OPEN-FILE REPORT 05-8

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

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State of Colorado

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Denver, Colorado
2005

FOREWORD

The purpose of Colorado Geological Survey Open File Report 05-8, *Geologic Map of the Buena Vista West 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. Consulting geologists James P. McCalpin and James R. Shannon completed the field work on this project during the summer of 2004.

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 04HQAG0075, 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 West quadrangle is located in Chaffee County, in the valley of the Arkansas River; the eastern edge of the quadrangle contains the town of Buena Vista (fig. 1). U.S. Highway 24 runs parallel to the Arkansas River in the northeast part of the quadrangle and passes through Buena Vista on its way to Leadville. A second paved highway, County Road 306, follows Cottonwood Creek across the entire width of the quadrangle from Buena Vista to the Sawatch Range. The highway continues west of the quadrangle boundary and crosses the Continental Divide at Cottonwood Pass 12 miles west of the quadrangle, then descends from the Sawatch Range into Taylor Park.

The principal geographic features in the Buena Vista West area are the valley of the upper Arkansas River, which comprises the eastern half of the quadrangle, and the Sawatch Range, which comprises the western half (fig. 1). The Arkansas River flows southeast down the east side of the valley toward Salida. The highest point in the map area is 14,040 feet above sea level, on a spur ridge of Mount Princeton in the extreme southwest corner of the quadrangle. The lowest point in the map area (7,920 feet above sea level) is in the northeastern part of the quadrangle on the Arkansas River near the town of Buena Vista. There is 6,120 feet of vertical relief in the Buena Vista West quadrangle, most of which is associated with the mountain front of the Sawatch Range (fig. 2).

Most of the mountainous part of the Buena Vista West quadrangle is publicly owned land administered by the U.S. Forest Service (San Isabel National Forest) and the U.S. Bureau of Land Management. Land in the Arkansas Valley part of the quadrangle is mostly privately owned.

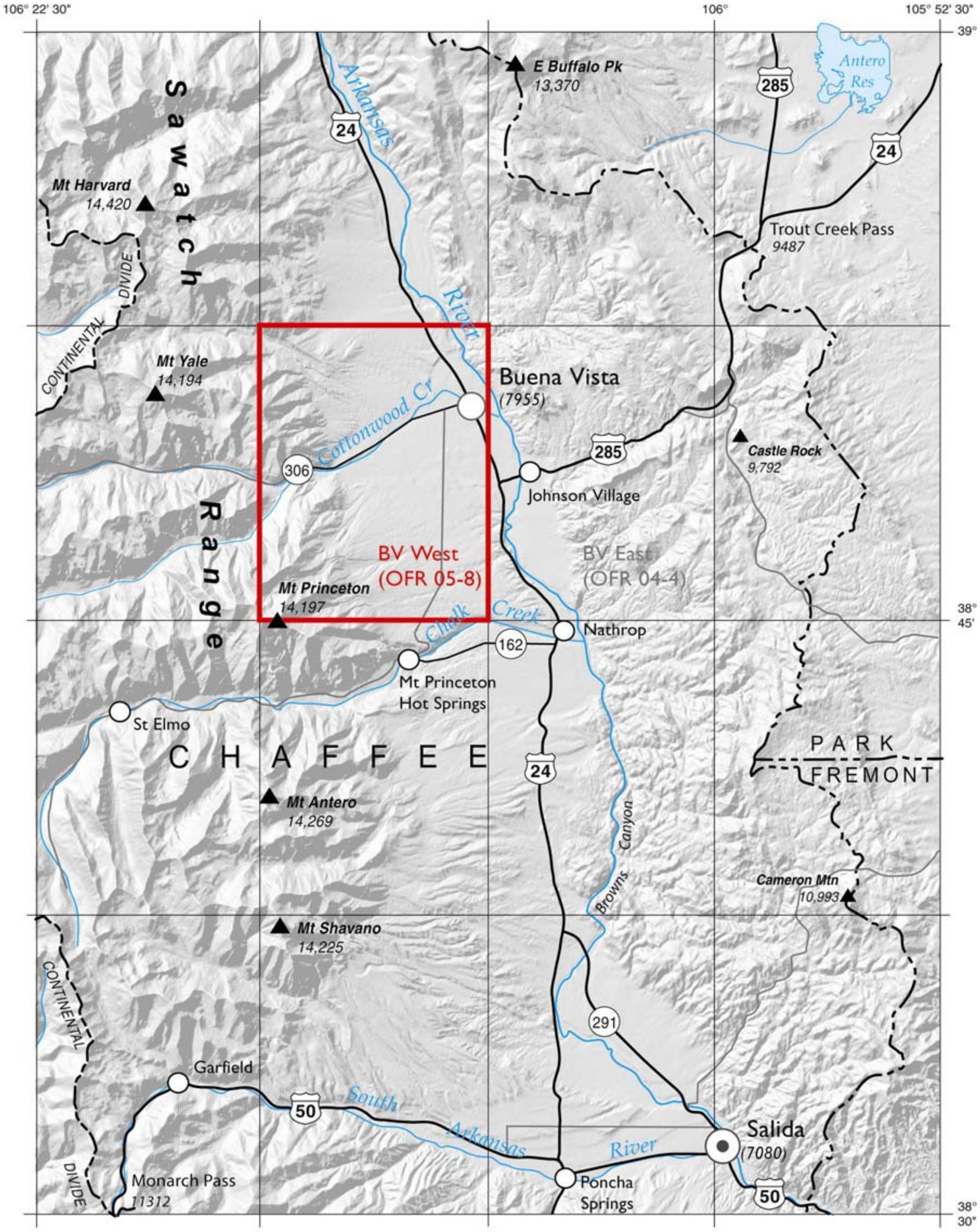


Figure 1. Shaded relief map showing the location of the Buena Vista West quadrangle (in red). Geology on the east half of the Buena Vista West quadrangle is similar to that of the previously mapped Buena Vista East quadrangle (CGS Open-File Report 04-4).

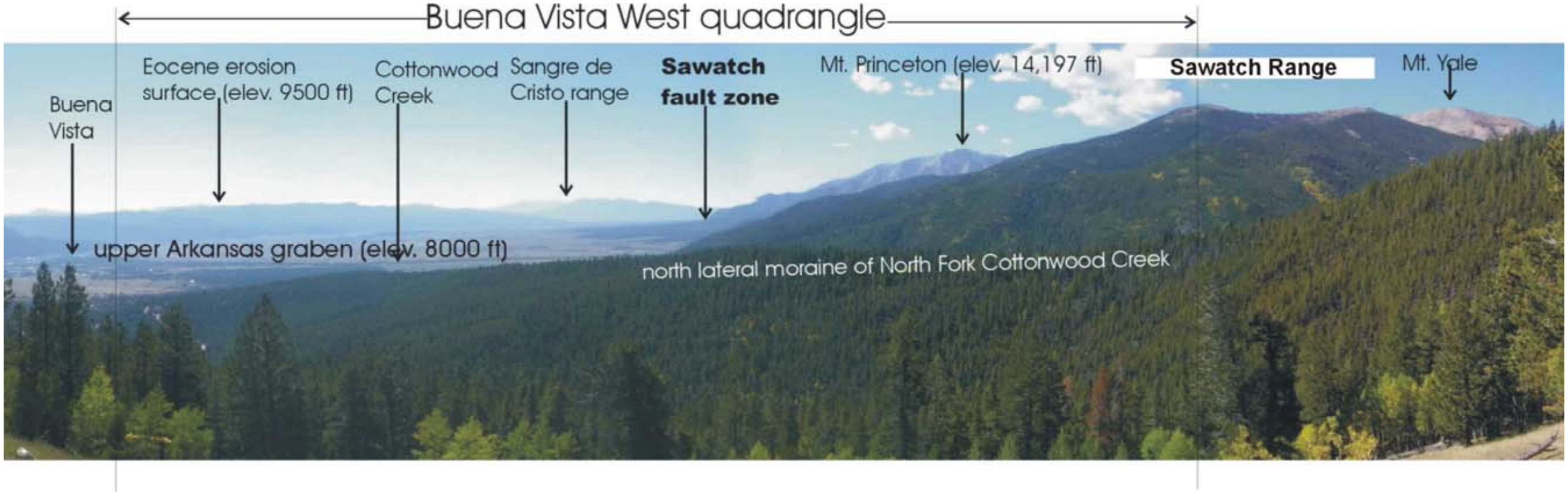


Figure 2. View looking south from the extreme northwest corner of the Buena Vista quadrangle, where the Colorado Trail [labeled "TRAIL (PACK)" on the topographic base map] passes above a small meadow at 10,000 ft elevation. The eastern half of the quadrangle lies in the upper Arkansas graben, with the town of Buena Vista and the Arkansas River (not visible due to deep incision) on its eastern margin. The graben surface is formed by coalescing glacial outwash fans of late to middle Pleistocene age (near the range front) and pediments of middle to early Pleistocene age (near the graben axis). At the center of the graben Miocene-Pliocene Dry Union Formation crops out in a narrow band, mostly east and south of the Buena Vista West quadrangle, probably an intragraben horst. The Sawatch fault zone lies in the center of the quadrangle and separates the upper Arkansas graben from the Sawatch Range, a rift-flank uplift. The highest peaks in the Sawatch Range (Mount Princeton, 14,197 ft elevation; Mount Yale, 14,196 ft elevation) have nearly identical elevations and lie close to the Sawatch fault, whereas the Continental Divide lies 8 miles west of the fault zone near the western side of the Sawatch Range. Rocks of the Sawatch Range are predominantly Tertiary intrusives of quartz monzonite composition, which were intruded into Precambrian basement rocks during the Oligocene. Photograph by J.P. McCalpin, Sept. 11, 2004.

ACKNOWLEDGMENTS

This mapping project was funded jointly by the Colorado Geological Survey and U.S. Geological Survey through the STATEMAP program of the National Cooperative Geologic Mapping Program under agreement No. 04HQAG0075.

The authors thank the many private property owners on the Buena Vista West quadrangle who granted us access to their land for mapping purposes. Paul Moltz, owner of ACA Construction Product, Inc., permitted access to the ACA gravel pit. Permission for access was also kindly given by land managers Harold Metz, Bill Butler, and Jenny Fox of Trail West Lodge, Nick Dryzmala of Lost Creek Ranch, and landowners Ron Heck and Cathy Manning of Cottonwood Hot Springs.

We also thank Karen Morgan and Jason Wilson of the Colorado Geological Survey who provided GIS support throughout the map editing process and produced the final, cartographic map product. Technical review by Dr. Richard P. Smith (Natrhop, Colorado), Chris Carroll (Colorado Geological Survey), John Keller (Colorado Geological Survey), and Dr. Vince Matthews (Colorado Geological Survey), improved the quality and accuracy of the map and text. Final preparation of the map and cross sections was by Jason Wilson, Karen Morgan and Larry Scott (CGS).

GEOLOGIC BACKGROUND

The Buena Vista West 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 range in age from Early Proterozoic to recent and 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).

In broad view, the geology of the Buena Vista West quadrangle is dominated by Tertiary and Precambrian crystalline rocks in the Sawatch Range and by unconsolidated Quarternary surficial deposits in the upper Arkansas Valley. Bedrock is exposed on both sides of the valley. The Sawatch Range comprises the western half of the quadrangle and is cored by Early Proterozoic mixed biotitic and felsic and hornblendic gneisses and meta-igneous rocks. The gneissic rocks predominate and are related to a metamorphic event that peaked at about 1,740 Ma (Tweto, 1987). In the northeastern corner of the quadrangle, 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 meta-igneous rocks predominate on the east side of the valley and locally occur within the gneisses on the west side. Small stocks of granite and dikes of granite and pegmatite of Early or Middle(?) Proterozoic age have intruded the older Proterozoic rocks.

The Laramide Sawatch uplift had most of the Paleozoic and Mesozioc sedimentary rocks removed by erosion from about 70 to 40 m.y. and a well-formed, widespread, low-relief erosion surface (late Eocene erosion surface) was developed over this part of Colorado (Epis and Chapin, 1975; Scott, 1975; Epis and others, 1976 and 1980). From about 38 to 28 m.y., the Thirtynine Mile volcanic field (Steven and Epis, 1968; Epis and Chapin, 1974) and the central Colorado volcanic field (McIntosh and Chapin, 2004) were developed on the late Eocene surface. One of the main components of the central Colorado volcanic field include a series of welded ash-flow tuff outflow units (tuff of Triad Ridge, Wall Mountain Tuff and Badger Creek Tuff) that have been interpreted to originate from the southern Sawatch Range (Lowell, 1969; Chapin and others, 1970; Epis and Chapin, 1974; Chapin and Lowell, 1979; Epis and others, 1976 and 1980; Toulmin, 1976; Taylor and others, 1984).

Four potential source calderas or large intrusions that may have had related calderas have been identified in the Sawatch Range: (1) the 36.6 Ma Mount Princeton pluton (Shannon, 1988); (2) the 36 Ma Bonanza caldera (Varga and Smith, 1984); (3) the 34.4 Ma Mount Aetna cauldron (Shannon and Epis, 1987, Shannon and others, 1987a; and Shannon, 1988); and (4) the 34 Ma Grizzley Peak cauldron (Cruson, 1973; Fridrich and Mahood, 1984; and Fridrich, 1986). The northeastern margin of the Mount Princeton pluton and the Mount Aetna cauldron dominate the bedrock geology of the southwest quadrant of the Buena Vista West quadrangle. The four volcano-plutonic subsidence systems formed over the tops of large calc-alkaline plutons which were emplaced in a 75-mile long north-northwest trending zone along the axis of the Laramide Sawatch uplift. The explosive silicic volcanism associated with the Sawatch Range caldera-cauldron systems may be related to the initial stages of relaxation of Laramide to middle Tertiary compression, which allowed orogenic, calc-alkaline magmas access to shallow levels in the crust (Varga and Smith, 1984; Shannon and others, 1987b; Shannon, 1988). The timing of this relaxation preceded initiation of Rio Grande rift faulting by about 5 to 6 million years.

No remnants of the late Eocene erosion surface or the silicic ash-flow outflow tuffs have been identified in the Buena Vista West quadrangle, but small patches of possible volcanics on the west side of the valley may be remnants. A major accumulation of the tuff of Triad Ridge (McIntosh and Chapin, 2004) is present in the Trout Creek paleovalley about three miles east of the western boundary of the Buena Vista West quadrangle (Keller and others, 2004). Additional remnants of the late Eocene erosion surface and ash flow tuffs are likely to be preserved at depth in the Arkansas Valley graben.

The most striking structural feature in the region of the Buena Vista West 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 Valley defines the axis of the rift at this latitude in Colorado and is a west-tilted half graben (Chapin, 1971; Chapin and Cather, 1994). The master normal fault of the rift is the Sawatch fault zone, which lies in the center of the quadrangle, dips northeast, and strikes about N30°W. Tweto (1979) suggested that rift-related faulting may have begun as early as 28 Ma and rift-related magmatism was initiated at about 26 to 27 Ma. Abundant faulting along the Sawatch Range front is related to formation of the Rio Grande rift. Minor mafic-felsic dikes were emplaced into rift-related fractures and represent bimodal rift-related magmatism.

The Sawatch Range is a classic rift-shoulder uplift, with the highest peaks at the eastern edge of the range and the drainage divide on the western side of the range. The range contains 15 of Colorado's 54 peaks over 14,000 feet elevation and is the one of the highest parts of the conterminous United States. Evidence for strong earthquake activity during the Quaternary exists in the form of Quaternary fault scarps that are arranged in a more or less continuous, en echelon zone along the base of the Sawatch Range.

The upper Arkansas Valley graben has been filled with as much as 5,000 feet of Miocene to Holocene basin-fill sediments. These sediments form prominent pediment surfaces that slope gently eastward from the range front to the Arkansas River. Older basin fill (Tertiary Dry Union Formation) is exposed in bluffs along the western margin of the Arkansas River flood plain in the extreme eastern part of the quadrangle.

The Dry Union Formation of Miocene and Pliocene age is exposed at three locations on the eastern margin and southeastern corner of the quadrangle. The Dry Union Formation consists of arkosic, partly volcaniclastic flood plain 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, and to the Santa Fe Group that fills basins of the Rio Grande rift farther south (Chapin and Cather, 1994).

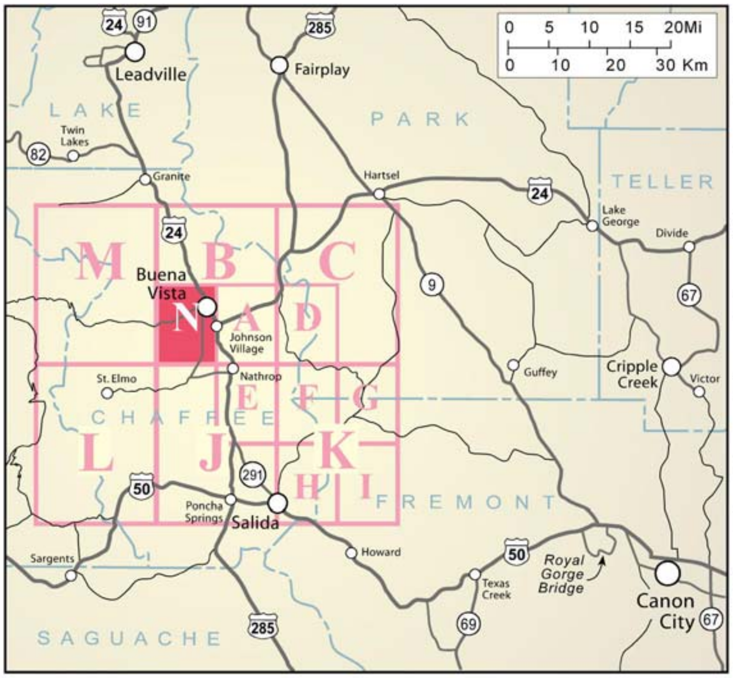
Surficial Quaternary deposits cover the floor of the Arkansas Valley and include large glacial outwash deposits traceable to terminal moraines at the Sawatch Range front, modern stream alluvium, and alluvial fan deposits. In the mountainous part of the quadrangle, glacial and periglacial deposits of Quaternary age exist in the four large, glaciated drainages (from north to south, North Fork Cottonwood Creek, Cottonwood Creek, Maxwell Creek, and Dry Creek).

