, east-northeast-trending ridge of the same name that dominates the skyline south of US Hwy 285 through the mountainous part of the Buena Vista East quadrangle. The tuff is also present on an unnamed ridge along the eastern boundary of the quadrangle. The tuff of Triad Ridge was deposited as an ignimbrite in the Trout Creek paleovalley and other unnamed paleovalleys that were incised into Proterozoic and Paleozoic rocks during the Eocene (Scott, 1975). The tuff of Triad Ridge was informally named by McIntosh and Chapin (2004) in their comprehensive geochronological study of the central Colorado volcanic field. Wallace and Keller (2003) termed it 'dacite tuff of Castle Rock Gulch', and De Voto (1971) termed it 'andesitic tuff of Castle Rock Gulch'. Epis and Chapin (1974) and Scott (1975) included the exposures of the tuff of Triad Ridge as part of the Badger Creek Tuff (33.8 Ma) in the area of Trout Creek. More detailed mapping and a $^{40}Ar/^{39}Ar$ biotite date of 37.18 ± 0.11 Ma from the unit in the Castle Rock Gulch quadrangle by Wallace and Keller (2003) showed that the tuff of Triad Ridge underlies, and is older than, the Wall Mountain Tuff, and is therefore also older than Badger Creek Tuff. Based on $^{40}Ar/^{39}Ar$ biotite and hornblende dates from three samples, McIntosh and Chapin (2004) also showed that the lower part of the tuff of Triad Ridge (37.49 ± 0.32 Ma) is indeed older than Wall Mountain Tuff. They dated Wall Mountain Tuff at 36.69 ± 0.09 Ma with sanidine. However, they also present an $^{40}Ar/^{39}Ar$ sanidine date from the upper part of the tuff of Triad Ridge (36.22 ± 0.32 Ma) that is younger than Wall

Mountain Tuff. The upper tuff of Triad Ridge was not mesoscopically distinguishable from the lower tuff of Triad Ridge in the field. A small area of gravel residuum containing clasts of Paleozoic and Proterozoic rock is present on top of Triad Ridge, 0.75 mi southwest of the only outcrop of Wall Mountain Tuff that we mapped on Triad Ridge. We tentatively mapped this residual deposit as volcaniclastic sediment and ash (Tva).

The tuff of Triad Ridge is light-gray, light-tan, light-reddish-gray, and light-orange-gray, moderately welded to locally densely welded tuff of dacitic composition. The tuff contains abundant pumice fragments, volcanic rock fragments, and abundant plagioclase and biotite crystals. Sanidine, hornblende, and quartz crystals are also present in small quantities. Phenocrysts comprise 25 to 30 percent of the rock. The groundmass consists of devitrified glass that shows both axiolitic and spherulitic textures (Bade, 1989). Pumice fragments are commonly wispy, lensoid streaks of conspicuous black glassy matrix material giving the rock a weakly eutaxitic texture. Flattened glass and pumice fragments up to 6 inches in diameter are common in some horizons. These often weather out, imparting a vuggy appearance to the rock. The tuff commonly displays slabby or platy primary flow layering or foliation that is generally perpendicular to the direction of cooling (sub-parallel to the paleotopography). Lithic fragments of Proterozoic crystalline rocks are locally common in the basal portion of the tuff. The maximum thickness of the tuff of Triad Ridge is approximately 700 ft (cross section A-A').

Tdd **Dacitic dikes (early Eocene?)** - A swarm of porphyritic dikes of dacitic to locally rhyolitic composition is present in the northwestern and south-central part of the Buena Vista East quadrangle. The dikes become increasingly numerous toward the west and the Arkansas Valley graben. The density and frequency of the dikes is highest near the Arkansas Valley floor and the western terminus of Triad Ridge. Figure 6 shows the distribution of Tertiary dikes that are exposed in the quadrangle. Whole-rock geochemical analyses of seven samples from these dikes are presented in Table 2. The dikes are geochemically similar to the tuff of Triad Ridge (Ttr), which was sampled and analyzed by Wallace and Keller (2003) who referred to it as 'dacite tuff of Castle Rock

Gulch'. The dikes are older than the tuff of Triad Ridge and are overlain by the tuff at one or more places. Lowry (2004) notes geochemical similarity of the dacitic dikes in the Buena Vista East quadrangle to the Eocene-age Mount Princeton Quartz Monzonite in the Sawatch Range. Dacitic dikes range in width from less than 2 ft to about 20 ft. Most of the dikes trend west-northwest, parallel to the dominant fault trend. The dikes can be steeply dipping to very shallow dipping. Several dikes near, and north of, US Hwy 285 dip at low angles to the north.

Dacitic dikes are porphyritic, medium- to dark-gray and greenish-gray on fresh, unweathered surfaces and light-brown, light greenish-tan, and light yellowish-brown on weathered surfaces. The dikes are usually fractured and surficial processes produce an abundance of angular float. Phenocryst size and abundance are variable, but typically make up 25 to 40 percent of the rock. Phenocrysts of plagioclase are always the most common and are typically less than 0.1 inch in diameter, but locally range up to 0.5 inch in diameter. Rounded quartz phenocrysts are typically present as well, but are less common than plagioclase. Hornblende phenocrysts and biotite phenocrysts are commonly present in varying abundance as well. The groundmass is aphanitic and dark in color. The dikes are usually altered to varying degrees. Alteration minerals include epidote, sericite, chlorite, and calcite (Limbach, 1975). At a few places, the rock is nearly aphanitic, with only tiny plagioclase or hornblende phenocrysts present. Dacitic dikes can vary texturally over relatively short distances.

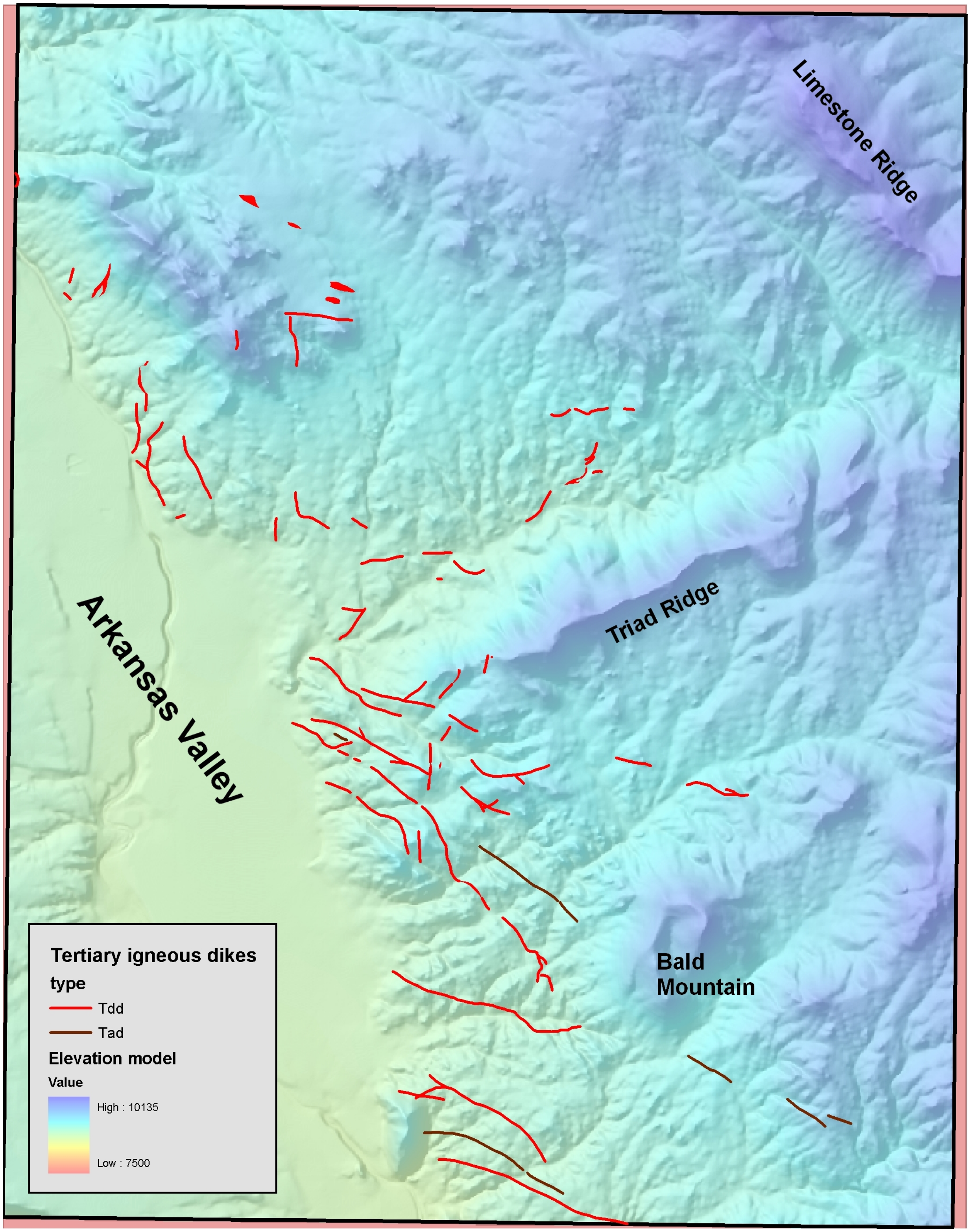


Figure 6. Distribution of Tertiary igneous dikes in the Buena Vista East quadrangle, Chaffee County, Colorado.