PREVIOUS STUDIES

Numerous geologic studies have established the regional geologic framework in the Sawatch 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 form the oldest bedrock in the Buena Vista West quadrangle. 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, which include volcanic rocks postulated to originate from the Mount Princeton and Mount Aetna intrusions.

The U.S. Geological Survey has published a number of reports with geological maps of areas adjacent to the Buena Vista West quadrangle and descriptions of many of the rock units (fig. 3). The Dings and Robinson (1957) study of the Garfield 15’ quadrangle (adjoins the SW corner of the BV West quadrangle) provided excellent, early descriptions of the Mount Princeton and Mount Aetna intrusions and the bimodal dikes. The Brock and Barker (1972) Mount Harvard 15’ quadrangle geologic map adjoins the western boundary of the Buena Vista West quadrangle and includes the northwestern portion of the Mount Princeton pluton, some elements of the northern Mount Aetna cauldron boundary, and many of the Proterozoic units that are present on the Buena Vista West quadrangle. Contiguous rock units that extend onto or occur on adjacent maps are described in Van Alstine (1969), Limbach (1975), Scott and others (1975), Scott (1975), Shannon (1988), Fridrich and others (1998), and Keller and others (2004).

Specific studies which focused on the geology of the Buena Vista West quadrangle include an unpublished Masters thesis by Limbach (1975) which 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; Scott and others, 1975) described geologic relations in the upper Arkansas Valley and southern Sawatch 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. Scott and others (1975) published the Poncha Springs 15-minute quadrangle, which lies directly south of the Buena Vista West 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; Keller and others, 2004). 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 West quadrangle is shown in 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 (Keller and others, 2004), CGS

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

C. Antero Reservoir 1:62,500 geologic map (De Voto, 1971), Colorado School of 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 and others, 1975), USGS

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

L. Garfield 1:62,500 geologic map (Dings and Robinson, 1957), USGS

M. Mount Harvard 1:62,500 geologic map (Brock and Barker, 1972), USGS

N. Buena Vista West 1:24,000 geologic map (THIS MAP)

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

PRESENT STUDY

The present study focuses on geologic mapping in the Buena Vista West 7.5-minute quadrangle at a scale of 1:24,000. Field work in the Buena Vista West quadrangle was undertaken during the summer and fall of 2004. Bedrock mapping was completed by James R. Shannon (Colorado School of Mines). The CGS provided a field assistant (Joel T. Poppert) for a few days of field work on Mount Princeton. Bedrock was mapped on an enlarged U.S. Geological Survey topographic base at scale of 1:12,000 and later compiled on to 1:24,000-scale base maps.

Surficial deposits were mapped by Jim McCalpin (GEO-HAZ Consulting) on U.S. Forest Service color aerial photographs (1:24,000-scale) taken in September 1996. Map unit contacts were transferred from mylar overlays of aerial photographs to a 1:24,000-scale paper field compilation map of the Buena Vista West 7.5' quadrangle. After all surficial and bedrock contacts were compiled on the paper map, they were transferred to a mylar base map. The mylar map was then scanned at 200 dpi and heads-up digitized in ArcGIS by the San Luis Valley GIS/GPS Authority in Alamosa, Colorado. Additionally, features of interest were surveyed with a handheld GPS (global positioning satellite) receiver.

Shannon and McCalpin described the structural geology of the quadrangle. McCalpin completed the geologic hazards analysis and the description of water resources. Shannon studied and described the mineral resources in the quadrangle.

Bedrock units and surficial deposits less than 5 feet thick or smaller than 150 feet in horizontal dimension were generally not mapped. However, some thin bedrock units, such as Proterozoic and Tertiary dikes, are represented on the map as a single line because they add to the structural understanding of the geology in the area. The cultural features of the topographic base map date from 1988 aerial photographs, with limited field checking done in 1994. Thus, roads, reservoirs, and buildings constructed after 1994 are not shown on the map base, and human-made deposits that postdate the 1988 aerial photography also are not shown on the map.

DESCRIPTION OF MAP UNITS

QUATERNARY DEPOSITS

Quaternary (surficial) deposits shown on the map are generally more than 5 feet thick. If the surface map unit is thinner than 5 feet and/or discontinuous we map a "fractional" map unit, shown by a map unit abbreviation that lists the upper deposit in the numerator and the underlying deposit in the denominator (for example, Qbto/Tmpm). Residuum and artificial fill of limited extent were not mapped. Contacts between surficial units may be gradational, and mapped units locally include deposits of another type. The Quaternary deposits of the Buena Vista West quadrangle are not well exposed, due to the lack of stream incision over most of the valley floor. Consequently, the thickness of most units is estimated and descriptions of physical characteristics such as texture, stratification, and composition are based on observations at a small number of localities. Particle size is expressed in terms of the modified Wentworth scale (Ingram, 1989), and sorting is expressed in the terminology of Folk and Ward (1957).

The terminology used for divisions of late Neogene (Quaternary) time is shown in table 1. Numerical ages have not been obtained for any of the surficial units in the Buena Vista West quadrangle. The ages assigned to surficial units are estimates based principally on stratigraphic relations, position in the landscape, degree of erosional modification, differences in degree of weathering and soil development, and correlations with deposits elsewhere in the region whose ages have been determined by numerical-dating methods. For example, middle and early Pleistocene alluvial units are correlated with contiguous deposits in the Buena Vista East quadrangle that contain dated volcanic ashes (Keller and others, 2004).

Table 1. Time terminology applied to surficial deposits in the Buena Vista West quadrangle (after Fullerton and others, 2003).

Formal time divisions			Informal time divisions	Informal nomenclature for glacial deposits	Approximate age (sidereal years)
ICS[1]	*historical (pre-2003)*	ICS[1]			
Neogene period	*Quaternary period*	Holocene epoch			
				— ? — ? — ? — ? —	11,580
		Pleistocene epoch	late Pleistocene	Pinedale	
				— ? — ? — ? — ? —	55,000
				— ? — ? — ? — ? —	128,000
			middle Pleistocene	Bull Lake	
				— ? — ? — ? — ? —	
					778,000
			early Pleistocene	pre-Bull Lake	
					1,806,000
	Tertiary period	Pliocene epoch			

[1] International Commission on Stratigraphy.

Note– Italicized time divisions reflect historical usage in the USA and Europe, which has been superceded in Europe by the ICS 2003 revisions.

HUMAN-MADE DEPOSITS

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

GLACIAL DEPOSITS – Gravel, sand, silt, and clay deposited by ice along glaciated valleys in the Sawatch Range (from north to south, North Fork Cottonwood Creek, Cottonwood Creek, Maxwell Creek, Dry Creek).

Qnt Neoglacial till (Holocene) - Heterogeneous deposits of gravel, sand, silt, and clay deposited by ice in terminal and ground moraines. May also include localized lenses of material transported by melt-water adjacent to ice. Deposits are light-gray, poorly sorted, unstratified or poorly stratified, matrix-supported, boulder, pebble, and cobble gravel in a silty-sand matrix. Clasts are typically angular to rounded and unweathered. Small kettle holes and hummocky topography are common. Soils comprised of moderately thin A-horizon and very weakly developed C-horizon. Lack of clast weathering, lack of soil development, very hummocky surface morphology, and location high in cirque basins suggest a Holocene age (early to mid Neoglacial, or 2-5 ka). Maximum thickness is unknown, but morphology suggests a thickness of at least 33 feet in places.

Qpt Pinedale till, undivided (late Pleistocene) – Heterogeneous deposits of gravel, sand, silt, and clay deposited by ice in terminal, lateral, and ground moraines. May also include localized lenses of material transported by melt-water adjacent to ice. Deposits are light-olive-gray, poorly sorted, unstratified or poorly stratified, matrix-supported, boulder, pebble, and cobble gravel in a silty-sand matrix. Clasts are typically angular to rounded and unweathered. Small kettle holes and hummocky topography are common. Soils comprised of moderately well-developed A-horizon and weakly developed C-horizon. Includes all Pinedale till mapped in Maxwell Creek and Dry Creek and ground moraine in Cottonwood Creek. Lack of clast weathering, limited soil development, and hummocky surface morphology suggest a late Pleistocene age (Pinedale equivalent, 15-35 ka). Maximum thickness is unknown.

Qpty Pinedale till, younger (late Pleistocene) – Heterogeneous deposits of gravel, sand, silt, and clay deposited by ice in terminal and lateral moraines. May also include localized lenses of material transported by melt-water adjacent to ice. Deposits are light-olive-gray, poorly sorted, unstratified or poorly stratified, matrix-supported, boulder, pebble, and cobble gravel in a silty-sand matrix (fig. 4). Clasts are typically angular to rounded and unweathered. Small kettle holes and hummocky topography are common. Soils comprised of moderately well-developed A-horizon and weakly developed C-horizon. Comprises inner Pinedale moraines in Cottonwood Creek and North Fork. Lack of clast weathering, lack of soil development, and very hummocky surface morphology suggest a late Pinedale age (15-22? ka). Maximum thickness is unknown, but roadcuts along County Roads 365 (North Fork Cottonwood Creek) and 343 (Cottonwood Creek) expose a thickness of at least 33 feet in places.

Figure 4. Younger Pinedale till (Qpty) exposed in a roadcut on the north side of CR 365 about 30 feet west of the Colorado Trail, in Sec. 5, T14S, R79W.

Qpto Pinedale till, older (late Pleistocene) – Heterogeneous deposits of gravel, sand, silt, and clay deposited by ice in terminal and lateral moraines. May also include localized lenses of material transported by melt-water adjacent to ice. Deposits are light-olive-gray, poorly sorted, unstratified or poorly stratified, matrix-supported, boulder, pebble, and cobble gravel in a silty-sand matrix. Clasts are typically angular to rounded and unweathered. Small kettle holes and hummocky topography are common. Soils comprised of moderately well-developed A-horizon and weakly developed C-horizon. Comprises outer Pinedale moraines in North Fork and Cottonwood Creeks. Limited clast weathering, weak soil development, and location outside of late Pinedale moraines suggest an early Pinedale age (22?-35 ka). Maximum thickness is unknown, but moraine morphology suggests it is probably thicker than unit Qpty.

Qbt Bull Lake till, undivided (middle Pleistocene) – Heterogeneous deposits of gravel, sand, silt, and clay deposited by ice in terminal and lateral moraines. Moraines lie adjacent to and outside of Pinedale moraines in Dry Creek, Maxwell Creek, and

Cottonwood Creek. Comprises lateral moraines on the south side of Maxwell and Dry Creeks. Deposits are yellowish-gray, poorly sorted, unstratified or poorly stratified, matrix-supported, boulder, pebble, and cobble gravel in a silty-sand matrix. Most clasts are angular to subangular and little weathered, but Mount Princeton quartz monzonite fragments are rounded and partly disintegrated. Some boulders are more than 15 feet in diameter. Generally, exposed boulders are half or more buried below surface of moraine. Moraine is only slightly hummocky and crest is rounded. Soils are moderately developed and have a weakly developed argillic B-horizon. Degree of clast weathering, soil development, and surface morphology suggest a middle Pleistocene (Bull Lake, 130-160 ka) age for these deposits. Maximum thickness is unknown but may be as much as 100 feet in moraines at the mouth of Maxwell Creek.

Qbty Bull Lake till, younger (late middle Pleistocene) – Heterogeneous deposits of gravel, sand, silt, and clay deposited by ice in terminal and lateral moraines. Moraines lie adjacent to and outside of Pinedale moraines in Dry Creek, Maxwell Creek, Cottonwood Creek, and North Fork Cottonwood Creek. Deposits are grayish-brown, poorly sorted, unstratified or poorly stratified, matrix-supported, boulder, pebble, and cobble gravel in a silty-sand matrix (fig. 5). Most clasts are angular to subangular and little weathered, but Mount Princeton quartz monzonite fragments are rounded and partly disintegrated. Some boulders are more than 15 feet in diameter. Generally, exposed boulders are half buried below surface of moraine. Moraine is only slightly hummocky and crest is rounded. Soils are moderately developed and have a weakly developed argillic B-horizon. Degree of clast weathering, soil development, and surface morphology suggest a late middle Pleistocene (Bull Lake, 60-130 ka) age for these deposits. Maximum thickness is unknown but may be as much as 100 feet in moraines at the mouth of Maxwell Creek.

Figure 5. Younger Bull Lake till (Qbty) exposed in a roadcut on the west side of Princeton Circle, on the north side of North Fork Cottonwood Creek. Note thin soil with weak B horizon at top of cut. Cut is about 10 feet high.

Qbto Bull Lake till, older (middle Pleistocene) – Heterogeneous deposits of gravel, sand, silt, and clay deposited by ice in terminal and lateral moraines. Moraines lie adjacent to and outside of younger Bull Lake moraines in Dry Creek, Maxwell Creek, Cottonwood Creek, and North Fork Cottonwood Creek. Deposits are reddish-gray, poorly sorted, unstratified or poorly stratified, matrix-supported, boulder, pebble, and cobble gravel in a silty-sand matrix (fig. 6). Most clasts are angular to subangular and weathered, but Mount Princeton quartz monzonite fragments are generally disintegrated (grussified). Some boulders are more than 8 feet in diameter. Generally, exposed boulders are 50-75% buried below surface of moraine. Moraine is smooth rather than hummocky and crest is rounded. Soils are moderately developed and have a red argillic B-horizon. Degree of clast weathering, soil development, and smooth surface morphology suggest a middle Pleistocene (Bull Lake, 130-160 ka) age for these deposits.

Moraines are truncated by Quaternary fault scarps at Dry Creek and Cottonwood Creek. Maximum thickness is at least 33 feet.

Figure 6. Older Bull Lake till (Qbto) exposed in a roadcut at the intersection of Columbia Drive and Mountaintop Drive, on the north side of North Fork Cottonwood Creek. Tape measure at upper right is 10 feet long. Note thick red soil beneath tape.

Qpbt Pre-Bull Lake till, undivided (early Pleistocene) – Heterogeneous deposits of gravel, sand, silt, and clay deposited by ice in terminal and lateral moraines. Moraines lie far from present streams and outside Bull Lake moraines in Maxwell Creek and North Fork Cottonwood Creek (fig. 7). Also includes five small areas perched on the range front north of the mouth of Cottonwood Creek. Deposits are reddish-gray, poorly sorted, unstratified or poorly stratified, matrix-supported, boulder, pebble, and cobble gravel in a silty-sand matrix. Most clasts are angular to subangular and weathered, but Mount Princeton quartz monzonite fragments are generally disintegrated (grussified). Surface boulders are rare, and those exposed are >75% buried below surface of moraine. Moraine surface is very smooth and crest is very broad and gentle. Soils are strongly developed and have an argillic B-horizon. Degree of clast weathering, soil development, smooth surface morphology, and disconnection from present valley axes suggest an early Pleistocene age for these deposits. Maximum thickness is unknown but may be as much as 100 feet in moraines north of the North Fork Cottonwood Creek.

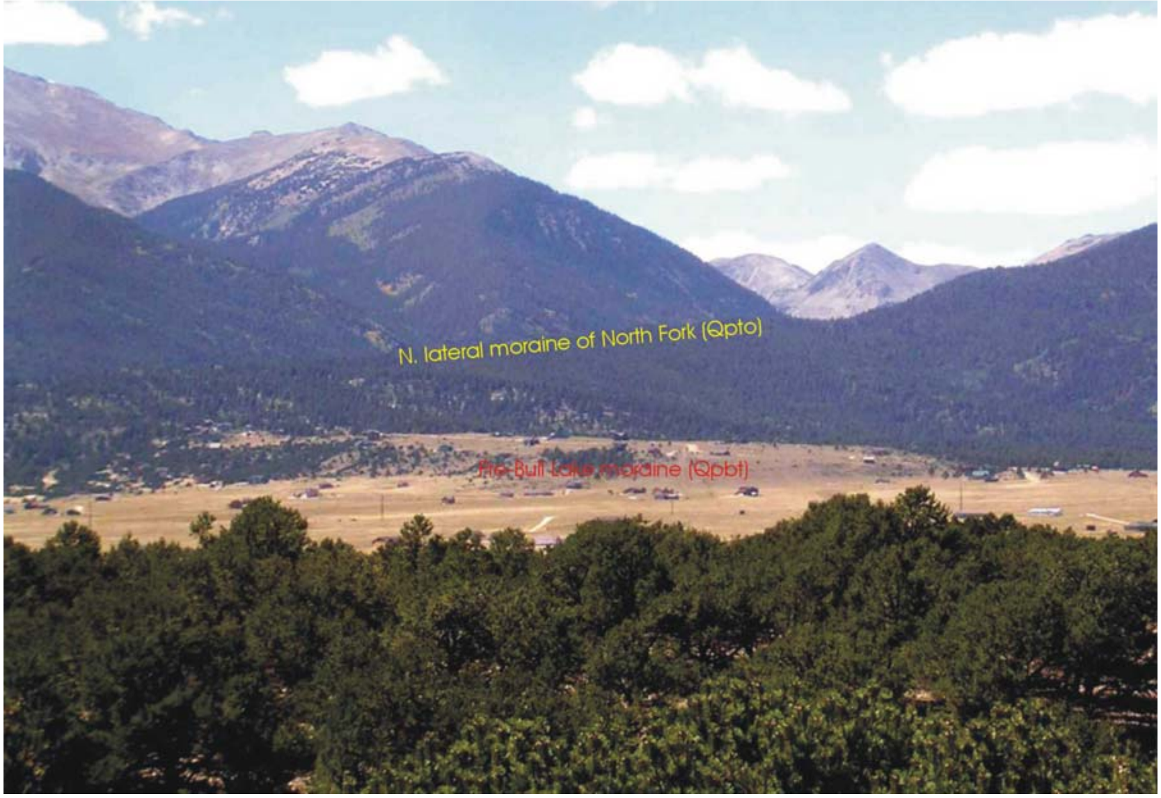


Figure 7. Telephoto of the pre-Bull Lake moraine on the north side of North Fork Cottonwood Creek (center, labeled in red). This moraine trends northeast and is truncated by younger Bull Lake and Pinedale moraines that trend southeast.

PERIGLACIAL AND LACUSTRINE DEPOSITS – Deposits formed in cold environments by freeze-thaw action, solifluction, and nivation. Includes lacustrine peat, clay, silt and sand deposited primarily by water in small glacial lake basins.

Qrg Rock glacier deposits, undivided (Holocene) – Poorly sorted angular to sub-angular boulders, cobbles, gravel, and sandy silt in a matrix of firn or glacier ice. The outer part of the rock glacier is typically clast supported, matrix free, and composed of angular to subangular, predominantly boulder-sized rock fragments. Downslope movement is the result of internal deformation of the firn or ice core. Rock glaciers commonly have a lobate or tongue-like morphology and form in cirque basins where sediment supply is abundant. Includes rock glaciers that are generally inactive, but may contain some small areas of later Holocene reactivation too small to map. Mapped only in the southwest corner of the map area, in the glaciated valleys of Maxwell Creek and Dry Creek. Maximum thickness about 66 feet.

Qrgo Rock glacier deposits, older (late Pleistocene) – Poorly sorted angular to subangular boulders, cobbles, gravel, in a matrix of sandy silt. The outer part of the rock glacier is typically clast supported, matrix free, and composed of angular to subangular, predominantly boulder-sized rock fragments. Rock glaciers commonly have a lobate or tongue-like morphology and form in cirque basins where sediment supply is abundant. Frontal slope is below the angle of repose. Boulders on top, sides, and front are covered with lichen and/or trees, so deposits are inferred to be stationary. Probably no longer contain ice cores. Mapped only in the southwest corner of the map area, in the glaciated valley of Maxwell Creek. May be covered with younger talus and colluvium on their edges. Maximum thickness about 33 feet.

Qta Talus deposits, active (middle to late Holocene) – Angular, cobbly and bouldery rubble with boulders as much as 6 feet in diameter. Deposits are derived from bedrock as fragments were 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. Lack of surface vegetation indicates that rubble deposition is continuing in modern times. Mapped only in the southwest corner of the quadrangle, on the valley walls of Maxwell and Dry Creeks, where rocks were derived from Mount Princton quartz monzonite (map units Tmpk and Tmpm). Thickness of the deposits is probably less than 33 feet. Talus areas are subject to rockfall, rock-topple, and rockslide hazards.

Qt Talus deposits, undivided (Holocene) – Angular, cobbly and bouldery rubble with boulders as much as 6 feet in diameter. Deposits are derived from bedrock as fragments were 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. Surface is partly vegetated, indicating that most of the surface is no longer receiving active deposition. Mapped only in one locality on the southeast corner of Bald Mountain, in Charcoal Gulch, where rocks were derived from Proterozoic gneiss and granodiorite (map units Xb and Xgdf). Thickness of the deposits is probably less than 16 feet. Talus areas are subject to rockfall, rock-topple, and rockslide hazards.

Qtf Talus fan deposits (Holocene) – Angular, cobbly and bouldery rubble with boulders as much as 6 feet in diameter deposited in steep cones marked by a prominent axial gully. Deposits are derived from bedrock as fragments were transported downslope by both rockfalls and debris flows. Axial gully is typically flanked by prominent debris-flow levees. This unit typically lacks matrix material near the surface, but dissected talus reveal significant matrix at depth. Surface is unvegetated, indicating that it has received recent active deposition. Thickness of the deposits is probably less than 16 feet. Mapped only in the southwest corner of the quadrangle, on the valley walls of Maxwell and Dry Creeks, where rocks were derived from Mount Princeton quartz monzonite (map units Tmpk and Tmpm). Talus fan areas are subject to rockfall and debris flows.

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

Ql Lacustrine deposits, undivided (Holocene) – Fine-grained sediments formed in lakes or swampy closed depressions where the water table is near or slightly above the ground surface. Typically overlain by dark-brown to black, organic-rich sediment in wetland areas; typified by standing water, beaver ponds, and dense willow stands. Surface organic sediment may be interbedded with thin, sandy alluvium. The reducing conditions in these stagnant environments slow the rate of decay of the organic matter, which favors accumulation of organic material. These types of sediments are found only in and adjacent to small glacial lakes (tarns) in upper Maxwell Creek. Lacustrine sediments are highly compactible. Basins in which these sediments are deposited have elevated water tables and may be prone to flooding. Maximum thickness 8-16 feet.

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

Qal Stream-channel, flood-plain, and low-terrace alluvium (Holocene) – Deposits are mostly clast-supported, pebble, cobble, and locally boulder gravel in a sandy-silt matrix. The deposits are locally interbedded with and commonly overlain by sandy silt and silty sand. Clasts are subangular to well rounded, and their varied lithology reflects the diverse types of bedrock within their provenance. This unit includes modern stream-channel deposits of perennial streams, adjacent flood-plain deposits, and low-terrace alluvium that lie a maximum of 10 feet above modern stream level. Deposits may be interbedded with colluvium or debris-fan deposits where the distal ends of fans extend into modern river channels and flood plains. Maximum thickness about 33 feet. Areas mapped as alluvium may be prone to flooding and sediment deposition. The unit is typically a good source of sand and gravel.

Qpo Pinedale outwash deposits, undivided (late Pleistocene) – Yellowish-gray crudely stratified alluvium containing well-rounded to subrounded boulders, cobbles, pebbles, and sand. Composed of Tertiary igneous rocks and Precambrian metamorphic and igneous rocks. Soil at top is weakly developed. Forms narrow channels or terraces on the glacial outwash fan of North Fork Cottonwood Creek, but unit there cannot be traced to Pinedale terminal moraines. Forms most of the flood plain of lower Dry Creek. Potentially commercial source of gravel. Thickness probably 10-30 feet.

Qpoy Pinedale outwash deposits, younger (late Pleistocene) – Yellowish-gray, crudely stratified alluvium containing well-rounded to subrounded boulders, cobbles, pebbles, and sand. Composed of Tertiary igneous rocks and Precambrian metamorphic and igneous rocks. Soil at top is weakly developed. Along Arkansas River north and south of Buena Vista forms a broad terrace about 30 feet above stream level. Underlies part of western Buena Vista. 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, 1984). Average size of boulders is about 4-6 feet, but the largest boulder recognized is 65 feet in diameter. Also forms narrow terraces flanking the modern flood plains of Cottonwood Creek and North Fork Cottonwood Creek, where unit can be traced to Pinedale terminal moraines. Forms most of flood plain of lower Maxwell Creek. Potentially commercial source of gravel. Thickness probably 10-30 feet.

Qpoo Pinedale outwash deposits, older (late Pleistocene) – Yellowish-gray, crudely stratified alluvium containing well-rounded to subrounded boulders, cobbles, pebbles, and sand (fig. 9). Composed of Tertiary igneous rocks and Precambrian metamorphic and igneous rocks. Soil at top is weakly developed (horizons A11/A12/AC in 1 foot-thick loess cover, horizon 2C in outwash) and contains the type pedon of the Dominson gravelly sandy loam (SCS, 1975). Forms most of the valley floor in the vicinity of the Arkansas River, in a terrace about 13 feet higher than the Qpoy terrace. Underlies downtown Buena Vista and southern residential area. 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, 1984). Also forms much of the alluvial fan area at the confluence of Cottonwood Creek and North Fork Cottonwood Creek. Commercial source of gravel from pit north of Buena Vista. Thickness probably 10-30 feet.

Figure 8. Older Pinedale outwash gravels (Qpoo) underlying a terrace on the western side of the Arkansas River, north of Buena Vista (Sec. 5, T14S, R78W). Photo shows the south wall of the Hard Rock Paving gravel pit. Note weak surface soil developed in sandy sediments overlying the cobbly channel gravels.

Qbo Bull Lake outwash deposits, undivided (middle Pleistocene) – Brownish-gray to light-gray, sandy bouldery alluvium. On the Arkansas River and in the mouth of Fourmile Creek, unit underlies a terrace 80 feet above stream level. Boulders there average about 10 inches in diameter, but some are larger than 4 feet and are well rounded to subround, fairly well sorted, fairly well stratified; composed 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. Also mapped as outwash fans and channels east of the Sawatch Range front at Charcoal Creek, Silver Prince Creek, east of the North Fork Cottonwood Creek, and Maxwell Creek. Soil at top is moderately well developed. Potentially commercial source of gravel. Thickness probably about 20 feet.

Qboy Bull Lake outwash deposits, younger (late middle Pleistocene) – Brownish-gray to light-gray, sandy cobbly alluvium. Distal fan deposits are well exposed in the upper 7-8 feet of the ACA gravel pit, where the deposit is 50% sand matrix and 50% pebble and cobble gravel (fig. 9). Cobbles average about 4-6 inches in diameter on the distal parts of fans near the Arkansas River, but boulders larger than 4 feet are common on the proximal parts of the fan. Clasts are well rounded to subround, fairly well sorted, poorly stratified, with a sand matrix; composed of Tertiary igneous and Precambrian metamorphic and igneous rocks. All rock types are slightly weathered. Soil at top is moderately well developed. Comprises about one-quarter of the area of glacio-fluvial alluvial fans along the Sawatch Range front south of Cottonwood Creek; occurs in broad channels slightly incised into older Bull Lake outwash. Comprises about half the area of glacial outwash from the North Fork Cottonwood Creek. Commercial source of gravel. Thickness less than 10 feet in distal fans, but thicker near the range front.

a

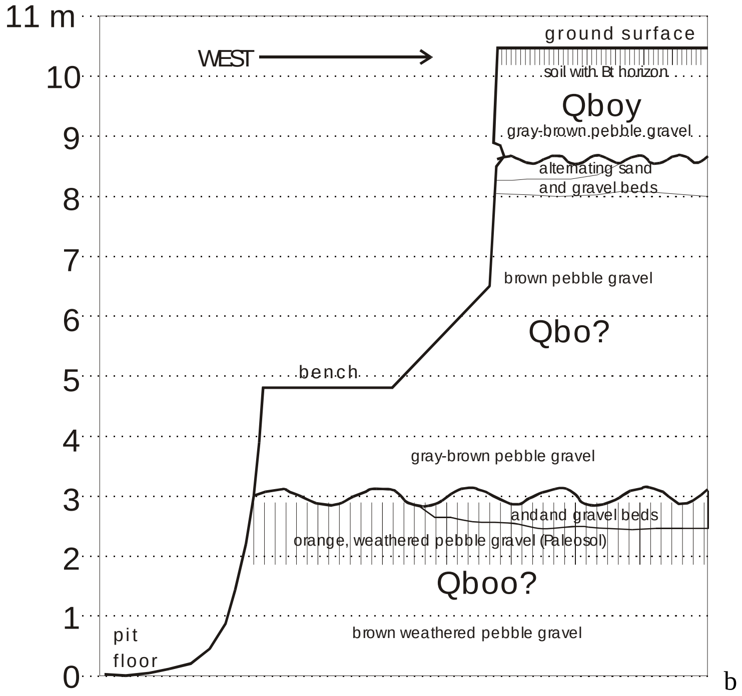


Figure 9. (a) Photograph of younger Bull Lake outwash gravels (unit Qboy, above dashed line) and older Bull Lake outwash gravels (units Qbo and Qboo, below dashed line) in the western wall of the ACA gravel pit, located 1.2 miles southwest of downtown Buena Vista. Height of wall visible is approximately 19 feet, and corresponds to the measured section above the bench; (b) Measured stratigraphic section in the western part of the ACA gravel pit. The surface is underlain by a 7-8 ft-thick outwash gravel (unit Qboy) topped by a soil with a 1 ft-thick argillic soil B horizon, indicating a younger Bull Lake age. That gravel is unconformably underlain by an 18 ft-thick, more oxidized gravel (unit Qbo?). The lowest 10 feet of the pit (not visible in the photograph) exposed a much more weathered gravel capped by a 3 foot-thick diffuse paleosol. This gravel could be older Bull Lake (unit Qboo?) or pre-Bull Lake. This exposure shows that distal outwash gravels far from the range front are deposited in broad but relatively thin sheets.

Qboo Bull Lake outwash deposits, older (middle Pleistocene) – Reddish-brown to light-brown, sandy cobbly alluvium. Distal fan deposits are well exposed in the lower half of the ACA gravel pit 1.2 miles southwest of downtown Buena Vista, where the deposit is 75% sand matrix and 25% pebble and cobble gravel. Cobbles average about 4-6 inches in diameter on the distal parts of fans near the Arkansas River, but clast size increases toward the fan heads, with boulders larger than 4 feet common. Clasts are well rounded to subround, fairly well sorted, poorly stratified, with a sand matrix; composed of Tertiary igneous and Precambrian metamorphic and igneous rocks. Clasts of Mount Princeton quartz monzonite are disintegrated; other rock types are only slightly weathered. Soil at top is moderately well developed. Comprises about half of the area of glacio-fluvial alluvial fans along the Sawatch Range front south of Cottonwood Creek, where fan heads are contiguous with Bull Lake moraines (unit Qbt). North of

Cottonwood Creek unit is mapped only in one unnamed drainage that intersects the northern map boundary. Commercial source of gravel. Thickness at least 20 feet in distal fans, but thicker near the range front.

Qpbo Pre-Bull Lake outwash deposits (early Pleistocene) – Reddish-brown sandy cobbly alluvium. Clasts are well rounded to subround, fairly well sorted, poorly stratified, with a sand matrix; composed of Tertiary igneous rocks. Clasts of Mount Princeton quartz monzonite are disintegrated. Soil at top is strongly developed. Mapped only in the center of the glacial outwash fan of Dry Creek, but is not associated with a pre-Bull Lake moraine. Gravel is too weathered and decomposed to be of commercial value. Thickness at least 20 feet in distal fans, but thicker near the range front.

Qi Illinoian (?) alluvium (middle Pleistocene) **–** Brownish-gray boulder alluvium containing well-rounded to subrounded clasts. Composed of igneous and metamorphic rocks and some siliceous sedimentary rocks. Soil at top is strongly developed. Mapped in two small terrace remnants at the foot of the more extensive Qk fan surface between Cottonwood and North Fork Cottonwood Creeks, and in one larger surface inset below the Qk pediment surface in the extreme southeast part of the quadrangle. Equivalent to unit Qg4 of Van Alstine (1969) and correlated to the Illinoian glacial stage of the midwestern USA. Thickness about 5-20 feet.

Qk Kansan (?) alluvium (early Pleistocene) – Brown to reddish-brown, fairly well stratified alluvium containing well-rounded to subrounded fragments of igneous and metamorphic rocks. Comprised of poorly sorted, angular alluvial fan facies near the range front and well-sorted piedmont and channel facies on the valley floor. Alluvial-fan facies is best exposed in a large fan remnant at Red Deer Creek (fig. 10). Piedmont facies forms broad, thin pediments on the valley floor; pediments that unconformably overlie older Quaternary alluvium or Tertiary Dry Union Formation. Forms small terrace remnants about 160-200 feet above the Arkansas River. Part of deposit resulted from a catastrophic flood that emplaced 20-foot boulders north of the Buena Vista West quadrangle (in S ½ Sec. 11, T13S, R79W). Overlain by fine-grained colluvial or overbank deposits which, 5-6 miles north of Buena Vista, contains type-O Pearlette ash, a marker volcanic bed with origin in Yellowstone National Park (Lava Creek B tuff, age 620 ka). Soil at top is strongly developed (horizons A/2Bt1/2Bt2/2C in gravel pit at SE corner of Sec. 15, T14S, R79W), with an 8 inch-thick Bt2 horizon (7.5YR5/6 sandy clay loam). Equivalent to unit Qg3 of Van Alstine (1969) and correlated with the Kansan glacial stage of the Midwestern USA. Thickness probably more than 20 feet.