Tad **Andesitic dikes (early Eocene?) -** A few andesitic dikes are present in the southeastern and south-central part of the Buena Vista East quadrangle, within the same general region as the dacitic dikes (Tdd). Andesitic dikes are much less common than dacitic dikes. Figure 6 shows the distribution of Tertiary dikes in the quadrangle. A whole-rock geochemical analysis of an andesitic dike (Table 2) show that they are chemically distinct from the dacitic dikes; the distinction is not always obvious in the field, however. Andesitic dikes trend west-northwest, parallel to most of the dacitic dikes and the dominant fault and fracture trend. No crosscutting relationships were observed between the andesitic dikes and the dacitic dikes, and no radiometric age dates have been determined for either set. Andesitic dikes range from about 2 ft to 10 ft in width. They are medium- to dark-gray and green-gray on fresh surfaces, and medium- to dark-greenish-brown and orange-brown on weathered surfaces. The dikes weather to a darker color than the dacitic dikes. Manganese oxide stain is locally abundant on weathered fracture surfaces. Andesitic dikes can be either porphyritic or, more rarely, equigranular. Hornblende is the most conspicuous phenocryst mineral and can be as long as 1 inch (Scott, 1975).

TKm **Monzonite (Late Cretaceous or Paleocene) -** The northwestern portion of a large monzonite sill is exposed in Chubb Park in the extreme northeast corner of the quadrangle. The sill is equigranular, medium- to coarse-grained, and moderate to dark green, and gray to brown gray in color. Although the monzonite has not been isotopically dated, it is lithologically similar to a few of the intrusive bodies exposed to the north near Leadville that have been isotopically dated as late Cretaceous or early Tertiary (Pearson and others, 1962). Therefore, a Cretaceous or Tertiary age is tentatively assigned to this monzonite sill. The sill was injected between the Leadville Limestone and the Belden Shale, centered on the axis of a broad, gentle syncline in the Castle Rock Gulch quadrangle to the east (Wallace and Keller, 2003). It measures over 1 mi in length and is calculated to be about 600 ft thick at its widest, in the central part of the exposure. The sill dips northeast based on monzonite chips that occurred in drill cuttings from a water well collared in the Belden Shale about 300 ft east of the monzonite contact in the

Castle Rock Gulch quadrangle. The upper and lower intrusive margins, for distances of 5 to 8 ft from the contacts, are finer-grained and slightly more silicic than the interior of the intrusive. The chilled margins are more resistant to erosion than the coarse-grained interior which is easily eroded and forms a soft grüs at the surface. Whole-rock geochemistry (Wallace and Keller, 2003) shows the monzonite to be undersaturated with respect to silica. Thin section analysis of a sample of medium-grained, equigranular, dense, resistant material from near the upper contact of the sill shows the rock to be composed of approximately 20-30 percent euhedral, elongated, prismatic hornblende (1-3 mm), 60-70 percent altered subhedral feldspar, some with relics of albite twinning still visible, 3 to 4 percent magnetite, and traces of biotite and pyroxene. Chlorite is present as an alteration product of the mafic minerals.

PALEOZOIC ROCKS

IPb **Belden Shale (Middle Pennsylvanian) -** The Belden Shale is exposed only in the far northeastern corner of the Buena Vista East quadrangle, where it underlies the gentle topography of Chubb Park. The Belden Shale is poorly exposed due to its nonresistant weathering style. The unit correlates with what was mapped as the lower member of the Belden Shale on the Castle Rock Gulch quadrangle to the east. The Belden Shale rests disconformably over the Leadville Limestone and consists of dark-gray, brownish-gray, and black shale and calcareous siltstone interbedded with medium- to dark-gray, dark-brownish-gray, and light-gray weathering, thin-bedded to locally flaggy-laminated, fetid limestone and argillaceous limestone. Some limestone beds are as thick as 15 ft, but generally, they are less than 6 ft thick. Limestone beds are typically fossiliferous and coquina was noted on the Castle Rock Gulch quadrangle (Wallace and Keller, 2003). Rare, discontinuous lenses of olive-drab to dark-reddish-green, fine- to medium-grained, micaceous arkose occur locally. Except for the limestone beds, this unit is very poorly exposed because of the recessive nature of the shale and siltstone. In the Castle Rock Gulch quadrangle where the full thickness of the Belden Shale is exposed, the formation ranges from about 600 to 1,000 ft in thickness (Wallace and Keller, 2003).

Ml **Leadville Limestone (Early Mississippian) -** The Leadville Limestone overlies the Chaffee Formation on a disconformable contact on Limestone Ridge in the northeastern part of the quadrangle. The Leadville Limestone is a moderate-gray and dark-gray, massive-weathering, thinly bedded micritic limestone and finely crystalline dolomite. Beds range in thickness from 3 inches to 6 ft. Black laminated chert nodules and lenticular chert beds occur at some stratigraphic levels, and red chert locally occurs as irregular replacement masses. The Leadville Limestone is about 180 ft thick on Limestone Ridge. The unit is as much as 440 ft thick in the Bassam Park area of the Castle Rock Gulch quadrangle (Wallace and Keller, 2003). Thickness variation may result from post-lithification solution of limestone and from volume reduction that resulted from solution and silicification of limestone. Most of the Leadville Limestone is composed of interbedded zones of finely crystalline dolomite and micrite, with lenticular interbeds of biomicrite and oölitic limestone that occur sporadically through the sequence (Wallace and Keller, 2003). Some limestone and dolomite beds are mottled light gray and moderate gray. Thin, silica-cemented orthoquartzite beds occur locally at the top of the Leadville Limestone east of Limestone Ridge. The sandstone is mostly fine- and medium-grained, silica-cemented orthoquartzite; the degree of rounding cannot be determined because detrital grain boundaries are not preserved.

Dc **Chaffee Formation (Late Devonian) -** The Chaffee Formation is exposed on Limestone Ridge and consists of two members that were not mapped separately: (1) the Parting Sandstone Member at the base, and (2) the Dyer Dolomite Member at the top (De Voto, 1971; Wrucke and Dings, 1979). The two members were mapped separately on the Castle Rock Gulch quadrangle to the east, but the Parting Sandstone was too thin to map separately on the Buena Vista East quadrangle. The Chaffee Formation rests disconformably on the Ordovician Fremont Dolomite. Campbell (1972) applied group rank to the Chaffee and applied formation rank to the Parting Quartzite and Dyer Dolomite. He subdivided the Parting Quartzite and Dyer Dolomite into several members based on measured sections. Members could not be mapped separately at a map scale of

1:24,000, so we retain the nomenclature of Wrucke and Dings (1979), as did Wallace and Keller (2003). The Chaffee Formation is less resistant to weathering than the massive-weathering Fremont Dolomite below and the massive-weathering Leadville Limestone above, so the Chaffee Formation forms slopes between the two carbonate units. The Chaffee Formation is 130 to 150 ft thick on Limestone Ridge. The Parting Quartzite Member is a light-gray, pale-brownish-gray, light-grayish-red, and pinkish-gray, fine-grained, silica-cemented, dense orthoquartzite. Rare thin interbeds of dolomite and green shale and some pebbly and granular quartzite interbeds are present. Some thin beds of dolomite and dolomitic quartzite are interbedded with silica-cemented quartzite. Thinly bedded and massive-weathering quartzite beds are generally 2 to 10 inches thick. Planar lamination, ripple-cross-lamination, and rare planar crossbeds are the principal sedimentary structures (Wallace and Keller, 2003). The thickness of the Parting Quartzite Member varies from about 3 ft to 15 ft in the Buena Vista East quadrangle. The Dyer Dolomite Member is a yellowish-gray, light-gray, tan, and pale-yellowish-gray, prominently laminated and microlaminated, finely crystalline and microcrystalline dolomite that contains some lenticular interbeds of light-grayish-green and light-greenish-gray shale and laminated yellowish-gray chert. The dolomite is bioturbated and flaggy (fig. 7) or massive-weathering. Rare chert layers are interbedded with dolomite and range from 0.5 to locally 2 inches thick. Near the top, the Dyer Dolomite Member commonly contains medium-gray, thin-bedded, or rarely massive-weathering, laminated limestone layers that have a greater resistance to weathering than the surrounding dolomitic rock. The Dyer Dolomite Member is 120 to 130 ft thick on Limestone Ridge.

Figure 7. Soft sediment deformation features in the Dyer Dolomite Formation, Chaffee Group (Dc), Limestone Ridge.

Of **Fremont Dolomite (Middle and Late Ordovician) -** The Fremont Dolomite overlies the Harding Quartzite on a disconformable contact. The Fremont Dolomite is 80 to 120 ft thick on Limestone Ridge, but thickness is difficult to measure precisely because exposures are mostly on forested dip-slopes. The Fremont Dolomite is a moderate- to light-gray, and brownish-gray, massive-weathering, crystalline, fetid dolomite that contains echinoid debris and dolomitized coral in a fine-grained dolomite matrix. Trilobite and brachiopod fragments occur on some bedding planes (Wallace and Keller, 2003), and echinoid fragments are common in most of the unit. Solitary and colonial corals are preserved locally. The dolomite may be mottled light gray and dark gray, or it is laminated and microlaminated. Beds are generally 2 to 36 inches thick and bedding is poorly preserved. This dolomite resists weathering and has a rough, uneven weathering surface that has sharp ridges.