Figure 10. Kansan alluvium (Qk), alluvial-fan facies, exposed along the jeep road to the mouth of Red Deer Creek. Angular clasts at this location are mainly Proterozoic gneiss.

Qna Nebraskan (?) alluvium (early Pleistocene) – Light-brown to reddish-brown, poorly sorted, poorly stratified, deeply weathered, sandy bouldery gravels. Mapped only in the northeast and southeast parts of the quadrangle. Piedmont facies forms broad, thin pediments on the valley floor; pediments that unconformably overlie older Quaternary alluvium or Tertiary Dry Union Formation. Possibly includes outwash from pre-Bull Lake glaciers, especially adjacent to the pre-Bull Lake moraine north of North Fork Cottonwood Creek (fig. 11). Lower part of deposit in northeast corner of quadrangle resulted from catastrophic flood that emplaced 18-ft boulders in abandoned Arkansas River channel in Sec. 31, T13S, R78W and Sec. 6, T14N, R78W (Scott, 1975). Here the deposit stands 120-160 feet above the Arkansas River. Soil at top is strongly developed (horizons A11/A12/A2/B2t/2C1/2C2) and contains the type pedon of the Pando gravelly sandy loam (SCS, 1975). In terrace remnants north of Buena Vista 60% of surface clasts are quartzite or fine-grained siliceous igneous rocks, with less-resistant coarser-grained igneous rocks having distingrated into grus. Thickness possibly as much as 80 feet.

Figure 11. Nebraskan alluvium (Qna) at driveway entrance to 30285 Valley View Drive, near the contact of Qna with the pre-Bull Lake moraine of the North Fork Cottonwood Creek (Sec. 2, T14S, R79W). Note well-developed red soil profile.

Qn Nussbaum alluvium (?)(earliest Pleistocene) – Brownish-gray to pale-brown, crudely stratified, poorly sorted bouldery alluvium. Composition varies widely depending on source. Deeply weathered; soil at top is very strongly developed. Mapped in only two small areas on the eastern border of the quadrangle. Lies 260-270 feet above Arkansas River. Equivalent to unit Qg1 of Van Alstine (1969). Thickness probably as much as 20 feet.

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

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. Mapped mainly at the base of the Sawatch Range front and at the base of steep slopes into major canyons (fig. 12). 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 feet; 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.

Figure 12. Colluvial deposits form large, planar aprons below outcrops of Mount Princeton quartz monzonite, on the north slope of Cottonwood Creek west of Cottonwood Hot Springs. These deposits are abnormally large and thick due to the weathered and altered nature of the bedrock, which is similar to that exposed in the Chalk Cliffs south of the Buena Vista West quadrangle. During episodes of intense precipitation these colluvial deposits are remobilized into debris flows (see description of unit Qfy).

Qls Landslide deposits, undivided (Holocene to middle? Pleistocene) –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 on map by thick dashed lines with ticks in direction of sliding). Mapped only in the Sawatch Range in three general areas: (1) on the ridge between Cottonwood and Red Deer Creeks in Proterozoic biotite gneiss (unit Xb, 4 slides), (2) southeast of Bald Mountain on the range front between Charcoal Gulch and Silver Prince Creek (also in unit Xb, 2 slides), and (3) 1.5 miles southwest of Bald Mountain in the Mount Princeton pluton (unit Tmpm, 1 slide). Except for the last locality, 6 of the 7 landslides are on or near north-northwest-trending rift-related normal faults. Larger landslide deposits may be more than 50 feet thick.

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 a mixture of alluvial deposits of ephemeral, intermittent, and small perennial streams, and of colluvial deposits deposited from valley sides. Interfingers with and is gradational with stream alluvium (Qal), alluvial-fan deposits (Qf), and colluvium (Qc) (fig. 13). Alluvium is typically composed of poorly to well-sorted, stratified, interbedded, pebbly sand, sandy silt, and sandy gravel. Colluvium may range from unsorted, clast-supported, pebble to boulder gravel in a sandy-silt matrix to relatively well-sorted sand composed of disintegrated granite or quartz monzonite (grus). Clast lithologies vary and are dependent upon the bedrock or surficial unit from which the deposit was derived. Maximum thickness of the unit is approximately 20 feet.

Figure 13. Alluvium and colluvium (Qac, in foreground) on the north side of Cottonwood Creek, west of Cottonwood Hot Springs. Deposit is derived from slopes of altered Mt. Princeton quartz monzonite (background) by a combination of rockfall, soil creep, slopewash, rillwash, and small debris flows (shown).

Qaco Alluvium and colluvium, older (middle to late Pleistocene) – Unit consists of a mixture of colluvial deposits deposited at the base of steep bedrock slopes of the Sawatch Range front, and of minor alluvial fan and sheetwash deposits too small to map. Gullies are sufficiently incised into the deposit that it cannot receive modern alluvial deposition. Mapped only in two range-front locations, east of Bald Mountain and north of Dry Creek. Colluvium may range from unsorted, clast-supported, pebble to boulder gravel in a sandy-silt matrix to matrix-supported, gravelly, clayey, sandy silt. Clasts and matrix are composed of disintegrated Precambrian biotite gneiss (map unit Xb). Maximum thickness of the unit is approximately 20 feet.

Qf Alluvial-fan deposits, undivided (Holocene to middle Pleistocene) – Moderately sorted sand- to boulder-size gravel in fan-shaped deposits from tributary streams. Mapped only in Fourmile Creek in the northeastern corner of the quadrangle (4 of 6 mapped fans), east of Bald Mountain (zone of coalesced small fans), and on the north side of Dry Creek. Deposits typically composed of both matrix-supported beds (debris flow facies) and clast-supported beds (streamflow facies), often interbedded. Clasts are mostly angular to subround with varied lithologies dependant upon local source rock. Sediments are deposited by debris flows, stream flows, 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 is less than 33 feet. 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 to late Pleistocene) – Moderately sorted sand- to boulder-size gravel in fan-shaped deposits from tributary streams. Deposits typically composed of both matrix-supported beds (debris flow facies) and clast-supported beds (streamflow facies), often interbedded. Clasts are mostly angular to subround with varied lithologies dependant upon local source rock. Sediments are deposited by debris flows, stream flows, and sheetwash. Fan-shaped deposits form where tributary drainages with steep gradients join lower gradient streams. Deposit overlies and thus post-dates Pinedale outwash and till deposits. The maximum estimated thickness may exceed 16 feet. Extraordinary precipitation events are likely to trigger future deposition on these young alluvial-fan deposits (fig. 14). Fan deposits may be prone to collapse when wetted or loaded.

Figure 14. Debris flow of 18 August 2004 on Qfy, 0.75 mile west of Cottonwood Hot Springs.

Qfo Alluvial-fan deposits, older (late to middle Pleistocene) – Moderately sorted sand- to boulder-size gravel in fan-shaped deposits from smaller unglaciated tributary streams at the Sawatch Range front. Deposits typically composed of both matrix-supported beds (debris flow facies) and clast-supported beds (streamflow facies), often interbedded. Clasts are mostly angular to subangular derived from the Mt. Princeton pluton. Deposit mapped only on the Sawatch Range front south of Dry Creek. May correlate in part with map unit Qfp that lies directly to the south. The maximum thickness is at least 16 feet.

Qfp Pinedale alluvial-fan deposits (late Pleistocene) – Moderately sorted sand- to boulder-size gravel in fan-shaped deposits from glaciated streams at the Sawatch Range front (Cottonwood Creek, Maxwell Creek) and larger unglaciated streams at the range front (Red Deer Creek). Deposits typically composed of both matrix-supported beds (debris flow facies) and clast-supported beds (streamflow facies), often interbedded.

Clasts are mostly angular to subangular derived from the Mt. Princeton pluton, except at Red Deer Creek where clasts are dominantly Proterozoic gneiss. Correlated with the Pinedale glaciation. The maximum thickness is at least 16 feet.

Qfb **Bull Lake alluvial-fan deposits (middle Pleistocene)** – Moderately sorted sand- to boulder-size gravel in fan-shaped deposits from unglaciated tributary streams at the Sawatch Range front. Deposits typically composed of both matrix-supported beds (debris flow facies) and clast-supported beds (streamflow facies), often interbedded. Clasts are mostly angular to subangular derived from Proterozoic gneiss. Mapped only in the northwestern corner of the quadrangle, where nonglacial fans have prograded out atop an older Kansan fan or pediment (unit Qk) or where fan is adjacent to a Bull Lake moraine. The maximum thickness is at least 16 feet.

TERTIARY ROCKS AND DEPOSITS

Tertiary rocks exposed in the Buena Vista West quadrangle include minor sedimentary rocks and relatively abundant (estimated 15 percent of area) igneous rocks. The igneous rocks consist of plutonic and hypabyssal intrusive rocks and two small areas of possible volcanic rocks.

TERTIARY SEDIMENTARY ROCKS – Exposed Tertiary sedimentary rocks are minor in the Buena Vista West quadrangle. The Dry Union Formation is the only Tertiary sedimentary formation exposed.

Td **Dry Union Formation (Pliocene and Miocene) –** Gray, yellowish-gray, reddish-gray, or greenish-gray layers of unconsolidated to semi-consolidated clay, silt, sand, and gravel (fig. 15). Clasts composed mainly of fragments of volcanic rocks but also containing Precambrian rocks. Sand and gravel layers are cross stratified. Contains white to gray volcanic ash beds. Some layers are cemented by calcium carbonate. Material deposited by streams and in ponds. Locally layers are tilted and faulted. Inferred to underlie the entire valley floor of the Arkansas Valley, but mostly buried by Quaternary alluvium. Thickness probably more than 5,000 feet where dropped down along deep western side of upper Arkansas Valley graben (Tweto, 1979).

Figure 15. Tertiary Dry Union Formation (Td) exposed in a quarry in unnamed drainage in Sec. 10, T15S, R78W, in western part of Buena Vista East quadrangle. Similar deposits are inferred to underlie the Arkansas Valley part of the Buena Vista West quadrangle.

TERTIARY IGNEOUS ROCKS – An estimated forty-five to fifty percent of the exposed bedrock rock area in the Buena Vista West quadrangle consists of Tertiary igneous rocks. They predominantly consist of rocks associated with the 36.6 Ma Mount Princeton pluton. Volumetrically minor igneous rocks represent the 34.4 Ma Mount Aetna cauldron magmatic event, and a younger Late Oligocene-Miocene rift-related, bimodal magmatic event.

Late Oligocene-Miocene rift-related bimodal magmatism – Relatively volumetrically minor, bimodal, lamprophyre and rhyolite porphyry dikes are present in the Buena Vista West quadrangle. They are part of a regional swarm of bimodal dikes that extend for over 13.5 miles along the east flank of the southern Sawatch Range. The dikes are important because they represent the only evidence of rift-related magmatism in the quadrangle. They predominantly cut the 36.6 Ma Mount Princeton pluton, and their orientations are a reflection of post-Mount Princeton stress fields, most likely related to development of the Rio Grande rift.

Tl Spessartite lamprophyre dikes (Miocene?) – Rio Grande rift-related magmatism is present as a regional swarm of bimodal lamprophyre-rhyolite dikes. The lamprophyre dikes include a set of four to five dikes on the ridge between Dry Creek and Maxwell Creek, and two occurrences southwest of Bald Mountain. They represent the northern extension of the Cascade dike swarm (Shannon, 1988), which include spessartite lamprophyre dikes that extend from near Jones Peak (Mount Antero quadrangle) to near Bald Mountain, a distance of about eleven miles. Lamprophyre dikes of the Cascade dike swarm are present cutting rocks of the Mount Princeton pluton both north and south of the Mount Antero and California leucogranite intrusions (Shannon, 1988). In the Chalk Creek area (just south of the Buena Vista West quadrangle) the dikes are 1.5 to 6.0 feet thick and are oriented N24°E with 60°NW dip. The spessartitie dikes predominantly intrude rocks of the Mount Princeton pluton. They also cut Mount Aetna ring dikes (Tma) about one mile south-southwest of Bald Mountain and on the north slope of Mount Antero (Shannon, 1988).

The Cascade dike swarm also includes a set of aphyric, flow-layered rhyolite dikes that extend for about 11.5 miles from south of Carbonate Mountain (St. Elmo quadrangle) to just east of the summit of Mount Princeton. These dikes are oriented N20°E with 61°NW dip, very similar to the spessartitie dikes. A small amount of flow-layered rhyolite was observed on the Latchaw mine dump. The presence of this rhyolite suggests that a flow-layered rhyolite dike extends into the Buena Vista West quadrangle and was probably intersected in the Latchaw mine workings. However, the flow-layered rhyolite dikes were not found on the surface.

Mapping in 2004 for the Buena Vista West quadrangle established cross cutting relations between the spessartite lamprophyre and rhyolite porphyry dikes. Lamprophyre and rhyolite porphyry dikes are exposed on steep slopes on the north side of the ridge between Dry Creek and Maxwell Creek. There is a set of four to five spessartite dikes from 0.5 to 10.0 feet thick and with orientations ranging from N5° to 28°W and variable dips from 26 to 64 degrees SW. They average about two to three feet thick with a general orientation of N20°W, 40°SW, which indicates a significant change in orientation as the dikes are traced south to the Chalk Creek area where the overall orientation is N24°E, 60°NW. In three places lamprophyre dikes cut across a rhyolite porphyry dike (fig. 16) and one of the cross-cutting lamprophyres contains an inclusion of rhyolite porphyry with a partial selvage of chilled lamprophyre (fig. 17).

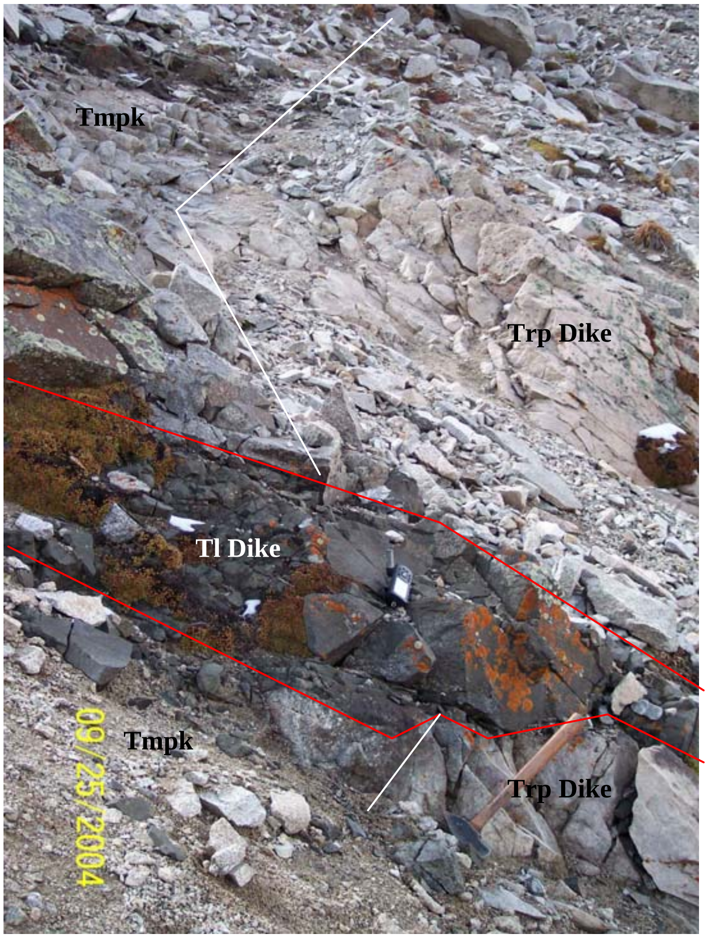


Figure 16. Spessartite lamprophyre dike (Tl; contacts outlined in red) cutting rhyolite porphyry dike (Trp) in Mount Princeton quartz monzonite (Tmpk subunit). The Trp-Tmpk contact is parallel to hammer handle (white line) and is truncated by Tl dike.

The spessartite lamprophyre contains about 7 to 18 percent olivine and augite phenocrysts (0.02 to 0.12 inch) in a fine-grained groundmass of plagioclase-augite-biotite-hornblende-magnetite (fig. 18). Dike margins are commonly chilled and phenocrysts are flow concentrated toward the centers of the dikes. Table 2 gives a whole-rock chemical analysis of a chilled margin of a spessartite dike (sample 04-199). The rock has a very low SiO_2 content of 43.43 percent indicating an unusual ultramafic composition, but with an elevated K_2O content. The spessartites are chemically similar to alkali gabbro and alkali basalt, but with significantly higher K_2O content. This spessartite dike has similar chemistry as a spessartite dike from the Cascade dike swarm (Shannon, 1988).

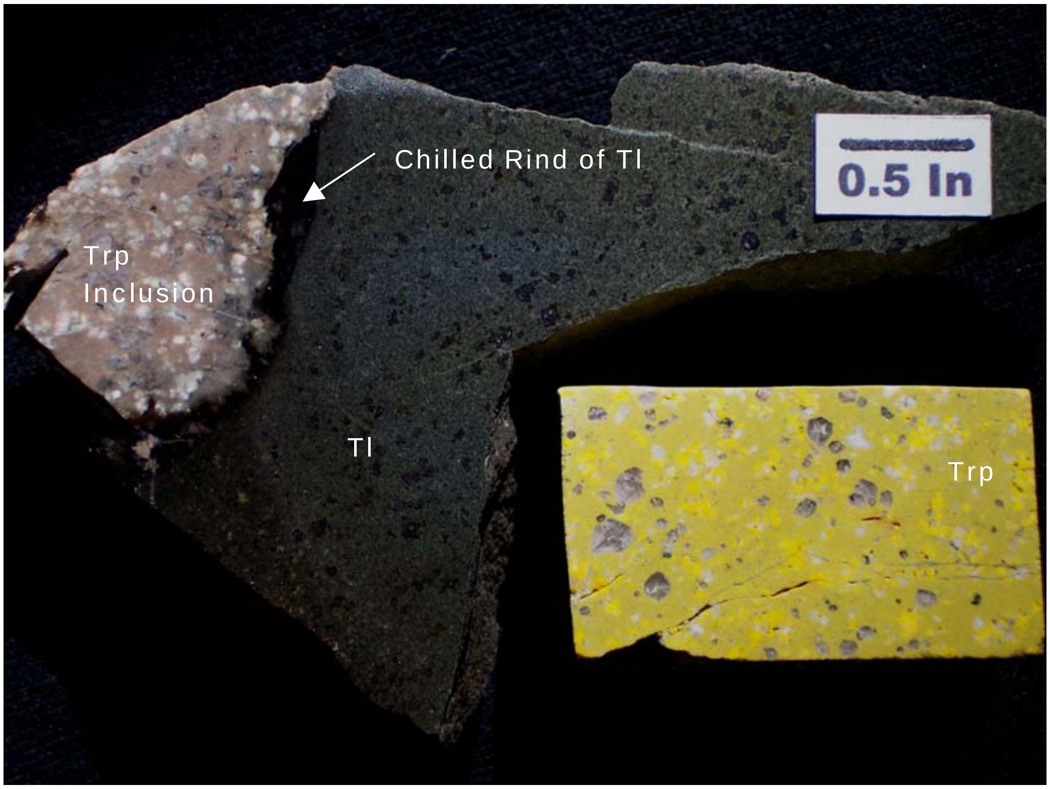


Figure 17. Spessartite lamprophyre (Tl) with inclusion of rhyolite porphyry (Trp) at left. Note fine embayments in inclusion and chilled margin and relic olivine phenocrysts in spessartite. Rhyolite porphyry billet is stained for K-feldspar (lower right) showing K-feldspar (yellow), quartz (gray), and plagioclase (white) phenocrysts.

One spessartite dike contains abundant zeolites that replaced olivine phenocrysts and groundmass plagioclase. Optical properties indicate that the zeolite is laumontite that has partially dehydrated to leonardite. The occurrence of zeolites as replacements of primary (plagioclase) and secondary (serpentinized olivine) minerals in the lamprophyre dikes is interesting, and may support that some zeolite alteration is genetically related to the mafic magmatism.

The Coal Camp dike swarm is a second swarm of bimodal rhyolite-lamprophyre dikes that is present about 3.5 miles west (St. Elmo quadrangle) of the Cascade dike swarm (Shannon, 1988). The dikes have similar orientations as the Cascade dike swarm in the Chalk Cliffs area and include kersantite lamprophyres. The kersantite dikes also cut rhyolite porphyry dikes, establishing that the spessartite and kersantite lamprophyre dikes are the youngest exposed intrusives in the region. The lamprophyre dikes have not been age dated and it is not known if they vented to the surface. If the Cascade dike swarm spessartite dikes vented to the surface it is possible that such evidence may be preserved as flows near the base of the Dry Union Formation, at depth along the western edge of the graben.

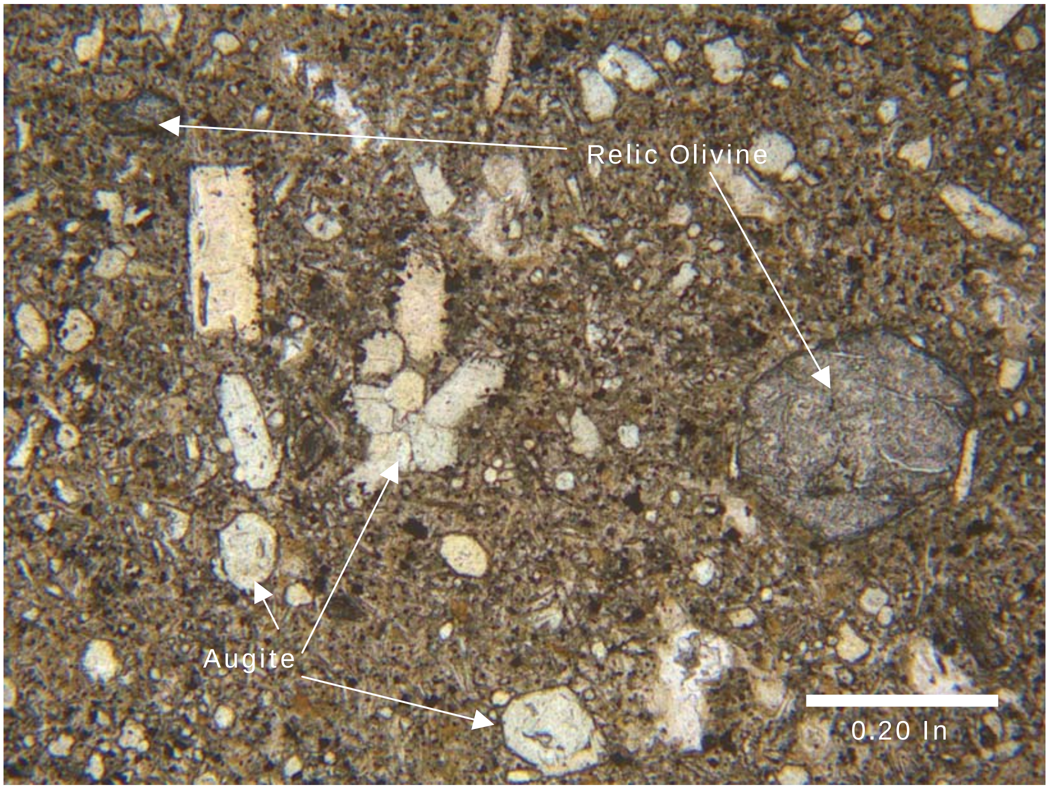


Figure 18. Digital photomicrograph of spessartite lamprophyre showing clinopyroxene and altered olivine phenocrysts in fine-grained groundmass of plagioclase-augite-biotite-amphibole-magnetite. Sample 04-199 was also analyzed for whole rock chemistry (see Table 2).

Trp Rhyolite porphyry dikes (late Oligocene?) – One nearly continuous rhyolite porphyry dike forms an arcuate outcrop pattern in the southeast corner of the Buena Vista West quadrangle. The dike forms small outcrops and concentrated float zones where crossing ridge crests but is difficult to follow across boulder talus slopes where the small pieces of rhyolite are lost in the coarse boulders of Mount Princeton rocks. For example, on the south side of Maxwell Creek the rhyolite porphyry makes up a large proportion of the Maxwell Creek adit dumps, but no rhyolite porphyry outcrop or float is present on the surface. Strong sericitic alteration and some quartz veining in the rhyolite indicate that the underground workings follow veins in, or adjacent to, the rhyolite dike.

The rhyolite porphyry dike is the northward extension of a set of four rhyolite porphyry dikes that are part of the Cascade dike swarm. These dikes are generally oriented N30°E with 40°NW dip in the Chalk Creek area. Rhyolite porphyry dikes are relatively abundant around the areas of the Mount Antero, California, and North Fork leocogranite intrusions (centered about seven miles south of the southwest corner of the Buena Vista West quadrangle). The rhyolites have a regional distribution extending for 13.6 miles from Mount Shavano (Maysville quadrangle) to Sheep Mountain (Mount Yale quadrangle). They are chemically highly evolved rhyolites with a spatial and genetic relationship to the 29 Ma evolved Mount Antero granites (Shannon, 1988). The Mount Antero rhyolite porphyry dike forms an arcuate, semi-circle outcrop pattern with two 3- to 4-mile-long segments. The dikes were interpreted to be possible cone sheets with a 4-mile diameter that formed about a rhyolite intrusive center in the head of Browns Creek (R.P. Smith, 1981, personal communication). A K-Ar whole-rock age determination of 25.4 +/- 1 Ma was obtained by Limbach (1975) on a rhyolite porphyry dike from the Chalk Cliffs. Shannon (1988) in a compilation of age determinations in the southern Sawatch Range presented a re-calculated age of 26.1 +/- 1 Ma for Limbach’s sample.

There are some textural (phenocrysts abundance and size) and compositional (phenocrysts proportions) variations in the rhyolite porphyry dikes and some were interpreted to be early dikes associated with the Mount Antero intrusion (Shannon, 1988). The more distal rhyolite porphyry dikes in the Cascade and Coal Camp dike swarms were inferred to be younger than the California granite intrusion and are commonly garnet bearing. The rhyolite porphyry dikes cut, and are younger than, the Tmpm and Tmpk phases of the Mount Princeton pluton (fig. 16). A rhyolite porphyry dike is cut by lamprophyre dikes on the north side of the ridge between Dry Creek and Maxwell Creeks (fig. 16).

The rhyolite porphyry dike in the southwest corner of the Buena Vista West quadrangle ranges from whitish to light pinkish gray to light greenish in color. It has variable thickness from about 10 to 50 feet. It contains about 22 percent (0.02 to 0.24 inch) phenocrysts of quartz (7 percent), K-feldspar (10 percent), plagioclase (4 percent), and biotite (1 percent) in an aphanitic groundmass (fig. 17). No garnet was observed in this dike, possibly due to weak hydrothermal alteration, which commonly effects biotite and plagioclase (sericitization). Table 2 gives a whole-rock chemical analysis (sample 04B-199A) of a rhyolite porphyry dike from the Buena Vista West quadrangle. It has the composition of a high-silica, alkali rhyolite with a very low CaO content. The chemistry of this rhyolite porphyry dike is similar to the chemistry of rhyolite porphyry dikes of the Cascade dike swarm (Limbach, 1975; R.P. Smith, 1981, written communication; and compiled by Shannon, 1988).

Table 2. Whole-rock chemical analyses of rocks from the Buena Vista West quadrangle. Whole-rock chemical analyses by XRF, by ALS-CHEMEX, Sparks, Nevada (2005-RE05011656).

SAMPLE	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
Tv	67.25	15.3	2.99	1.77	0.78	2.42	5.18	<0.01	0.49	0.05	0.21	0.03	0.11	2.38	98.99
Tl	43.43	13.22	10.74	9.68	8.67	1.98	3.47	0.07	1.62	0.18	1.02	0.12	0.16	4.36	98.71
Xqd-W	53.93	15.57	11.49	6.47	3.74	2.56	2.01	0.01	1.61	0.14	0.28	0.03	0.07	0.71	98.6
Tdd-W	70.09	15.34	2.22	0.9	0.71	4.28	3.02	<0.01	0.24	0.05	0.19	0.04	0.14	1.71	98.93
Trp	75.6	12.82	0.7	0.2	0.07	3.77	4.32	0.01	0.1	0.06	0.02	<0.01	0.01	0.64	98.31
Tqd-E	55.76	15.79	8.91	5.77	4.38	2.72	2.36	0.01	1.13	0.12	0.36	0.05	0.08	1.01	98.45
Tdd-E	64.63	15.77	2.94	3.16	0.39	2.86	3.51	<0.01	0.33	0.06	0.15	0.02	0.15	4.37	98.34

Sample locations are shown on the geology map.

Tv	04-04A Tertiary volcanic rocks south of Bald Mountain
Tl	04-199 Spessartite lamprophyre on Mount Princeton- ridge between Maxwell and Dry creeks
Xqd-W	04-425 Quartz diorite from Mercury Creek
Tdd-W	04-437 Dacite porphyry dike from west side of rift, un-named creek Section 9
Trp	04B-199A Rhyolite porphyry dike on Mount Princeton- ridge between Maxwell and Dry creeks
Xqd-E	04B-271 Quartz diorite from east side of rift, old railroad grade
Tdd-E	04B-490A Dacite porphyry dike from east side of rift, Hop Gulch

* LOI- Lost On Ignition(volatiles)

Early Oligocene(?) magmatism – Two rock units in the Buena Vista West quadrangle are grouped as miscellaneous early Oligocene (?) magmatism. They lack absolute age determinations and field relations do not tightly constrain their ages. They include one or two dikes of monzonite-trachyte porphyry and two small areas of possible Tertiary volcanic and volcaniclastic rocks.

Tmd Monzonite porphyry to trachyte porphyry dikes (Oligocene?)- Monzonite porphyry occurs as one or two east-northeast-trending dikes hosted in Xb south of Bald Mountain on the west side of the rift. The dikes rarely crop out but make fairly continuous concentrated float zones. They only cut Proterozoic rocks in the Buena Vista West quadrangle. Similar east-northeast-trending monzonite porphyry dikes occur on the east flank of Mount Shavano (Maysville and Mount Antero quadrangles) where they cut Xb and Xgd (Shannon, 1988). One dike in the Mount Antero quadrangle cuts a Mount Aetna ring dike (Tma), and more monzonite porphyry dikes are present in the Garfield quadrangle where they cut Proterozoic biotite granite (YXg) and the Mount Princeton quartz monzonite. Thus, if all of the monzonite porphyry dikes are contemporaneous, then they represent a minor, but widespread magmatic event that is younger than the Mount Princeton pluton (36.6 Ma) and the Mount Aetna cauldron (34.4 Ma).

In the Buena Vista West quadrangle, outcrop and float zones suggest the dikes are about 3 to 20 feet thick. The monzonite porphyry is characterized by a medium purplish-gray color with about 15 percent K-feldspar, 7 to 8 percent plagioclase, 4 percent biotite, and trace quartz phenocrysts in an aphanitic, locally flow-layered groundmass. The rock is classified as a pheno-trachyte on the basis of the phenocryst assemblage and IUGS classification (Streckeisen, 1979). The tabular K-feldspar phenocrysts are generally fresh, pink crystals up to about 0.32 inch in size and are locally aligned parallel to flow layering in the groundmass. The dikes are typically moderately chloritized and weakly sericitized.

Tv Volcanic (or hypabyssal?) rocks (late Eocene to early Oligocene?) – Two small patches of possible Tertiary volcanic rocks are present in the Proterozoic rocks south of Bald Mountain. The two patches are areas 250 to 500 feet across, of concentrated float of biotite-quartz latite porphyry. Two types of material predominate: a non-fragmental porphyritic phase that displays weak flow banding and may represent lava flows (fig. 19); and a fragmental porphyritic phase that appears to be completely devitrified, densely welded ash-flow tuff. The latter unit contains large fragments of glassy sanidine and angular clasts of Xb. Unfortunately there are no outcrops of these possible volcanic rocks and the relationship to the surrounding Precambrian rocks is ambiguous.

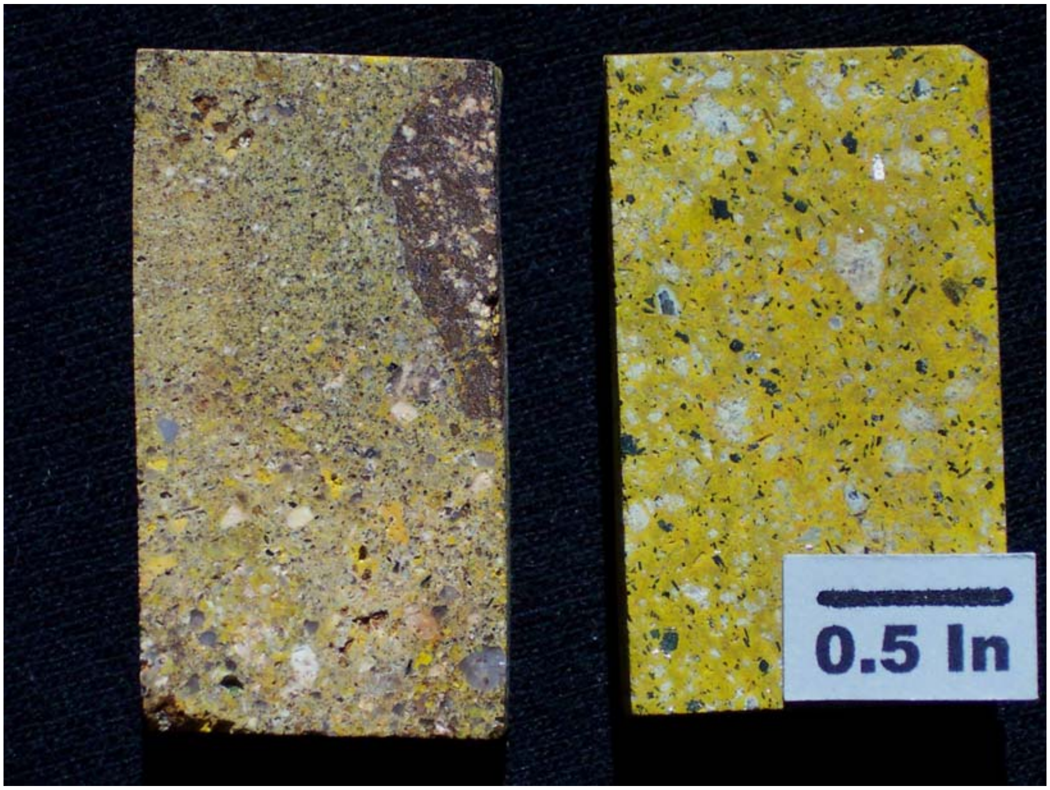


Figure 19. Billets stained for K-feldspar of Tertiary volcaniclastic (left) and volcanic (right) rocks from south of Bald Mountain. Both rocks contain minor fragmental sanidine crystals.