Oh **Harding Quartzite (Middle Ordovician) -** The Harding Quartzite overlies the Manitou Limestone on a disconformable contact. The Harding Quartzite is a dark-reddish-gray, dark-grayish-orange, dark-grayish-red, light-gray, moderate-gray, and rusty-orange, fine- to medium-grained, well-sorted, silica-cemented, dense, mottled orthoquartzite. The orthoquartzite is completely cemented by silica, and it has the conchoidal fracture typical of a quartzite. This indurated, cliff-forming unit is about 100 ft thick on Limestone Ridge, but thickness is difficult to measure precisely because exposures are mostly on forested dip-slopes. Quartzite beds range from 1 to about 12 inches thick. They contain planar lamination and planar crossbeds (Wallace and Keller, 2003), which commonly are obscured by pervasive replacement of diagenetic quartz. At a few places, the Harding Quartzite consists of angular breccia fragments of white quartzite in matrix of hematite-stained, maroon to dark-red quartzite. These breccias appear to be related to faulting. Pebbly beds are present but are not common.

Om **Manitou Limestone (Ordovician) -** The Manitou Limestone overlies the Sawatch Quartzite on a disconformable contact, or, where the Sawatch is absent, the Manitou Limestone overlies Proterozoic rocks. The unconformity upon which the Manitou Limestone was deposited was developed over a highland area that arose in the area of southern Colorado during Ordovician time. Myrow and others (2003) have termed this highland area the mid-*Rossodus* uplift. On the Buena Vista East quadrangle, rocks assigned to the Manitou Formation represent only the upper part of the Manitou Limestone as defined regionally by Myrow and others (2003). The Manitou Limestone is composed mostly of dolomite in the map area, rather than limestone. This unit is composed of moderate-, and light-gray, thin- to thick-bedded dolomite and cherty dolomite and rare beds of dark-gray limestone. Dolomite is medium-crystalline and typically weathers light brown to light pinkish-brown. The Manitou Limestone is about 200 to 220 ft thick on Limestone Ridge. Dolomite and limestone are laminated and mottled, and beds range between 1 and 36 inches in thickness. A distinctive characteristic of the Manitou Limestone is the occurrence of black and light-grayish-white chert nodules, lenses, and beds in the dolomite. The chert is internally laminated and parallel to bedding. The bedded chert lenses and layers are most common in the lower one-third of the formation. The top of the formation commonly has no chert, or only rare white chert.

Ꞓs **Sawatch Quartzite (Late Cambrian) -** The oldest Paleozoic unit in the Buena Vista East quadrangle is the Sawatch Quartzite. The Sawatch Quartzite overlies Early Proterozoic rocks in the northern and central part of Limestone Ridge. Deposition of the Sawatch Quartzite filled irregularities in an erosion surface developed on Proterozoic rocks. Regionally, the Sawatch Quartzite thins from north to south beneath the mid-*Rossodus* unconformity that developed on the mid-*Rossodus* uplift during Ordovician time in the area of southern Colorado (Myrow and others, 2003). The Sawatch Quartzite is about 10 ft thick north of Lenhardy Cutoff near the northern boundary of the Buena Vista East quadrangle. The Sawatch Quartzite is absent from the southern part of Limestone Ridge and in the Trout Creek area of the Castle Rock Gulch quadrangle. To the south of the Castle Rock Gulch quadrangle along the western side of the Cameron Mountain quadrangle, the Sawatch Quartzite thickens to about 25 ft (Wallace and Lawson, 1998). The Sawatch Quartzite is a light-gray, purplish-gray, and light grayish-yellow, fine- to medium-grained, well-sorted, massive-weathering, silica-cemented orthoquartzite and pebbly orthoquartzite (fig. 8) that contains planar crossbeds, ripple cross-lamination, and planar lamination at places where bedding is preserved. Pebbly quartzite contains rounded vein-quartz clasts.

Figure 8. Sawatch Quartzite exposed in prospect pit north of Lenhardy Cutoff. Note small, well-rounded quartz pebbles floating in a matrix of sandstone.

PROTEROZOIC ROCKS

YXp **Pegmatite (Early or Middle Proterozoic) -** Pegmatites (YXp) intrude granodiorite, and, to a lesser extent, granite stocks, in parts of the Buena Vista East quadrangle. The pegmatite bodies are typically white to light pink in color and are composed primarily of albite, microcline, and quartz. Crystal size ranges up to 6 ft or more. Pegmatites form lensoid dikes and irregularly shaped bodies that may be zoned or unzoned and range in thickness from 1 to 30 ft. Pegmatite bodies commonly contain accessory biotite and muscovite in different proportions. Several large pegmatites contain accessory garnet, polycrase, and allanite (Hanson and others, 1992; Hanley and others, 1950). Several of the pegmatites were mined in the past for their potassium feldspar (pink microcline) but are also notable for their rare-earth-element minerals (Hanson and others, 1992). The larger pegmatites that were mined historically are part of the Trout Creek Pass pegmatite district that extends eastward from the Buena vista East quadrangle into the northern part of the Castle Rock Gulch quadrangle. The pegmatites are spatially and probably genetically related to the intrusion of the granite bodies (YXg). The Mineral Resources section below describes the larger pegmatites in more detail.

YXg **Granite (Early or Middle Proterozoic) -** Proterozoic granite occurs as relatively small stocks and plugs scattered throughout the Proterozoic terrane of the Buena Vista East quadrangle. Locally it grades into quartz monzonite depending on quartz content. These masses intrude the older granodiorite unit (Xgd). The granite is pale pinkish orange to light grayish pink, medium to coarse grained, hypidiomorphic granular. It is mostly non-foliated to weakly foliated. However, granite masses are strongly foliated (gneissic) within the area mapped as foliated granodiorite (Xgdf). De Voto (1971) described this unit as a leucogranite to leuco-quartz monzonite because of the lack of mafic minerals. Corresponds to similar granite mapped in the Castle Rock Gulch quadrangle to the east and labeled YXgt (Wallace and Keller, 2003). Van Alstine (1969) mapped similar granite intrusives in the Nathrop quadrangle (formerly called the Poncha Springs NE quadrangle), directly south of the Buena Vista East quadrangle. Wrucke and Dings (1979) mapped similar intrusive bodies as quartz monzonite of both Early and Middle

Proterozoic age in the Cameron Mountain 15-minute quadrangle to the southeast of the Buena Vista East quadrangle. A whole-rock geochemical analysis of a sample of the granite from the Castle Rock Gulch quadrangle shows the rock to consist of 78 percent SiO_2 (Wallace and Keller, 2003). This places the sample well into the range for granite on the I.U.G.S. classification scheme based on CIPW norms. The granite consists primarily of quartz, alkali feldspar (including perthite), plagioclase, and sparse muscovite and biotite. Some muscovite appears to be an alteration product of biotite. Plagioclase is weakly altered to sericite in places. Large pegmatites (YXp) that have been mined in the past at a few places in the quadrangle are spatially and probably genetically related to these granite intrusions.

YXm **Mafic dikes (Early or Middle Proterozoic?) -** Mafic dikes were mapped in only a few locations in the Buena Vista East quadrangle. The dikes are somewhat variable in texture and composition, and are from about 2 to 10 ft in width. They are dark gray to dark green-gray, fine-grained to locally medium-grained, and equigranular to weakly porphyritic. The dikes are composed principally of hornblende, plagioclase, and minor constituents including quartz. Whole-rock geochemical analyses were performed on two of the dikes (Table 2). A northwest-trending mafic dike on the northwest side of Sugarloaf Mountain has a peculiar medium-coarse, equigranular texture (sample YXm-K745, Table 2). Scott (1975) describes the northwest-trending mafic dike south of Midland Hill as a lamprophyre based on its texture and the presence of hornblende phenocrysts (sample YXm-K637, Table 2). Mafic dikes usually decompose more rapidly than the enclosing granitic rock and are often poorly exposed. Mafic dikes on this quadrangle are assumed to be Proterozoic in age (Scott, 1975), but no radiometric analyses have been performed on these rocks. Shannon (1988) described and presented geochemical data for lamprophyre dikes in the Mount Antero area of the Sawatch Range, about 5 mi southwest of the Buena Vista East quadrangle. Major oxide geochemical data for the lamprophyres show that they are chemically dissimilar to the mafic dikes in the Buena Vista East quadrangle.

YXd **Diorite (Early or Middle Proterozoic) -** Diorite was mapped as an irregular, roughly north-trending mass in secs. 8 and 17, T. 14 S., R. 77 W. It has intruded the strongly foliated granodiorite (Xgdf). Scott (1975) mapped this diorite mass as metamorphosed quartz diorite. Whole-rock analyses completed for this report show that the diorite intrusive (sample YXd-K538, Table 2) is less silicic and contains more iron and magnesium than quartz diorite (samples Xqd-K001 and Xqd-674). Diorite is somewhat less mafic than the mafic dike rocks we analyzed (samples YXm-K637 and YXm-K745). Diorite is dense, very dark gray to black, fine to medium grained, and is massive to very weakly foliated. It is weakly porphyritic with white to clear plagioclase laths up to 7 mm long set in the dark gray groundmass. It weathers into angular, dark reddish-brown fragments.