Thin sections and slabs (stained for K-feldspar) of the fragmental porphyritic phase indicate it contains about 15 to 18 percent subhedral plagioclase, 2 to 4 percent subhedral to broken sanidine, 3 to 5 percent subhedral biotite, and accessory opaque, sphene, apatite and zircon in an aphanitic groundmass. Plagioclase crystals are usually whole but commonly cracked and locally broken. Biotite grains are locally kinked and disrupted. There is no evidence of hornblende, indicating a biotite-dominant mafic mineral assemblage. The relative proportion of feldspar crystals indicates a low sanidine to plagioclase ratio. The matrix commonly displays irregular color banding which is subparallel to elongated crystals and may represent flow banding or compaction foliation. Lithic and crystal fragments of Proterozoic biotite gneiss are locally common. The groundmass consists of very fine microlites and locally displays a circular to ovoid pattern suggesting remnants of devitrification spherulites (fig. 20). There is no clear evidence of relic glass shards or fiamme/collapsed pumice in any of the samples.

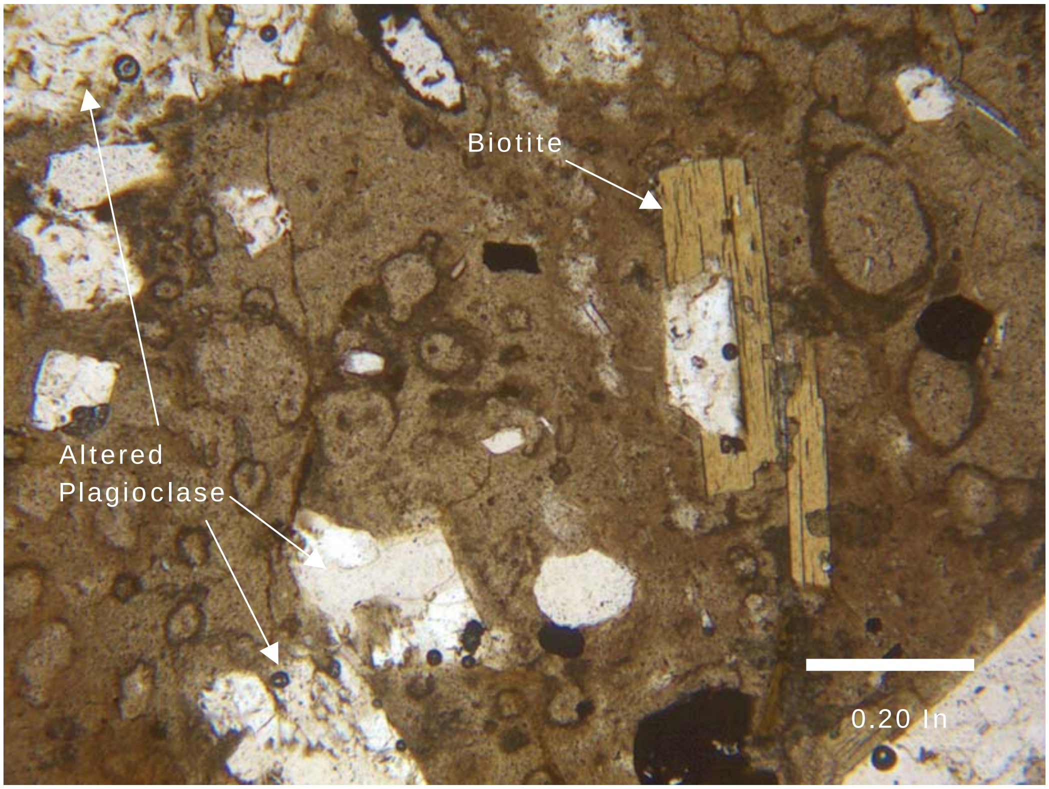


Figure 20. Digital photomicrograph of quartz latitic volcanic rock (Tv) from near Bald Mountain showing peculiar circular structures in matrix thought to be related to relic spherulitic divitrification textures.

The quartz latitic rocks are moderately altered or weathered. Plagioclase crystals, which are preferentially affected, are moderately to strongly altered and replaced by clay and carbonate. The sanidine and biotite crystals are usually fresh. This alteration is not typical of the locally moderate to strong hydrothermal alteration (predominantly sericitization and chloritization) in the surrounding Proterozoic rocks. Slabs stained for K-feldspar show a wide variation in the K-feldspar content of the matrix. Most slabs show very strong staining of the matrix indicating abundant very fine-grained K-feldspar. A whole rock chemical analysis of the freshest sample (weak to moderate alteration of plagioclase) of quartz latite (sample 04-4A) is given in table 2. The major-element chemistry of the rock is generally compatible with a quartz latitic composition, except that CaO and NaO are significantly lower and K_2O is significantly higher. The decrease in CaO and NaO might be related to the alteration of plagioclase, which seems more akin to a low-temperature alteration, perhaps surface weathering. The variable K-feldspar content of the matrix and very high K_2O content (5.18 percent) of the analyzed sample suggest an unusal potassium alteration or metasomatism. Smith (1982) noted a similar potassium metasomatism in many samples of the Wall Mountain Tuff on the east side of the rift. High, variable K_2O contents in the range of 5.18 to 7.07 percent were suggested to be the result of long-term ion-exchange between potassium in ground water and mono-valent cations such as sodium.

There are additional concentrated float blocks of these possible volcanic rocks at the range front, in the mouth of Charcoal Gulch, which drains the area with the concentrated float patches. Relatively fresh blocks of the quartz latite exhibit a range of textures from porphyro-aphanitic to igneo-fragmental. In addition, there are minor blocks of a peculiar bedded, clastic rock consisting of biotite gneiss (Xb) detritus and possible volcaniclastic material (fig. 19).

The small size and innocuous location along the base of the Sawatch Range mountain front belies the importance of these possible volcanic rocks. The quartz latitic rocks could also represent shallow, hypabyssal intrusives that represent a vent for lava flows and ash flow tuffs. The orientation of contacts and flow layering in the quartz latite is critical in determining if they are subvolcanic or volcanic in origin. If the quartz latite porphyry and clastic rocks represent patches of volcanic rocks, then they are the only remnants of the Eocene paleo-erosion surface on the east side of the southern Sawatch Range that were not preserved in the down dropped subsidence block of the Mount Aetna cauldron. Remnants of early Oligocene volcanic rocks preserved in the Mount Aetna collapse structure include pre-collapse volcanic rocks and syn-collapse intracauldron welded tuffs and megabreccias (Shannon and Epis, 1987 and Shannon, 1988). These volcanic rocks represent remnants of the Eocene erosion surface. The only other remnants of this surface in the region are minor patches of welded tuff (Lower Bonanza Tuff?) along the old Monarch Pass road on the west side of the Continental Divide (Shannon, 1988).

Mount Aetna cauldron (early Oligocene; 34.4 Ma) – The northeastern portion of the ring zone of the Mount Aetna cauldron collapse structure occurs in the southwestern part of the Buena Vista West quadrangle. The ring zone consists of three main elements: (1) ring dikes (Tma) of biotite-hornblende quartz latite porphyry; (2) ring shears (Trs), an anastamosing array of ductile-brittle shears and faults; and (3) intrusive breccia dikes (Tib) related to explosive venting of volcanic gases and fluids along the ring zone (Shannon and Epis, 1987 and Shannon, 1988). All three of these ring zone features are present in an arcuate zone hosted in the older Mount Princeton pluton. Pseudotachylytes, a forth ring zone feature developed along the southern portion of the Mount Aetna cauldron ring zone (Shannon and Epis, 1987), were not observed in the Buena Vista West quadrangle. In general, the ring zone features are poorly exposed in the Buena Vista West quadrangle, thus the distribution of features was determined by mapping concentrated float. Much better outcrop and structural information is found on the westward continuation of the Mount Aetna cauldron ring zone, present on Sheep Mountain approximately 3,000 feet west of the Buena Vista West quadrangle boundary (Shannon, 1988). There, both ring shears and intrusive breccias have moderate to steep dips, both inward and outward, and ring dikes dip steeply outward.

Shannon and others (1987) compiled all available age determinations on the Mount Aetna cauldron (resurgent intrusion and ring dikes) and the intracauldron and outflow Badger Creek Tuff. The average of 21 age determinations by K-Ar and fission-track dating methods was 34.4 Ma. More recent, high precision ^{40}Ar/^{39}Ar age determinations by McIntosh and Chapin (2004) indicated a mean age of 33.81 +/- 0.11 Ma for five samples of the Badger Creek Tuff (outflow) and 34.07 +/- 0.90 Ma for a mean of three ages on the Mount Aetna intrusions.

Tma Mount Aetna quartz latite porphyry ring dikes (early Oligocene)- The float/outcrop pattern of the Mount Aetna ring dikes (Tma) in the Buena Vista West quadrangle supports a near vertical orientation. The dikes vary from less than 10 feet thick up to about 400 feet thick. Ring shears and intrusive breccias were not observed to cut the dikes, supporting that the ring dikes are the last ring zone features to form. This is compatible with general cross cutting relationships around the rest of the Mount Aetna cauldron ring zones (Shannon and Epis, 1987). Shannon and others (1987) reported four fission-track age determinations (sphene 35.9 +/- 3.6 Ma; allanite 33.8 +/- 3.4 Ma; zircon 34.6 +/- 3.3 Ma and apatite 23.8 +/- 2.4 Ma) on the west extension of the Mount Aetna ring dike on Sheep Mountain, in the Mount Yale quadrangle. The apatite age is interpreted as an uplift age, and the average of sphene, allanite, and zircon ages is 34.8 Ma.

The ring dikes are pheno-andesites on the basis of mineralogical classification using modal analysis of phenocryst assemblages and are quartz latitic on the basis of chemical analysis (Shannon and others, 1987). They have similar chemistry and mineralogy (low sanidine to plagioclase ratios and contain both biotite and hornblende) as the Mount Aetna intracauldron tuff, the Badger Creek Tuff (outflow), and the tuff of Triad Ridge. The age determinations support a genetic relationship between the ring dikes and the Badger Creek Tuff. Mount Aetna ring dikes are characterized by large, tabular orthoclase phenocrysts from 0.5 to 1.5 inches in size and smaller plagioclase, biotite and hornblende phenocrysts in an aphanitic groundmass (fig. 21).

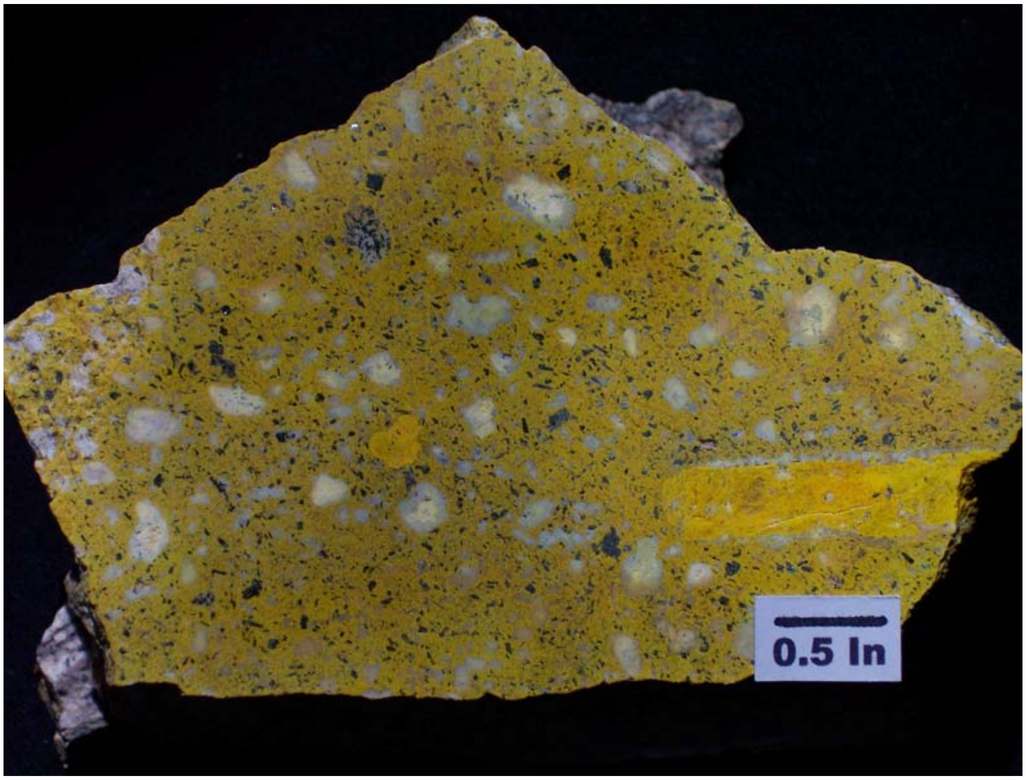


Figure 21. Slab of Mount Aetna ring dike (Tma) stained for K-feldspar. Note partial rapakivi plagioclase overgrowth on large orthoclase phenocryst and low K-feldspar to plagioclase ratio.

Trs Mount Aetna ring shears (early Oligocene) – The ring shears associated with the Mount Aetna cauldron ring zone are structures produced in the Mount Princeton quartz monzonite during collapse and resurgence of the Mount Aetna cauldron. They are described here because they are present as mappable zones that are spatially and genetically associated with ring dikes and intrusive breccias. The distribution of concentrated float zones suggest that ring shear zones (Trs) range from isolated narrow zones less that one foot wide to complex, anastamosing zones hundreds of feet wide. The outcrop pattern of the ring shears suggests that they are vertical to moderate-steep inward dipping. The ring shears consist of complex shear zones with both ductile and brittle deformation features. Ductile deformation includes the development of proto- to ultra-mylonitic fabrics, including local well developed S-C fabrics (Lister and Snoke, 1984), in the Mount Princeton pluton wall rocks (fig. 22). Some ductile shears cut intrusive breccias but not ring dikes in the Buena Vista West quadrangle. Brittle deformation features include brecciation of wall rock and development of microbreccia seams. Local cross cutting relationships between ductile and brittle deformation features suggest complex alternation of deformation mechanisms probably related to significant changes in strain rate in the dynamic ring zone during cauldron collapse (Shannon and Epis, 1987).

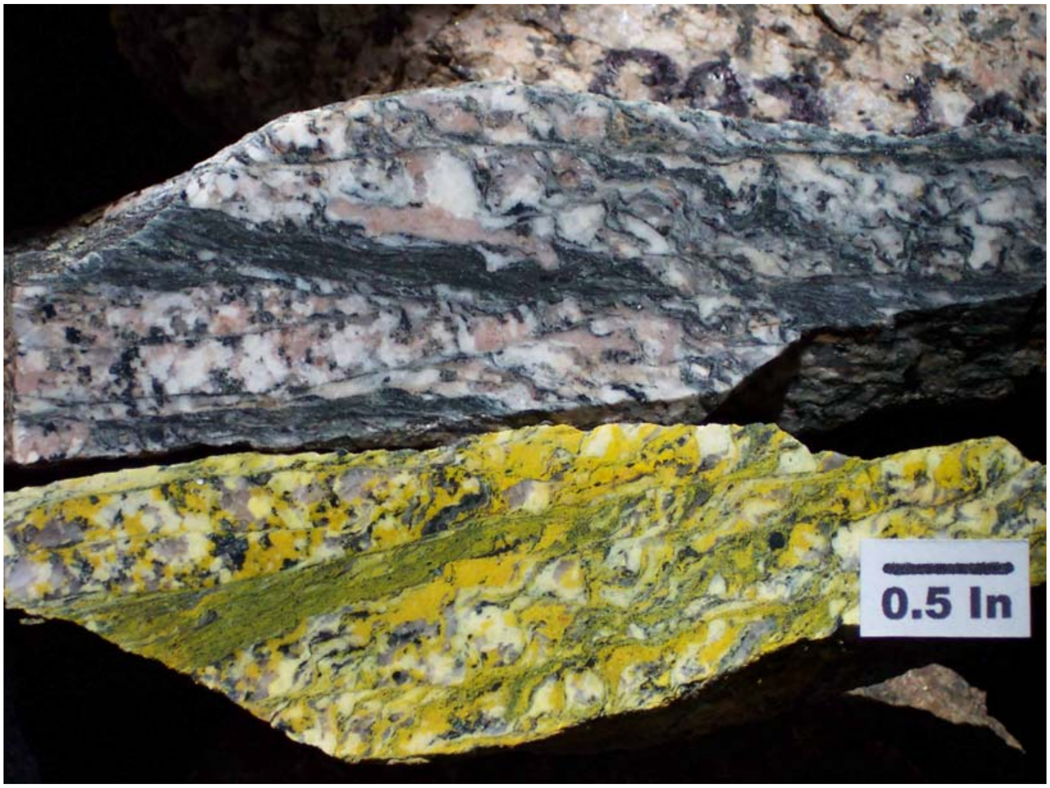


Figure 22. Mount Aetna cauldron ductile ring shears (Trs) cutting Mount Princeton quartz monzonite (Tmpm) displaying well-developed S-C deformation fabrics and truncated ultramylonite bands. Lower matching slab is stained for K-feldspar.

Tib Mount Aetna intrusive breccias (early Oligocene) – Intrusive breccias (Tib) occur as dike-like bodies cutting Mount Princeton pluton rocks. They are typically associated with ring shear zones but sometimes occur as isolated bodies. Concentrated float zones and subcrop indicate that intrusive breccias range from seams about a half inch thick to dikes up to about 3 feet thick. The outcrop pattern of intrusive breccias is similar to ring shears and suggests the breccias are vertical to moderate-steep inward dipping. Intrusive breccias are characterized by angular to sub-rounded clasts and crystal fragments of Mount Princeton pluton phases in a very fine-grained matrix of crushed rock (fig. 23). The amount of lithic and crystal clasts is variable from about 1 percent to more than 50 percent. The intrusive breccias are always green in color due to the ubiquitous chloritization (+/- epidote) of mafic minerals. Intrusive breccias contain clasts of ring shears and are locally cut by ductile shear bands suggesting that they are more or less contemporaneous with ring shearing and cauldron collapse. Intrusive breccias have not been observed cutting ring dikes, which they apparently predate. They lack evidence of any magmatic component (that is, not intrusion breccias) including phenocrysts, fragmental phenocrysts or a melt that contributed to the matrix. Therefore, intrusive breccias are interpreted to be emplaced by fluidization processes related to episodic venting of magmatic gases and fluids during the collapse stage (Shannon and Epis, 1987; Shannon, 1988).

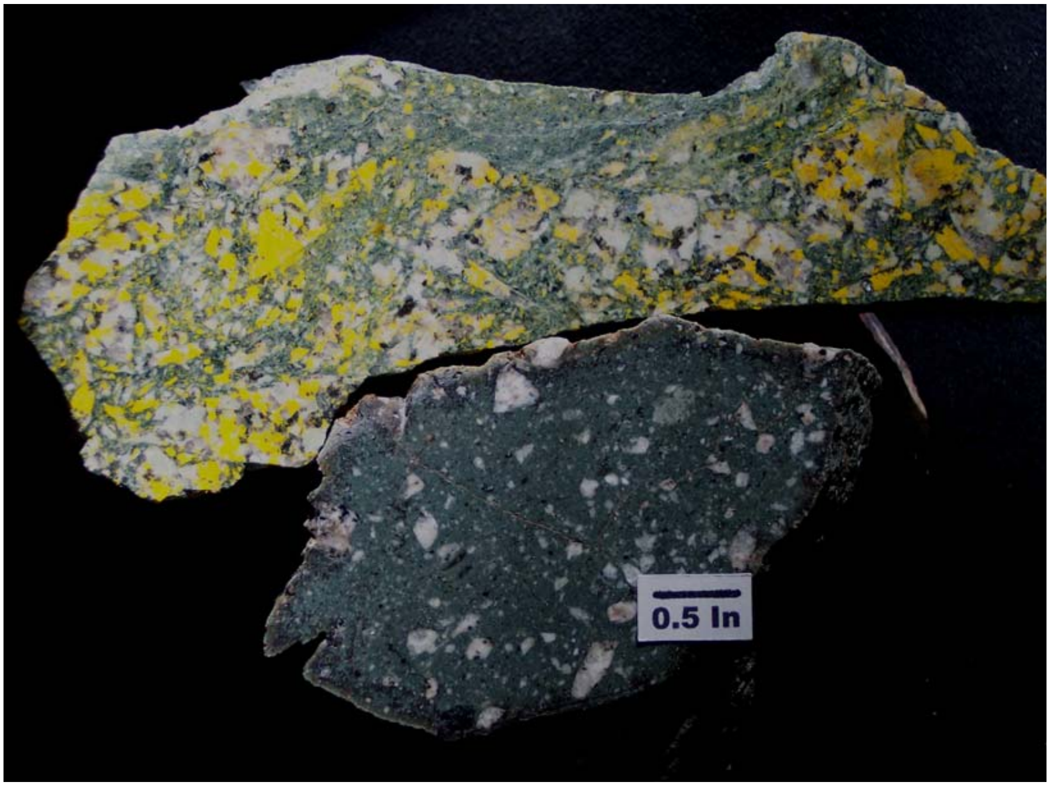


Figure 23. Mount Aetna ring zone intrusive breccias (Tib) showing high clast (top, stained for K-feldspar) and low clast (bottom) varities. All clasts and crystal fragments are derived from Mount Princeton pluton wall rock.

Mount Princeton pluton (late Eocene; 36.6 Ma) – The northeastern flank of the Mount Princeton pluton is exposed over a large part of the southwestern quadrant of the Buena Vista West quadrangle. The Mount Princeton pluton is about 24 miles long and 14 miles wide and has a slight elliptical elongation in a N15° to 20° E direction. It intrudes Precambrian rocks along the northwest part of Bald Mountain, the very east edge of the Cottonwood Creek cliffs (near Cottonwood hot springs), and in the Red Deer Creek drainage. The Precambrian-Mount Princeton pluton contact provides one of the most useful datums with which to document fault offsets related to younger Rio Grande rift faulting. In the southwest quadrant of the Buena Vista West quadrangle, the Mount Princeton pluton is cut by the ring zone of the younger Mount Aetna cauldron, including ring dikes (Tma), ring shears (Trs) and intrusive breccias (Tib). It is also cut by rift-related, bimodal lamprophyre-rhyolite porphyry dikes. Field relations, although not conclusive, suggest that the Mount Princeton pluton is younger than the dacite dikes (Tdd). The relative age of monzonite-trachyte porphyry dikes (Tmd) is unclear in the Buena Vista West quadrangle, but similar dikes cut the Mount Princeton pluton and Mount Aetna ring dikes in the Mount Antero and Garfield quadrangles suggesting the porphyry dikes are younger.

Shannon (1988) compiled all available age determinations on the Mount Princeton pluton \and the Wall Mountain Tuff. The average of six K-Ar ages, five fission- track ages, and one U-Pb age on the Mount Princeton pluton is 36.6 Ma. The U-Pb zircon age determination of 36.6 +/- 0.4 (Ed DeWitt, 1987, written commication) may be the most reliable indication of the age of the Mount Princeton pluton because other age determinations may be reset by younger magmatism. The average of six K-Ar ages and three fisson-track ages from the Wall Mountain Tuff is 36.6 Ma, the same age as the Mount Princeton pluton. McIntosh and Chapin (2004) presented new high precision $^{40}Ar/^{39}Ar$ age determinations for the Wall Mountain Tuff. The mean of five ages is 36.69 +/- 0.09 Ma. New age determinations for the Mount Princeton pluton mostly record reset ages associated with the Mount Aetna cauldron (Chapin, 2003, personal commication).

Shannon (1988) compiled published and new chemical analyses and new modal analyses of Mount Princeton pluton rocks. On the basis of IGUS Classification (Streckeisen, 1976), the bulk of the intrusion (Tmpf, Tmpk, and Tmpm subunits) is biotite-hornblende granite B. However, the informal names Princeton quartz monzonite (Crawford, 1913) and Mount Princeton quartz monzonite (Dings and Robinson, 1957) are in common usage, and quartz monzonite is here retained for the medium- to coarse-grained, equigranular to porphyritic phases that make up most of the pluton.

Large areas of the Mount Princeton pluton were mapped by Crawford (1913), Dings and Robinson (1957), and Shannon (1988). Many previous workers have noted textural and compositional variations in the pluton (Crawford, 1913; Dings and Robinson, 1957; Limbach, 1975; and Sharp, 1976). A distinctive coarsely porphyritic phase with about one-inch pink K-feldspar phenocrysts was first recognized as a mappable unit by R. P. Smith (1979, unpublished reconnaissance map; 1981, personal communication.). Shannon (1988) continued the delineation of the K-feldspar porphyritic phase (Tmpk) of the pluton, and described and mapped other systematic textural and compositional variations including a complex sequence of border units in the roof zone, preserved south of Chalk Creek. The pluton was divided into a border unit with seven subunits and an interior unit with three subunits. The delineation of mappable textural and compositional phases in the Mount Princeton pluton was continued during this study. However, the distribution of the various subunits of the border unit (Tmpb) is too variable and complicated to be mapped individually.

The contact between the Mount Princeton border unit and the interior unit is an abrupt transition from the heterogeneous, finer-grained border unit into the more homogeneous, coarser-grained interior units. Shannon (1988) subdivided the interior into three subunits: an outer interior subunit consisting of about 1,000 to 1,500 feet of medium-grained, equigranular Mount Princeton quartz monzonite (Tmpf in this report); an intermediate interior subunit consisting of about 300 to 1,100 feet of coarsely porphyritic Mount Princeton quartz monzonite (Tmpk in this report); and an inner interior subunit of medium-coarse grained, equigranular Mount Princeton quartz monzonite (Tmpm in this report). The contacts between the three interior units are always gradational with a gradual increase in K-feldspar phenocrysts as the Tmpk subunit is approached from units both above (Tmpf) and below (Tmpm). In the central part of the pluton, the Tmpf and Tmpm subunits are essentially indistinguishable because they have the same mineralogy and texture. There is no evidence that the porphyritic Tmpk subunit is intrusive into Tmpf or Tmpm subunits. Consequently, Shannon (1988) suggested that the textural and compositional diversity is related to changing conditions in the magma body as it sequentially crystallized inward.

Tmpb **Mount Princeton border unit (late Eocene)-** The Mount Princeton border unit is about 100 to 300 feet thick and is generally poorly exposed in the Buena Vista West quadrangle. The main contacts of the pluton with the Precambrian rocks are not exposed; however, these contacts have been delineated by detailed float mapping. The general relationships of the Mount Princeton pluton and Precambrian rocks north of Middle Cottonwood Creek suggest that the contact is outward dipping and is gently to moderately inclined northward. The border unit consists of a heterogeneous package of ‘chilled’, finer-grained rocks that generally have a more granitic composition than interior phases and with a higher proportion of K-feldspar to plagioclase and a lower mafic content (fig. 24). The most abundant border lithology in the Tmpb unit is a granitic aplite porphyry with plagioclase, K-feldspar, quartz and biotite phenocrysts in a fine-grained, K-feldspar-rich groundmass. Other variants of porphyritic subunits include a K-feldspar porphyritic subunit similar to Tmpk but with smaller K-feldspar phenocrysts and a plagioclase porphyritic subunit. The border unit also has abundant pink biotite-bearing aplite (fig. 24) which is locally miarolitic and contains traces of disseminated sulfides (pyrite and/or chalcopyrite).

Figure 24. Billets of Mount Princeton pluton phases: Top, left and right- Tmpb border phases, porphyry and fine aplite; Bottom, left- Tmpm quartz monzonite subunit; Bottom, right- Tmpk porphyritic K-feldspar subunit.

Tmpf Mount Princeton finer-grained quartz monzonite subunit (late Eocene) – The finer-grained quartz monzonite subunit consists of medium-grained biotite-hornblende quartz monzonite that occurs below or interior to the border (Tmpb) unit and above or exterior to the porphyritic K-feldspar (Tmpk) subunit. It is the predominant Mount Princeton phase exposed on the north side of Cottonwood Creek near Cottonwood Hot Springs. In addition, a small area of the subunit is present interior to the intrusive Mount Princeton pluton-Proterozoic gneiss contact about 4,000 feet west-southwest of Bald Mountain. In this area of the northeastern flank of the Mount Princeton pluton, the finer-grained quartz monzonite subunit is about 1,600 feet thick.

Overall, the Tmpf subunit is slightly finer grained and has less total mafic minerals and a higher proportion of biotite to hornblende (fig. 25) than the interior quartz monzonite subunit (Tmpm). It is light pinkish gray with a medium-grained, equigranular texture. The average of three modal analyses of the Tmpf subunit from the central part of the pluton indicates 23.6 percent quartz, 29.3 percent K-feldspar, 36.5 percent plagioclase, and 9.8 percent biotite and hornblende (Shannon, 1988). In comparison to the interior quartz monzonite subunit, the Tmpf subunit has a little more K-feldspar and less hornblende. The Tmpf subunit is granite B (IUGS classification).

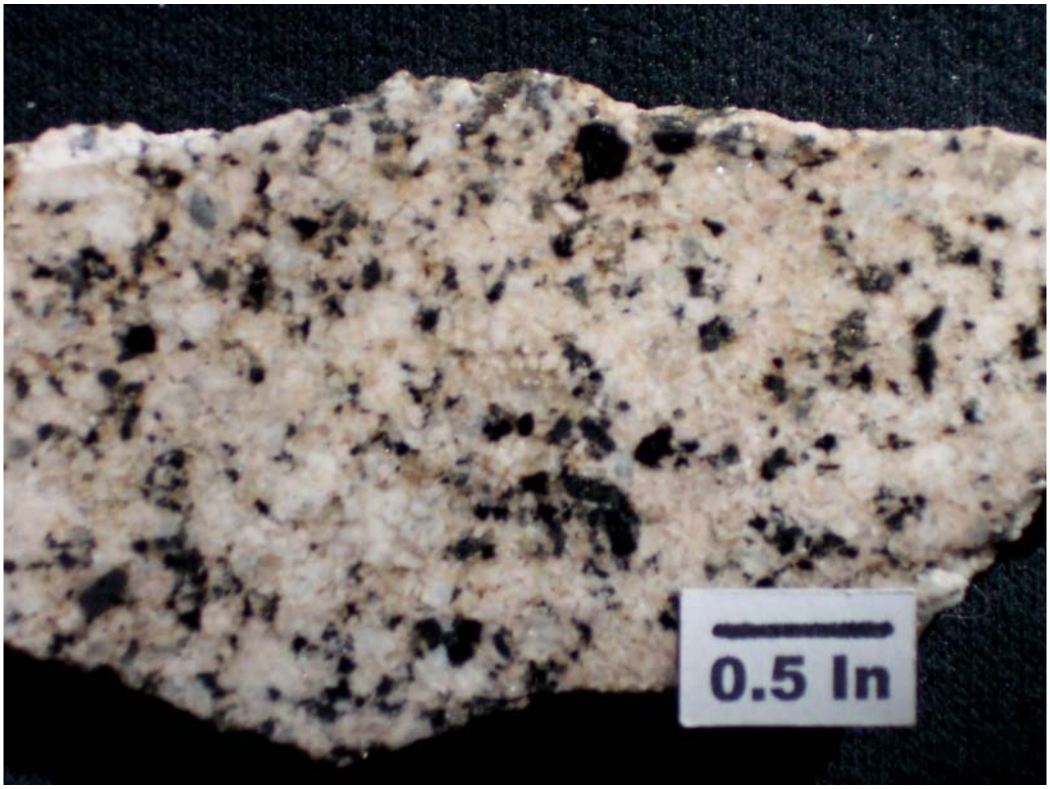


Figure 25. Slab of Mount Princeton quartz monzonite showing typical medium-grained Tmpf subunit which is slightly finer grained and less mafic than Tmpm subunit.

Tmpk Mount Princeton porphyritic K-feldspar subunit (late Eocene) – The porphyritic K-feldspar subunit forms a large zone that circles the summit area of Mount Princeton and is present along the tops of the two main northeast-trending ridges that extend into the southwest corner of the Buena Vista West quadrangle. There are some zones of finer-grained, porphyritic border textures that occur in the Tmpk subunit along the top of the ridge between Maxwell Creek and Dry Creek. There are also areas of concentrated Tmpb phases in the large patch of pre-Bull Lake till (Qpbt?) on the north side of lower Maxwell Creek. The origin of these border textured rocks is uncertain, but it is suspected that there may be some down-faulted slices of Tmpb in these areas.

The K-feldspar phenocryst content is variable from about 5 to 20 percent and locally there are quartz phenocrysts as large as about 0.2 inch (figs. 24 and 26). The average of five modal analyses on Tmpk (Shannon, 1988), indicate about 24.6 percent quartz, 29.6 percent K-feldspar, 36.3 percent plagioclase and 8.7 percent biotite and hornblende. There is about 1.0 percent of accessory magnetite, sphene, allanite, apatite, and zircon. In comparison to the Tmpm phase, Tmpk has slightly higher K-feldspar and quartz content and lower mafic mineral content (fig. 24). On the basis of modal mineralogy and IUGS classification (Streckeisen, 1976) the Tmpk subunit is granite B. Whole-rock chemical analyses (Limbach, 1975) of the porphyritic phase (Tmpk) and the equigranular phase (Tmpm), indicate that Tmpk has slightly higher SiO_2 and K_2O, and slightly lower CaO, Fe_2O_3 and MgO than Tmpm.

The Tmpk subunit is at least 500 feet thick in the Buena Vista West quadrangle, and the float distribution patterns suggest thicknesses up to 800 feet and possibly 1,000 feet. The Tmpk subunit has been disrupted by numerous rift-related faults. The lower contact of the Tmpk subunit with the interior quartz monzonite subunit (Tmpm) has been offset down-to-the-east by a series of rift-related faults.