Xgdf **Foliated granodiorite (Early Proterozoic) -** Foliated granodiorite forms a cohesive north-trending elongated mass in the eastern part of the quadrangle. It is a strongly foliated variation of granodiorite (Xgd) and was not separately mapped by Scott (1975). Foliated granodiorite is compositionally similar to massive or weakly foliated granodiorite (Xgd; see description below). Foliation is usually gradational over a few feet or tens of feet from massive or weakly foliated granodiorite (Xgd). Augen derived from large feldspar phenocrysts progressively become more elongated and flattened in the direction of foliation (fig. 9). Where foliation is most intense, the rock is compositionally banded gneiss and it is not possible to distinguish former augen or large phenocrysts. Foliation has a dominant N05W to N25E strike direction, and is interpreted by the authors to be tectonic in genesis. The foliation is parallel or sub-parallel to faults with Proterozoic origin on this quadrangle and on the Castle Rock Gulch quadrangle to the east. It is also roughly parallel to the axis of the Kaufman Ridge anticline (Schmidt and others, 1993), and to an unnamed paleovalley represented by the large mass of tuff of Triad Ridge (Ttr) that is exposed on the extreme eastern edge of this quadrangle and on the Castle Rock Gulch quadrangle.

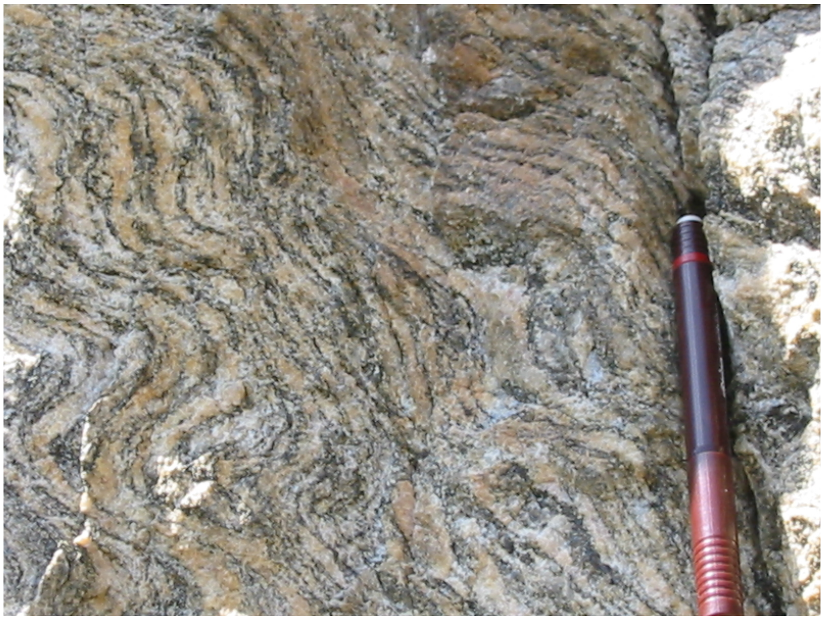


Figure 9. Foliated granodiorite (Xgdf). Light bands composed mainly of stretched feldspar phenocrysts and/or augen. Small-scale folding is locally common.

Xqd **Quartz diorite (Early Proterozoic) -** Quartz diorite forms a series of sub-parallel northeast- to east-trending lensoidal intrusive masses in the west-central part of the quadrangle. Map relationships suggest quartz diorite intrudes granodiorite (Xgd), but contact relationships are ambiguous. At some outcrops it appears that granodiorite intrudes quartz diorite. The two units may be comagmatic. Scott (1975) noted that quartz diorite grades into granodiorite or may be older than granodiorite. Quartz diorite is dark to medium gray, medium to coarse grained, equigranular to weakly porphyritic, and is composed of plagioclase (oligoclase-andesine), hornblende, biotite, microcline, and quartz. The rock locally displays a "salt-and-pepper" color texture. Quartz diorite masses generally dip moderately to gently north and display weak foliation sub-parallel to the orientation of the intrusive masses. The foliation is interpreted to be primary magmatic flow structure. Foliation commonly imparts a "slabby" character to outcrops, which weather to a dark grayish-brown color (fig. 10). Quartz diorite often contains numerous small masses of pegmatite and aplite. Whole-rock geochemical analyses of quartz diorite (samples Xqd-K001 and Xqd-674) are given in Table 2, above.

Figure 10. Proterozoic quartz diorite (Xqd) commonly displays a slabby weathering pattern. The slabs are along faint foliation planes that are typically parallel to the attitude of the intrusive contacts. The foliation appears to be primary, intrusive foliation.

Xgd **Granodiorite (Early Proterozoic) -** Granodiorite is the predominant bedrock unit in the Buena Vista East quadrangle. It is part of a large and irregularly shaped body of intrusives of the Routt Plutonic Suite that is exposed from the western edge of the Sawatch Range to the southern edge of the Front Range north of Canon City (Tweto, 1987). Barker and Brock (1965) applied the formal name Denny Creek Granodiorite Gneiss to similar rocks in the Mount Harvard 15-minute quadrangle in the Sawatch Range northwest of Buena Vista. The granodiorite is medium to light gray, grayish orange, and grayish yellow, speckled, coarse to very coarse grained, massive to moderately foliated. It typically weathers into massive, rounded outcrops in which large-scale jointing patterns are visible (fig. 11). Granodiorite grades into strongly foliated and sheared (?) granodiorite (Xgdf) of similar composition that was mappable as a distinct unit in the eastern part of the Buena Vista East quadrangle. Granodiorite is pinkish gray to greenish gray on unweathered surfaces. The chief mineral constituents are plagioclase, microcline, quartz, biotite, and hornblende. This unit commonly contains phenocrysts of quartz up to 0.5 inch in diameter (~20 percent), and phenocrysts of microcline feldspar 0.5 inch to locally 2.5 inches in length (~25 percent). Alignment of biotite, which makes up about 15-20 percent of the rock, defines the foliation. Subhedral plagioclase (~35 percent) is white and is partially altered to clay minerals and sericite. Locally biotite has been altered partly to chlorite, and at some places, biotite is replaced by muscovite. The percentage of quartz is variable and this unit commonly compositionally grades into quartz monzonite (Streckeisen, 1973). At some places, particularly in the west-central part of the quadrangle north of US Hwy 285, the granodiorite is medium grained with much smaller phenocrysts of feldspar and is slightly darker in color than is typical elsewhere. The granodiorite is of Boulder Creek age and has been dated at 1,672±5 Ma (Bickford and others, 1989) in the adjoining Cameron Mountain quadrangle. Granodiorite is locally overlain by small, discontinuous, unmapped pockets of grüsy Quaternary alluvium-colluvium more than 10 ft thick.

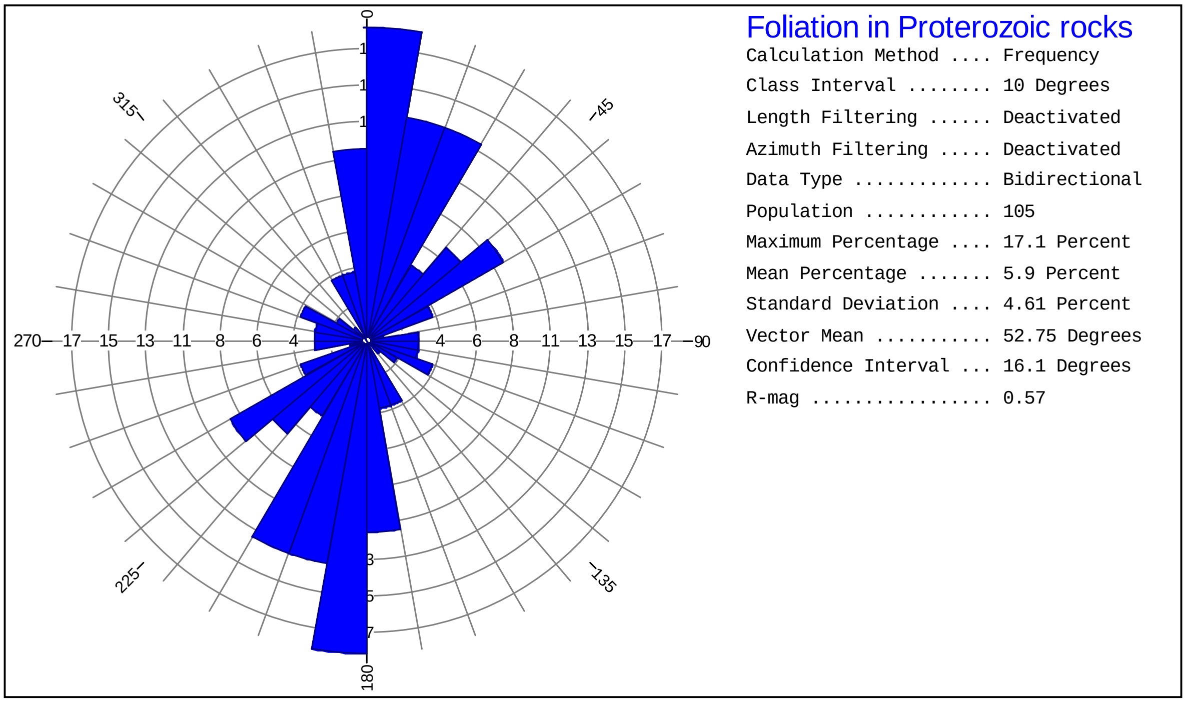
Figure 11. Proterozoic granodiorite (Xgd) often forms massive, spheroidally weathering outcrops with widely spaced joints. Looking north; Triad Ridge is on the far horizon.

Xb **Biotite gneiss (Early Proterozoic)** - Biotite gneiss is inferred to be the oldest rock on the quadrangle. Biotite gneiss occurs as elongated, dike-like xenoliths (?) within the large granodiorite mass. Similar masses of biotite gneiss were mapped in the Castle Rock Gulch quadrangle to the east (Wallace and Keller, 2003), and in the Nathrop quadrangle to the south (Van Alstine, 1969). Biotite gneiss is well foliated, dark-gray to black, medium grained, and equigranular. It consists principally of biotite, quartz, plagioclase, and hornblende (?). The rock is schistose where biotite comprises more than about 50 percent of the rock mass. Biotite gneiss is similar to metamorphosed sedimentary rocks found elsewhere in central and northern Colorado (Tweto, 1987). The sedimentary rocks from which the gneiss is derived were deposited sometime in the interval of 1.75 to 1.95 Ga (Hedge and others, 1986).

STRUCTURAL GEOLOGY

The Buena Vista East quadrangle lies within the area of intersection of three major tectonic and tectono-stratigraphic features of regional to continental scale: the Rio Grande rift (Chapin, 1971; Chapin and Cather, 1994); the Colorado mineral belt (Tweto and Sims, 1963; CD-Rom Working Group, 2002); and the Central Colorado trough (De Voto, 1972; 1980). The rocks within the quadrangle have undergone structural deformation repeatedly through geologic time. Notable deformation events occurred in central Colorado during the Proterozoic (Tweto, 1980a; Reed and others, 1987; Shaw and others, 2001); the Pennsylvanian (De Voto, 1972); the Laramide Orogeny of Late Cretaceous and early Tertiary time (Tweto and Sims, 1963; 1980b); and during middle and late Tertiary time (Epis and others, 1980). Scott (1975) mapped young, potentially active faults related to activity on the Rio Grande rift that have offset deposits of Quaternary gravel on the Buena Vista 1:62,500 scale quadrangle. Our mapping has confirmed the presence of Quaternary faulting on the Buena Vista East quadrangle.

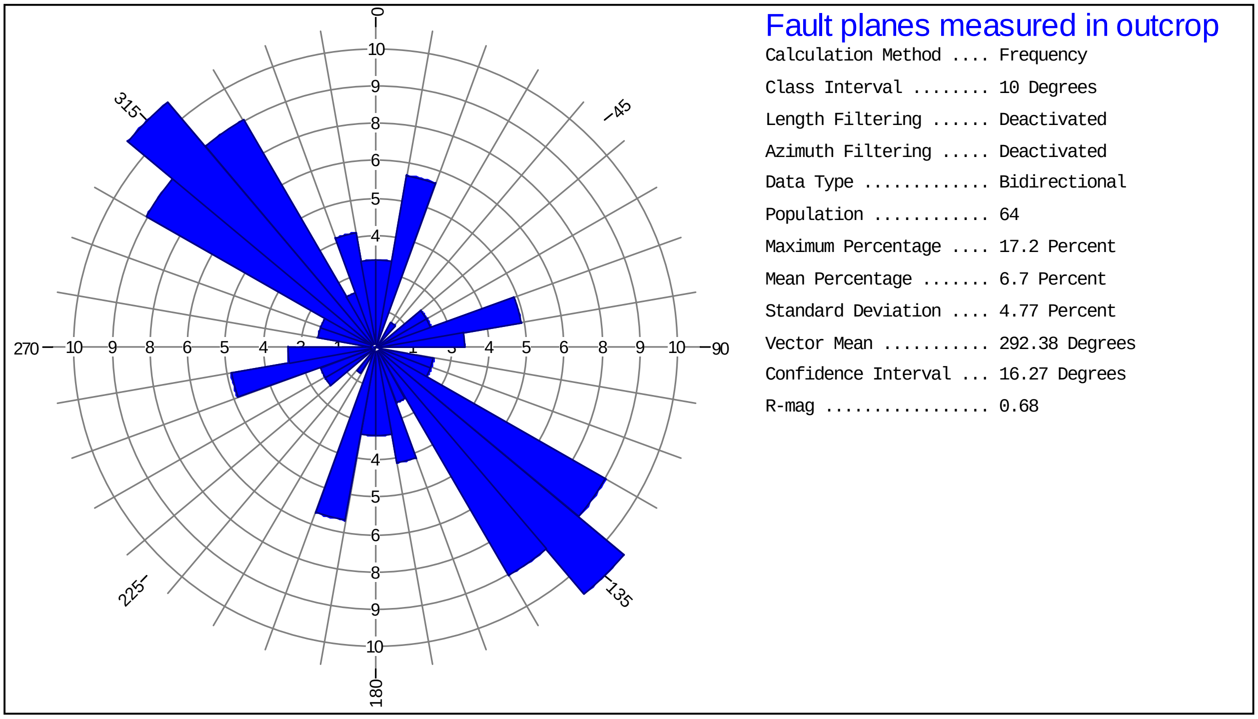
Proterozoic structural deformation is most clearly represented by foliation and local shear fabrics in strongly foliated granodiorite (Xgdf) and biotite gneiss (Xb). Figure 12 is a Rose diagram of foliation strike directions in Proterozoic rocks. The dominant north- to north-northeast direction is tectonic foliation, principally in foliated granodiorite. The secondary northeast strike direction is primary intrusive foliation, mainly in quartz diorite (Xqd). Faults of Proterozoic age certainly exist on the quadrangle, but many or most these have probably been reactivated or displaced by later tectonism. North-northeast- to north-northwest-trending faults and east-northeast-trending faults that we have mapped correspond to dominant Proterozoic fault systems identified by Tweto (1980a). Some of the northwest-trending faults, which are clearly the most numerous and most readily identifiable on the Buena Vista East quadrangle, may be faults of Proterozoic origin. Figure 13 shows the principal strike directions of all faults in the quadrangle, as measured at outcrops. The orientations of fractures and joints (fig. 14) roughly parallel the northwest-trending and east-northeast-trending faults, but not the set of north-northeast-trending faults.



Foliation in Proterozoic rocks

```
Calculation Method .... Frequency
Class Interval ........ 10 Degrees
Length Filtering ...... Deactivated
Azimuth Filtering ..... Deactivated
Data Type ............. Bidirectional
Population ............ 105
Maximum Percentage .... 17.1 Percent
Mean Percentage ....... 5.9 Percent
Standard Deviation .... 4.61 Percent
Vector Mean ........... 52.75 Degrees
Confidence Interval ... 16.1 Degrees
R-mag ................. 0.57
```

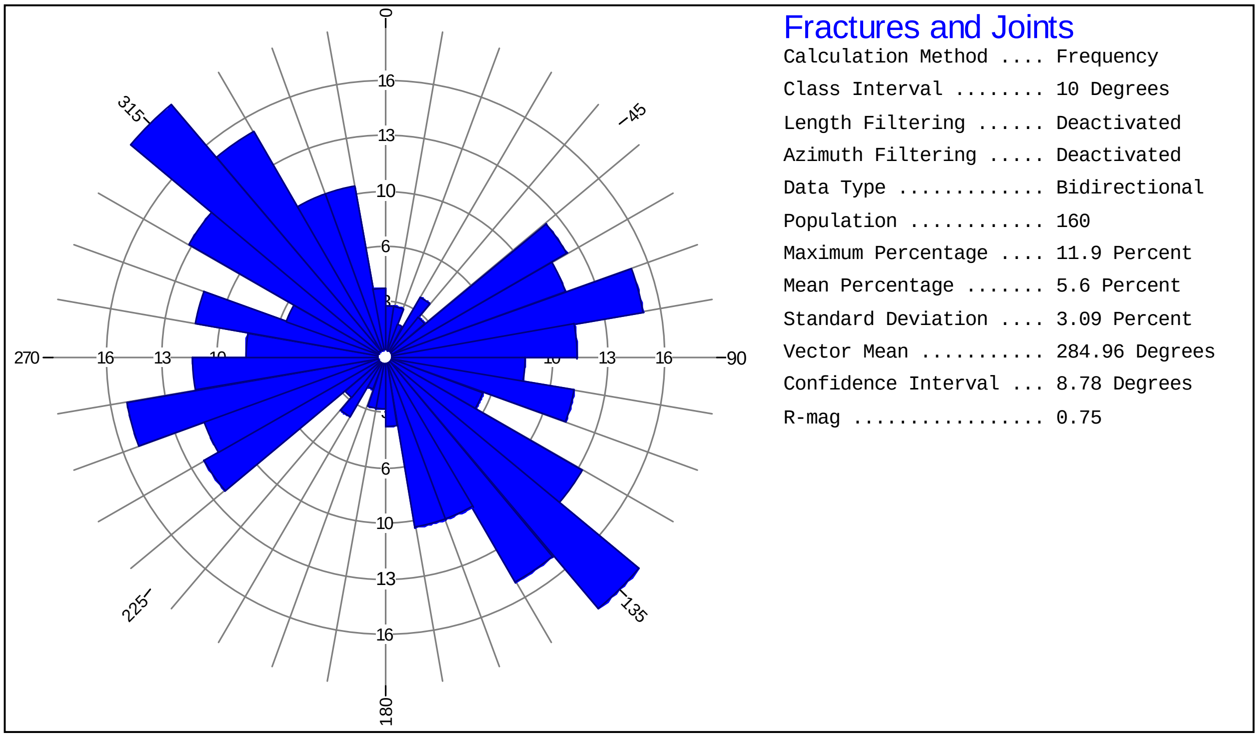
Figure 12. Rose diagram of foliation strike orientations measured in outcrop in Proterozoic metamorphic and igneous rocks in the Buena Vista East quadrangle. Dominant north-northeast strike direction represents tectonic foliation granodiorite (Xgdf and Xgd). Secondary east-northeast strike direction represents primary magmatic foliation (?) in quartz diorite (Xqd).



Fault planes measured in outcrop

```
Calculation Method .... Frequency
Class Interval ........ 10 Degrees
Length Filtering ...... Deactivated
Azimuth Filtering ..... Deactivated
Data Type ............ Bidirectional
Population ........... 64
Maximum Percentage .... 17.2 Percent
Mean Percentage ....... 6.7 Percent
Standard Deviation .... 4.77 Percent
Vector Mean .......... 292.38 Degrees
Confidence Interval ... 16.27 Degrees
R-mag ................ 0.68
```

Figure 13. Rose diagram of fault plane strike orientations measured in outcrop, Buena Vista East quadrangle.



Fractures and Joints

```
Calculation Method .... Frequency
Class Interval ........ 10 Degrees
Length Filtering ...... Deactivated
Azimuth Filtering ..... Deactivated
Data Type ............ Bidirectional
Population ........... 160
Maximum Percentage .... 11.9 Percent
Mean Percentage ....... 5.6 Percent
Standard Deviation .... 3.09 Percent
Vector Mean .......... 284.96 Degrees
Confidence Interval ... 8.78 Degrees
R-mag ................ 0.75
```

Figure 14. Rose diagram of strike directions of fractures and joints measured in outcrop in the Buena Vista East quadrangle.

No direct evidence of Pennsylvanian or Permian deformation was observed during our mapping. However, the Trout Creek fault (U.S. Geological Survey, 1935), also known as the Mosquito-Weston fault, is a major, regional fault mapped by De Voto (1971) and Wallace and Keller (2003) that transects the Castle Rock Gulch quadrangle north to south, just east of the Buena Vista East quadrangle. That fault was active during the Pennsylvanian tectonic event that produced the ancestral Front Range and Sawatch uplifts and the Central Colorado trough. The Buena Vista East quadrangle lies within the eastern arm of the Central Colorado trough, between the ancestral Sawatch uplift to the west, and the ancestral Front Range uplift to the east (De Voto, 1980).

Evidence for Laramide (Late Cretaceous and Paleocene) deformation is represented by northeast-trending faults and a large-scale, northeast-trending open synclinal fold on Limestone Ridge in the northeastern part of the Buena Vista East quadrangle. De Voto (1971) named the syncline the Pony Springs syncline, and it continues northeast and north for at least 5 mi beyond the Buena Vista East map area. The syncline and faults deform Proterozoic and Lower Paleozoic rocks. The Pony Springs syncline and the northeast-trending faults on Limestone Ridge are related to the larger Kaufman Ridge anticline of Laramide age (De Voto, 1971; Schmidt and others, 1993), which lies to the east on the Castle Rock Gulch quadrangle. A large monzonite sill tentatively assigned as Laramide in age (De Voto, 1971; Wallace and Keller, 2003) has intruded along the contact between the Leadville Limestone and the Belden Shale near the Pony Springs syncline.

The Rio Grande rift is a major continental rift zone that has been tectonically active from Oligocene time to the present (Chapin, 1971). The north-northwest-trending Arkansas Valley parallels the Upper Arkansas rift basin, which is one of the axial basins of the Rio Grande rift and is a structural graben or half-graben (Chapin and Cather, 1994). Van Alstine (1969, p.27) postulated a major west-dipping, graben-bounding fault in sec. 14, T. 15 S., R. 78 W., near the town of Nathrop. Numerous northwest- and north-northwest-trending high-angle normal faults, mostly down-to-the-west, are manifestations of extensional rift tectonism within the map area. Most of the faults we have mapped east of the Arkansas Valley have displacements of only tens of feet to possibly hundreds of feet.

The Nathrop Volcanics in the southwestern map area were erupted around the time that major tectonic extension along the Rio Grande rift began in Oligocene time, around 30 Ma (McIntosh and Chapin, 2004). Great thicknesses of clastic debris that make up the Dry Union Formation began filling the Upper Arkansas rift basin in Miocene and Pliocene time, as the basin subsided (Van Alstine, 1969). The subsurface configuration of the Upper Arkansas Basin is the least known of all of the axial basins of the Rio Grande rift (Chapin and Cather, 1994). The thickness of the sedimentary fill in the Arkansas Valley near Nathrop, which includes the Dry Union Formation and overlying Quaternary alluvial and glacial deposits, is not known. Using gravity data, Gridley and others (1991) estimated that these basin-fill sediments have maximum thicknesses of approximately 5,000 ft near Salida and 3,000 ft near Leadville. We estimate that the sedimentary fill is approximately 2,000 ft thick in the southwestern part of the Buena Vista East quadrangle, thickening westward toward the Sawatch Range (cross section A-A').

At least one northwest-trending fault displaces Quaternary sediments in the southwest part of the map area (fig. 15). A down-to-the-southwest fault displaces Nebraskan (?) alluvium (unit Qna). Fine-grained older alluvium (Qaof) has been deposited against the fault on its downthrown side in secs. 4 and 9, T. 15 S., R. 78 W., and ditch exposures east of Dry Creek show the older alluvium has been subsequently deformed, probably by earthquake shaking. New radiocarbon dates for two samples (BVE-C5 and BVE-C6) of carbon-rich sediment from above and below the deformed alluvium interval bracket the timing of this earthquake between 3,140 - 3,600 cal yr BP (calibrated years before present) and 14,100-15,350 cal yr BP. A parallel fault lies directly west of US Highway 285. Some fault segments cut the Miocene and Pliocene Dry Union Formation but not the overlying Quaternary gravels. This relationship was observed in the Nathrop quadrangle as well (Van Alstine, 1969).

Figure 15. Panoramic view to the northeast of the southwest-facing Quaternary fault scarp in sec. 4, T. 15 S., R. 78 W., Buena Vista East quadrangle.

GEOLOGIC HAZARDS

Potential geologic hazards in the Buena Vista East 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 rare in the Buena Vista East quadrangle, because the Precambrian granitic rocks that underlie most of the quadrangle are generally too competent for slope failure. Previous regional landslide mapping at 1:250,000 scale (Colton and others, 1975) and 1:62,500 scale (Scott, 1975) identified four small areas of slope instability in the east-central part of the Buena Vista East quadrangle. In addition to these four deposits we map an additional eight landslide deposits, for a total of 12. Nine of the 12 landslide deposits are mapped as landslides (**Qls**) undifferentiated by age or movement type (Table 3).

Table 3. Summary of landslide deposit areas, by map unit.

Map Unit	Description	Number of Deposits	Range of Areas (acres)	Mean Area (acres)
Qls	Landslide deposit, undifferentiated	8	0.99 - 44.5	22.2
Qls?	Landslide deposit, undifferentiated, questionable	1	54.4	54.4
Qlsy	Landslide deposit, younger	1	3.95	3.95
Qlso	Landslide deposit, older	2	42.0 - 118.6	79.1
	TOTALS	12	0.99 - 118.6	32.1

The mean area of all landslide deposits is 32.1 acres, with a range from 0.99 acres to 118.6 acres. These areas do not include the source area from which the landslide slid, which lies between the slide headscarp and the upslope margin of the landslide deposit.

Landslides are strongly controlled by geology and nearly always occur in certain bedrock units. Most of the landslides, including the largest one (118.6 acres), occur on the flanks of Triad Ridge and the unnamed ridge along the eastern quadrangle boundary. Both of the ridges are capped by thick deposits of Eocene tuff that overlie Proterozoic granitic rock, or locally, Lower Paleozoic sedimentary rock. The tuffs were deposited in paleovalleys that were incised into the Eocene surface. The landslide deposits are composed mainly of Eocene volcanic rocks. Presumably, the failure plane was a weak layer within the volcanic formations, such as a thin, unwelded ash bed, but this was not observed directly in the field. A similar large compound failure in volcanic rocks composes the southeast flank of Bald Mountain and includes a larger, older landslide deposit (**Qlso**) and a smaller younger landslide inset within it (**Qlsy**).

Opposite the Bald Mountain landslide are two landslides derived mostly from Precambrian granodiorite. Normally the granite does not generate these types of slope failures. These landslides are, however, located within an Eocene-Oligocene paleovalley, and the top of the ridge that generated the slides has retained a tiny erosional remnant of Wall Mountain Tuff.

Most of the landslides on this quadrangle do not appear to have moved in historic time (the past 150 years). They may become reactivated in the future by triggers such as rapid snowmelt (Chleborad, 1997), intense rainfall, or earthquake shaking.

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, Qaly**) in the quadrangle lies on modern floodplains and is potentially subject to flooding. An additional, unmapped flood hazard exists in the same stream channels where they are eroded into older Quaternary deposits (such as most of the Arkansas River) or into bedrock (typically Precambrian granite), but contain no mappable Holocene alluvium.

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 mapped Holocene alluvial fans (**Qf, Qfy**) are potentially subject to debris-flow deposition over most of their surfaces. Fans with the highest hazard are those whose drainage basins are largest (Trout Creek, Arnold Gulch, Bald Mountain Gulch), or which contain large areas of exposed bedrock with sparse vegetation (McGee Gulch, Shields Gulch).

ABANDONED MINES

Collapse of abandoned mine shafts and tunnels, many of which may be covered by thin surficial material, pose a potential hazard, but abandoned mines are not abundant in the quadrangle (the Triad Mine, on the south side of Triad Ridge in sec. 30, T. 14 S., R. 77 W., is one such mine that poses a hazard). Several other abandoned mines and prospect shafts and tunnels in the quadrangle have been safely closed by the Colorado Divisions of Minerals and Geology. Several small open pits excavated into pegmatite veins are also present in the quadrangle, but these do not present a collapse hazard.

SEISMICITY

The Buena Vista East 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 no instrumental earthquakes in the quadrangle, nor within a 10 km (6 mile) radius of the center of the quadrangle. However, two earthquakes did occur in the vicinity of Buena Vista in the historical, pre-instrumental period. The larger was the 15 November 1901 earthquake that caused shaking of Intensity VI at Buena Vista (Modified Mercalli Scale; see Kirkham and Rogers, 2000, p. 46). The limited size of the felt area led Kirkham and Rogers (2000) to conclude that the earthquake "may have occurred at a fairly shallow depth, and may have been only magnitude 4.0 to 5.0 or perhaps even smaller." A smaller local earthquake (Intensity IV at Buena Vista) was felt on 27 November 1961, with an estimated epicenter about 6 miles northeast of Buena Vista (Kirkham and Rogers, 2000, p. 72).

Despite the relative scarcity of historic seismicity, geologic evidence suggests that some faults in the quadrangle have been active in Quaternary time. For example, in the southwestern part of the quadrangle a down-to-the-southwest fault displaces Nebraskan (?) alluvium (unit Qna). Fine-grained older alluvium (Qaof) has been deposited against the fault on its downthrown side, and ditch exposures east of Dry Creek show the older alluvium has been subsequently deformed, probably by earthquake shaking. New radiocarbon dates for two samples (BVE-C5 and BVE-C6) of carbon-rich sediment from above and below the deformed interval in the older alluvium bracket the timing of the possible earthquake between 3,140 -3,600 cal yr BP (calibrated years before present) and 14,100-15,350 cal yr BP. No detailed studies of Quaternary faulting (such as trenching studies) have yet been performed in the Buena Vista East quadrangle.

MINERAL RESOURCES

Mineral resources in Buena Vista East quadrangle include construction sand and gravel, gold, limestone, feldspar and rare-earth-minerals in pegmatites, perlite, and gem-quality garnet and topaz. Construction sand and gravel and placer gold are the only mineral resources that are presently being mined on the quadrangle from sites with active mining permits from the Colorado Division of Minerals and Geology (Guilinger and Keller, 2004). There is little or no potential for oil, natural gas, or coal resources in the quadrangle.

SAND AND GRAVEL

Sand and gravel deposits in the Arkansas Valley are presently the most economically significant mineral resource on the Buena Vista East quadrangle. There are currently five active sand and gravel pits in the quadrangle. The Cogan family operates a medium-sized sand and gravel pit near the mouth of Arnold Gulch in the SE 1/4, sec. 2, T. 15 S., R. 78 W. ACA Products, Inc. operates the Trout Creek pit in the NE1/4 of sec. 27, T. 14 S., R78 W. This pit is below the site of the new Trout Creek dam and near the point where Trout Creek emerges from the mountain front into the Arkansas Valley. Chaffee County sporadically mines sand and gravel from a small pit directly north of U.S Highway 285 near the KOA campground in the SE1/4 of sec. 22, T. 14 S., R. 78 W. Kerr and Son Trucking operate the Jesse Lee sand and gravel pit along the Arkansas River in the NE1/4 of sec. 33, T. 14 S., R. 78 W. The Jesse Lee pit also produces placer gold. Another small sand and gravel pit, Pit No. 1, is located about one mile south of Johnson Village in the SE1/4 of sec. 27.

On the Buena vista East quadrangle, sand and gravel is presently produced from Quaternary alluvial fan deposits (Qfy) and alluvial deposits which were deposited by the Arkansas River (Qal, Qpoy). Locations of active and inactive pits in the map area show that nearly all of the various Quaternary surficial deposits in the Arkansas Valley are sources of sand and gravel (Keller and others, 2002).

PLACER GOLD

As stated above, the Jesse Lee pit is an active and permitted mining operation that produces placer gold from alluvial sand and gravel deposits along the Arkansas River. Production figures have not been disclosed. Vanderwilt (1947) reported that placer gold operations along the Arkansas River between Buena Vista and Salida were small and intermittent. Parker (1992) stated that placer gold was mined in small quantities in the past on Trout Creek "one mile from the Arkansas River".

LIMESTONE

The Leadville Limestone in the northeastern part of the Buena Vista East quadrangle is a potential source of high-purity limestone. The far western portion of the historic Newett Quarries is located on the north slope of Limestone Ridge in the SE1/4 of sec. 4, T. 14 S., R. 77 W. Most of the series of dip-slope pits that comprise the Newett Quarries are located on the Castle Rock Gulch quadrangle to the east. A sample of Leadville Limestone (Ml) from the main quarry on the Castle Rock Gulch quadrangle showed that it is of metallurgical grade because of its low content of magnesium and other impurities (Wallace and Keller, 2003). Quarried Leadville Limestone was transported via the Colorado Midland Railroad to Leadville for use as a smelter flux during the early 1900s (Argall, 1949). However, the smaller quarry located on the Buena Vista East quadrangle is in Fremont Limestone, which is largely dolomitic and is not pure like the Leadville Limestone in this region.

PEGMATITE MINERALS

Several formerly active pegmatite mines are located in the Buena Vista East quadrangle. The pegmatites here, along with several on the adjoining Castle Rock Gulch quadrangle to the east, comprise the Trout Creek Pass pegmatite district. The pegmatites were mined principally for their potassium feldspar content (pink microcline), but they are also notable for their rare-earth-element minerals (Hanson and others, 1992). All of the mining in the district was finished some time prior to 1944 (Hanley and others, 1950). Mapping shows that all of the pegmatites are spatially related to small bodies of Proterozoic granite (YXg) that have intruded older Proterozoic granodiorite (Xgd) and quartz diorite (Xqd).

The Yard mine is in sec. 7, T. 14 S., R. 77 W., about four miles north of U.S. Highway 285; the location of this mine was misplaced by Hanley and others (1950). The Yard mine consists of a northeast-trending open cut about 100 ft long, 30 ft wide, and 20 ft deep. There is also an adit that appears to access lower parts of this pegmatite from the bottom of the narrow drainage west of the open cut. The pegmatite has a shallow dip to the southeast. The principal minerals are quartz, pink microcline, and sericitized plagioclase. Accessory minerals include biotite, muscovite, monazite, and polycrase (Hanson and others, 1992).

The Crystal No. 8 mine is in the NW1/4 of sec. 16, T. 14 S., R. 77 W., on a low hill that lies about 1/4-mile south of U.S. Highway 285/24. The mine consists of an open cut about 80 ft long and 10 to 30 ft wide, and several smaller pits and one short adit that is now caved. The pegmatite trends about N85E. The footwall contact is exposed at several places in the workings (Hanley and others, 1950). The principal minerals are quartz, pink microcline, and plagioclase. Dark red garnet is common near the contacts with the coarse granodiorite wallrock. Accessory minerals include biotite, minor muscovite, and the rare-earth-element minerals allanite and polycrase (Hanson and others, 1992).

Several small, unnamed pegmatite mines or prospects are located in the low hills adjacent to the Arkansas Valley in the NE1/4 of sec. 2 and the NW1/4 of sec. 1, T. 15 S., R. 78 W., and the SE1/4 of sec. 35, T. 14 S., R. 78 W. These small open-cuts and shallow pits are developed on pegmatites that appear to be mineralogically similar to the larger pegmatites described above.

PERLITE

Perlite is a hydrated volcanic glass that can be expanded by heating and is used as lightweight insulation and lightweight aggregate. A small tonnage of perlite was mined from the deposit on the east side of Ruby Mountain in sec. 13, T. 15 S., R. 78 W. The Persolite Company mined the material and shipped it to an expansion plant in Florence, Colorado (Schwochow, 1981). The Ruby Mountain deposit is up to 110 ft thick (Van Alstine, 1969). The perlite dips to the west and is overlain by rhyolite of the Nathrop Volcanics. It is underlain by pitchstone, pumiceous tuff, and locally, obsidian (Bush, 1951; Nickel, 1987).

Perlite has also been mined in the past from a small open-cut mine on Bald Mountain in sec. 32, T. 14 S., R. 77 W. The perlite is present at the base of the rhyolite unit of the Nathrop Volcanics on the northeast and northwest sides of Bald Mountain. It is gray to black and commonly displays concentric fracture pattern typical of perlite elsewhere. The deposit on Bald Mountain is about 15 to 30 ft thick, but the contacts with overlying and underlying units are not exposed well.

VEIN DEPOSITS (METALS)

Several small, silver- and gold-bearing vein deposits are present on the Buena Vista East quadrangle. None of these deposits ever achieved major production. All of the veins are hosted by Proterozoic igneous intrusive rocks and all dip steeply. Most veins strike northwest and are on or parallel to mapped faults. Vanderwilt (1947) and Davis and Streufert (1990) designated the area of small mines and prospects south of Midland Hill and north of U.S. Highway 285/24 in secs. 15, 22 and 23, T. 14 S., R. 78 W. as the Free Gold district. This includes the Nellie Bly mine, shown on the topographical map in the NE1/4 of sec. 23. Low-grade silver and gold mineralization occurs in narrow and discontinuous veins associated with northwest-trending faults and fractures. The host rock is Proterozoic granodiorite. A small amount of native gold was found in placer deposits in this area also. Vanderwilt (1947) reports that only a few tons of low-grade ore from the vein deposits and a few ounces of placer gold were recorded as production from the district, all in the early 1930s. The Colorado Division of Minerals and Geology performed mine closure work on the Nellie Bly mine in 1989. Two shafts, both of which were 20 ft deep at the time of closure, were backfilled.

A few other areas in the quadrangle have similar vein deposits that have been developed by small mines and prospect pits, but with no recorded metal production. The Triad Mine, in sec. 30, T. 14 S., R. 77 W., is a similar small vein deposit and is also located along a northwest-trending fault. It may be the same fault or fault system associated with the Nellie Bly and other small mines north of Triad Ridge. The host rock at the Triad Mine is also Proterozoic granodiorite.

The Be True mine is an 80-ft-deep shaft with a small, intact headframe and a sizable waste-rock dump on private property in the SW1/4 of sec. 26, T. 14 S., R. 78 W. The Be True mine is not shown on the 7.5-minute topographical map of this quadrangle. The shaft is located on a significant northwest-trending normal fault in Proterozoic rocks. The shaft has been closed by locked grate for safety reasons by the Colorado Division of Minerals and Geology.

Several unnamed mine shafts are present in the northeast corner of sec. 3, T. 14 S., R. 78 W. Although the U.S. Geological Survey 7.5-minute topographic map of the quadrangle shows only one prospect pit in the area, there are actually several shafts that were reclaimed in

December 2000 by the Colorado Division of Minerals and Geology. The prospects are located within a northwest-trending shear zone.

Several shafts and prospects are located at the head of McGee Gulch in sec. 6, T. 14 S., R. 77 W. These prospects have similarly been developed on small veins (quartz-oxides) that occur principally along a northwest-trending fault in Proterozoic granodiorite. Two other small, abandoned, inaccessible mines are located along the same fault system further south in McGee Gulch, in sec. 8 of the same township.

GARNET AND TOPAZ, RUBY MOUNTAIN

Ruby Mountain is one of Colorado's most famous localities for mineral collecting. Lithophysae and vesicles in the rhyolite of the Nathrop Volcanics sometimes contain well-formed crystals of deep-red spessartine garnet and topaz, particularly at Ruby Mountain in sec. 13, T. 15 S., R. 78 W. Both garnet and topaz crystals are generally less than 0.25 inch in diameter, but a few specimens measure up to 0.5 inch in diameter. The uncut garnet crystals have as many as six smooth, glassy faces and have been used in jewelry (Voynick, 1994). Topaz is less common than garnet and is "wine-yellow" when a cavity is first opened, but upon exposure to sunlight fades to pale blue or colorless (Honea, 1955). Some specimens are of gem-quality and have been faceted into gemstones.

MOLYBDENUM EXPLORATION

AMAX Exploration Company conducted limited exploration work for molybdenum deposits in the region in the late 1970s and early 1980s. The Nathrop Volcanics were considered to be high-level volcanic expressions of a Climax-type molybdenum porphyry system at great depth (J. Shannon, 2004, personal communication). No target was developed and the system was not tested by drilling. The Nathrop Volcanics contain topaz, garnet, and elevated levels of fluorine, all of which are characteristic of igneous rocks which host Climax-type molybdenum deposits (White and others, 1981). The Climax molybdenum porphyry deposit is located about 35 miles north of the Buena Vista East quadrangle. The Climax intrusive system is of similar age to the Nathrop Volcanics and was emplaced along faults in the northern part of the Rio Grande rift between 33 and 24 Ma (White and others, 1981; Bookstrom and others, 1987).

GEOTHERMAL EXPLORATION

AMAX Exploration drilled eight geothermal exploration wells in 1979, 240 to 440 ft in depth, west and southwest of Nathrop and just west of the western boundary of the Buena Vista East quadrangle. Well reports show that all of the holes were terminated in gravel deposits (probably the Dry Union Formation). None of the wells were commercially developed and the geothermal exploration project was abandoned (R. Smith, personal communication, 2004).

WATER RESOURCES

SURFACE WATER

The Arkansas River flows through the quadrangle from north to south; it is the major drainage and forms the local base level for all tributary streams. Upstream of the U.S. Geological Survey stream gage near the Buena Vista municipal athletic fields (elevation 7,920 ft), the Arkansas River has a drainage area of 611 square miles. In the period 1965-1992 the annual mean streamflow at the gage ranged from a low of 187 cfs (cubic ft per second) in 1977 to a high of 645 cfs in 1965 (U.S. Geological Survey, NWIS Web Data). Mean monthly flow reaches a maximum in June (averaged 1,627 cfs between 1965-1993), due to snowmelt in the upper drainage basin. Lowest monthly flows occur in December (mean of 131 cfs) and January (mean of 137 cfs). The highest (peak) flow recorded between 1965 and 1993 was 3,950 cfs on June 11, 1980.

The largest tributary stream in the quadrangle is Cottonwood Creek, which enters the Arkansas River from the west at Buena Vista. In the period 1911-1985 the annual mean streamflow at the gage near Cottonwood Hot Springs (west of the quadrangle) ranged from a low of 23.5 cfs in 1977 to a high of 97 cfs in 1957. Mean monthly flow reaches a maximum in June (averaged 196 cfs between 1911-1986), due to snowmelt in the upper drainage basin. Lowest monthly flows occur in March (mean of 19.5 cfs) and February (mean of 20.6 cfs). The highest (peak) flow recorded between 1912 and 1986 was 1,180 cfs on July 1, 1957.

Trout Creek is the second largest tributary in the quadrangle, but it is not gaged. A privately owned dam was built on Trout Creek in the early part of 2000 in sec. 26, T. 14 S., R. 78 W. The dam is located where the creek passes through a narrow canyon in Proterozoic granodiorite, just upstream of where the creek enters the Arkansas River Valley (fig. 16). The reservoir behind the dam occupies an area of approximately 30 acres.

Surface water is also distributed by ditches from the Arkansas River and from drainages flowing east from the Sawatch Range into the southwest part of the quadrangle. The Trout Creek and Helena Ditches carry water from Cottonwood Creek and the Arkansas River, respectively, and spread it on the broad older Pinedale outwash terrace (Qpoo) east of the Arkansas River.

There are numerous springs in the quadrangle and most are located along mapped faults. Two obvious groups of springs occur along the two NNW-trending faults in the southwestern part of the quadrangle. Large springs occur along the western fault in the beds of Dry Creek, Thompson Creek, and Maxwell Creek (the latter just west of the quadrangle). Smaller springs occur along the eastern fault, for example, at the cabin north of Coal Kiln Gulch. These springs are not marked on the U.S. Geological Survey topographic map. A spring that is marked on the map in the bed of Coal Kiln Gulch is not on a mapped fault.

Springs in the Precambrian bedrock terrane are typically on faults, such as Lost Spring at the head of Hop Gulch near Piles Pasture, and the two springs mapped southeast of Piles Pasture in Big Sandy Draw. Two other springs in lower Big Sandy Draw may be on cross-faults. Other mapped springs occur in upper Arnold Gulch, Bald Mountain Gulch, and Little Cottonwood Creek.

Figure 16. Dam on lower Trout Creek, constructed in 2000. Spheroidal-weathering Proterozoic granodiorite (Xgd) has been eroded by Trout Creek and forms a tight canyon at this point. The Arkansas Valley is in the background, upper right.

GROUND WATER

Ground water is an important resource in the Buena Vista East quadrangle, as indicated by the 191 registered water wells recorded by the Colorado Division of Water Resources. The wells are concentrated in the Arkansas Valley in the southwestern part of the quadrangle, with the highest concentration west of the river. Most of these wells are shallow (less than 100 ft), and 77% have a static water level less than 100 ft below the surface. Fifty percent of wells have a static water level of 50 ft below the surface, or less. The wells in the Arkansas Valley generally have yields of 10-20 gpm (gallons per minute). Based on their depth and yield, it is inferred that these wells produce water from coarse-grained, well-sorted, permeable outwash gravels of Pinedale and Bull Lake age.

Scattered wells do exist in the bedrock hills that comprise the majority of the quadrangle, and these wells produce water from fractures in bedrock, typically Proterozoic granitic rock. Due to the disconnected nature of the fractures, depth to static water varies considerably over short distances. For example, wells in the valley of Trout Creek have consistent static levels of 10-28 ft, whereas static levels in the bedrock hills flanking the creek range widely (18, 40, 63, 64, 100, and 205 ft). Yields from these wells are likewise rather low and erratic, being (respectively) 10, 5, 5, 7, 3, and 10 gpm.

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