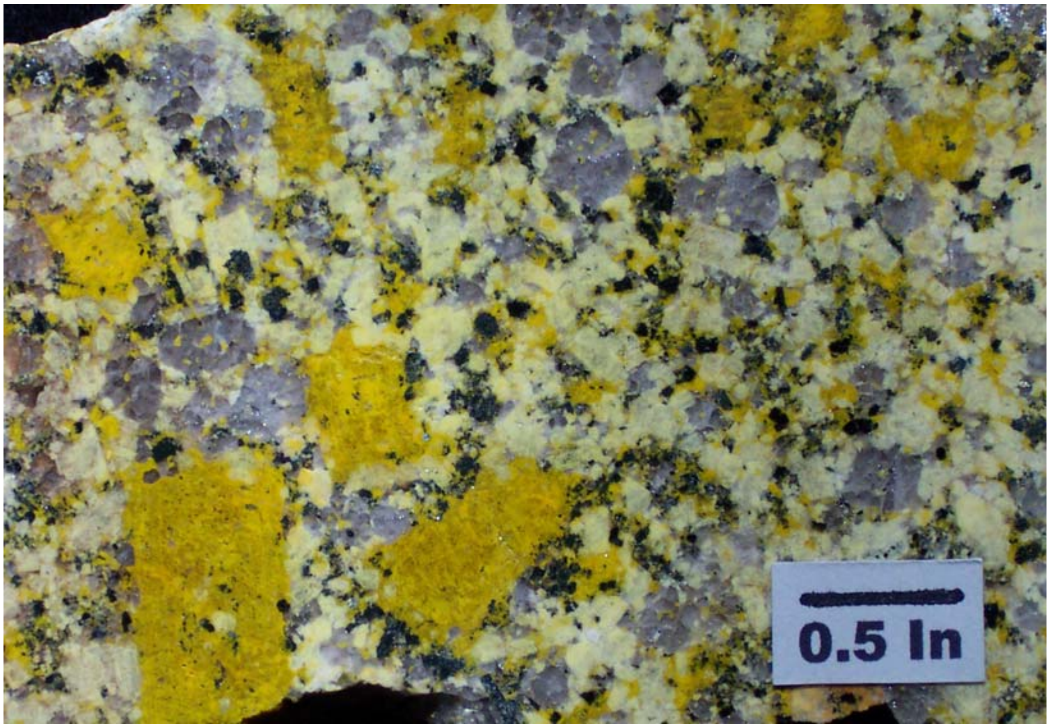


Figure 26. Slab of Mount Princeton porphyritic K-feldspar subunit (Tmpk), stained for K-feldspar. Note large tabular K-feldspars (yellow) and smaller quartz (gray) phenocrysts in matrix of medium-grained, K-feldspar-poor groundmass.

Tmpm Mount Princeton quartz monzonite interior subunit (late Eocene) – The Mount Princeton quartz monzonite interior subunit is the predominant phase of the pluton and the most abundant phase exposed in the Buena Vista West quadrangle. It occurs below and interior to the porphyrytic K-feldspar subunit. Up to 1,800 feet of the Tmpm subunit occurs below the Tmpk subunit on the north side of the ridge between Maxwell Creek and South Cottonwood Creek.

The Mount Princeton quartz monzonite interior is light gray and has a medium-coarse grained, equigranular texture (fig. 24). The average of six modal analyses from Shannon (1988) indicates 23.9 percent quartz, 28.1 percent K-feldspar, 36.6 percent plagioclase, and 10.4 percent biotite and hornblende. Relatively abundant sphene is conspicuous in hand sample and there is also accessory magnetite, allanite, apatite, and zircon. The Tmpm subunit is granite B, on the basis of mineral modes and IUGS classification.

Late Eocene magmatism – There is one bedrock unit in the Buena Vista West quadrangle that is volumetrically minor but has widespread occurrence on both the east and west sides of the rift. Dacite porphyry dikes represent miscellaneous late Eocene magmatism that probably pre-dates the Mount Princeton pluton.

Tdd Dacite porphyry dikes (early to middle Eocene?) – Early Eocene dacite porphyry dikes cut Proterozoic biotite granodiorite (Xgd) on the east side of the rift in the northeast corner of the Buena Vista West quadrangle. These dikes are the continuation of a swarm of dacite porphyry dikes (Tdd) shown on the map of the Buena Vista East quadrangle (Keller and others, 2004). They described predominantly north-northwest-trending dikes that cut all of the main Proterozoic units (Xgd, Xqd, and YXg) and that are older than the lower tuff of Triad Ridge (37.5 Ma).

In the northeast corner of the Buena Vista quadrangle, the dacite porphyry dikes range from about 3 to 30 feet thick. Two relatively continuous dikes were mapped. One dike occurs along the Buena Vista West quadrangle boundary just south of Hop Gulch. This dike is interesting because it was intruded along an east-west-trending, Laramide-reactivated (?), Precambrian shear zone. The dike occurs as sporadic subcrop and almost continuous float for about 500 feet in the Buena Vista West quadrangle. It was followed for another 1,300 feet eastward, in to the Buena Vista East quadrangle. To the west the dacite dike is abrubtly terminated at a north-south-oriented fault, and a thin discontinuous dacite porphyry dike occurs along the northern part of the cross fault, almost to Hop Gulch (not shown on map). The main, reactivated (?) Precambrian fault continues westward and intersects Hop Gulch at the old railroad trestle site, where there is a large spring. One dacite dike contact was observed, suggesting a N79°E strike and 75°SE dip for the fault-dike structure. The second dacite porphyry dike is better exposed as a N10° to 40°W-trending dike that extends for about 3,000 feet immediately east of the Arkansas River. This dike has variations in strike and dip and thickness along its length.

Similar dacite porphyry dikes (Tdd) were recognized and mapped in the Proterozoic rocks on the west side of the rift in the western part of the Buena Vista West quadrangle. Three dacite porphyry dikes intrude the Proterozoic biotite gneiss (Xb) unit outside the northeast margin of the Mount Princeton pluton, between Deep Creek and

Cottonwood Creek. A probable fourth dike occurs at the south end of the Precambrian mass at Bald Mountain. The dikes are poorly exposed but occur as semi-continuous concentrated float zones that have minor subcrop where they cross ridge tops. Concentrated float and subcrops suggest that the dikes range from about 1 to 10 feet thick. Concentrated float from one dike was followed to the northern contact of the Mount Princeton pluton. The dacite porphyry float stopped abruptly at the Mount Princeton contact and no float was observed in the Mount Princeton pluton on the strike projection. These relations suggest that the dacite porphyry dikes are older than the Mount Princeton pluton, which is compatible with the relative age of pre-37.5 Ma (age of lower tuff of Triad Ridge) established by field relations in the Buena Vista East quadrangle (Keller and others, 2004).

The dacite porphyry dikes are characterized by about 20 percent small (0.02 to 0.08 inch) phenocrysts of plagioclase, quartz, biotite, and amphibole in an aphanitic groundmass (fig. 27). The dacite porphyry dikes on both sides of the rift in the Buena Vista West quadrangle are texturally similar fine-phenocryst porphyries. However, Keller and others (2004) noted significant textural and compositional variations in the dike swarm in the Buena Vista East quadrangle. Slabs of dacite porphyry from both sides of the rift were stained for K-feldspar, which shows that they generally do not contain K-feldspar phenocrysts. The groundmass contains little or no K-feldspar in the dacite dikes on the east side of the rift whereas the groundmass contains irregularly distributed patchy areas with K-feldspar in some of the dacite dikes on the west side of the rift.

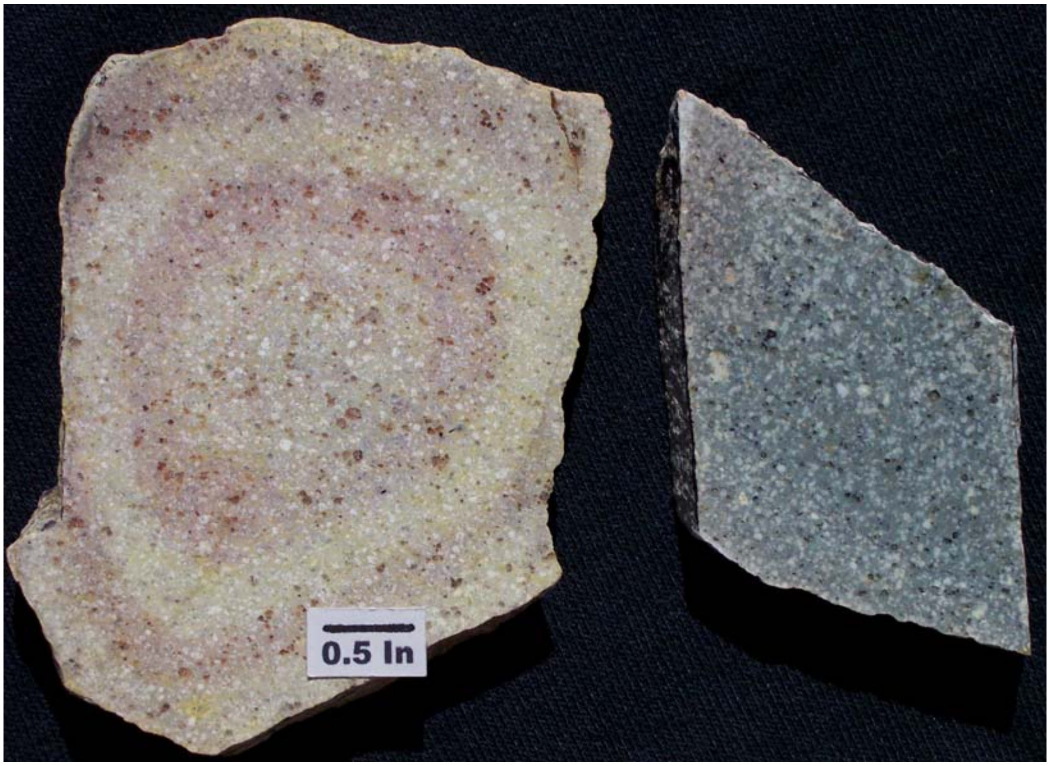


Figure 27. Digital photograph of slabs (stained for K-feldspar) of dacite porphyry dikes (Tdd) from the west (left) and east (right) sides of the rift.

The dacite porphyry dikes on both sides of the rift are further characterized by associated propylitic hydrothermal or deuteric alteration consisting of pervasive strong chloritization/sericitization of biotite and hornblende and moderate sericitization (locally with abundant carbonate) of plagioclase and in places the groundmass. There is locally abundant disseminated epidote in the rock and fine chlorite and/or epidote coatings on joint surfaces. Rare quartz veinlets, locally with epidote, cut the dacite porphyry, and weak to moderate Fe- and Mn-oxide staining on fracture surfaces is common.

Whole-rock chemical analyses of dacite porphyry dikes from the east (sample 04B-490A) and west (sample 04-437) sides of the rift are given in table 2. The freshest samples were analyzed, but they still had complete alteration of biotite to sericite and moderate to strong alteration of plagioclase. These two dikes have significant differences in SiO_2, CaO, and Na_2O and show a wider variation in chemistry than six samples, analyzed by Keller and others (2004) of dacite porphyry dikes from the Buena Vista East quadrangle. Thus, as a group, the dacite porphyry dikes on the east and west sides of the rift have similar mineralogy and texture and are similarly age bracketed at pre-37.5 Ma on the east side and pre-36.6 Ma on the west. The dikes have considerable variations in whole-rock chemical characteristics that hinder chemical comparisons to evaluate a genetic relationship. Some of the chemical variations may be related to variations in mineralogy, and variations in CaO, NaO, and K_2O could be related to differing degrees of hydrothermal or deuteric alteration.

PROTEROZOIC ROCKS

Three main groups of Proterozoic basement rocks are present in the Buena Vista West quadrangle and include igneous rocks of the Berthoud Plutonic Suite, meta-igneous rocks of the Routt Plutonic Suite, and metamorphic rocks of the Layered Gneiss Complex.

Berthoud Plutonic Suite (1.4 Ga) – A group of volumetrically minor granitic rocks occur as small stock-like bodies and dikes cutting older Proterozoic rocks on both sides of the rift in the Buena Vista West quadrangle. They have characteristics similar to the Berthoud Plutonic Suite of approximately 1,400 Ma granite and quartz monzonite intrusions (Tweto, 1987).

YXg Biotite granite (Early to Middle Proterozoic?)- Proterozoic biotite granite occurs as small intrusions and numerous dikes intruding the granodiorite-quartz monzonite (Xgd) and quartz diorite (Xqd) in the northeast corner of the Buena Vista West quadrangle. The biotite granite is light pinkish gray and fine to medium grained. The rock consists of K-feldspar, plagioclase, quartz, and minor biotite. It is usually equigranular and massive but locally has a slabby parting in outcrop that parallels a weak foliation. Weak foliation tends to be present in narrow dikes and is parallel to the contacts. Some dikes are folded. The largest body (about 400 feet thick) of biotite granite in the very northeast corner of the quadrangle is not foliated. The variation in the development of foliations and the folding of some bodies suggests that some Proterozoic deformation continued, at least locally, until intrusion of some of the biotite granite bodies. Another possibility is that there is an older episode of granite intrusions related to the Routt Plutonic Suite.

YXp Pegmatite (Early to Middle Proterozoic?) – Some smaller biotite granite dikes contain pegmatitic segregations, and the larger pegmatite bodies are spatially associated with biotite granite. In general, the pegmatites do not make good outcrop but are expressed by concentrated float zones of very coarse grained, quartz-feldspar pegmatite with small outcrops of biotite granite. Large areas of pegmatite float in Proterozoic granodiorite (Xgd) and quartz diorite (Xqd) suggest that they occur as dike swarms possibly above bodies of biotite granite. The larger biotite granite bodies are massive and do not have associated pegmatites. These relations suggest that the pegmatites are related to small dikes of the biotite granite peripheral to larger biotite granite intrusions. Most of the small prospect pits in the Precambrian terrane in the northeast corner of the Buena Vista West quadrangle are associated with pegmatites. The pegmatites contain quartz, K-feldspar, and biotite. Quartz crystals are locally smokey, suggesting the presence of radioactive accessory minerals.

Small bodies and dikes of biotite granite and pegmatite are present in the biotite felsic and intermediate gneisses on the west side of the rift. Some of the granite-pegmatites are concordant layers to segregations that commonly have garnet and are foliated. These granite-pegmatites are probably older intrusions related to felsic intrusions of the Routt Plutonic Suite. Some of the granite and pegmatite bodies are non-foliated, discordant, and cut across the foliation and gneissic layering. They are interpreted to be equivalent to granite (YXg) and pegmatite (YXp) intrusions of the Berthoud Plutonic Suite.

Routt Plutonic Suite (1.70 Ga)- The main groups of Proterozoic intrusions in the Buena Vista West quadrangle have similar characteristics to the Routt Plutonic Suite of approximately 1,665 to 1,700 Ma granodiorite and quartz monzonite intrusions (Tweto, 1987). They dominate the Precambrian terrane in the northeast corner of the Buena Vista West quadrangle and occur as irregular intrusions in the older gneisses (Xb) on the west side of the rift.

Xhy Hybrid dike (Early Proterozoic?) – Proterozoic biotite-hornblende diorite and biotite granite occurs as a heterogeneous dike cutting granodiorite (Xgd) in the northeast corner of the Buena Vista West quadrangle. The dike is oriented N40W with moderate to steep northeast dip and is well exposed for about 1,000 feet. It is 0.5 to 6.5 feet thick and has sharp contacts with the granodiorite (Xgd). The dike ranges from a peculiar spotted, foliated, or gneissic diorite to a composite dike of spotted diorite and biotite granite to biotite granite with irregular inclusions of the spotted diorite. Compositionally, the diorite is similar to the fine-grained variant of quartz diorite (Xqd) found at contacts with the granodiorite (Xgd). It has both biotite and hornblende with abundant plagioclase and minor quartz. Local spotted textures in the diorite are similar to textures that are locally developed in the quartz diorite (Xqd) at contacts with the granodiorite (Xgd). The biotite granite is compositionally and texturally similar to some of the dikes of biotite granite (YXg) that are weakly foliated. The general relationships suggest that the diorite intruded first, and then biotite granite was intruded along the same conduit. Bulbous inclusions of diorite appear to have chilled margins and are locally net veined by granite veinlets. Additional conflicting relationships with stretched inclusions of granite in the diorite may be best interpreted as contemporaneous diorite and granite magmas along the same conduit. The latter interpretation suggests that there are some minor biotite granite intrusions that are older than the Berthoud Plutonic Suite (YXg) and are part of the Routt Plutonic Suite.

Xqd Quartz diorite (Early Proterozoic?)- Proterozoic biotite-horndlende quartz diorite (Xqd) occurs as small masses within the granodiorite (Xgd) on the east side of the rift, in the northeast corner of the Buena Vista West quadrangle. Similar Proterozoic biotite-hornblende quartz diorite (Xqd) is present as irregular masses in biotite gneiss (Xb) on the west side of the rift, in the west part of the Buena Vista West quadrangle. The similar compositional and textural variations that are displayed by the quartz diorite on both sides of the rift (figs. 28 and 29) and the relative age relationships with surrounding Proterozoic rocks suggest that they are correlative.

The quartz diorite (Xqd) on the east side of the rift was previously described by Scott (1975) and Keller and others (2004). Scott (1975) suggested that the quartz diorite is an earlier intrusion than, or marginal phase of, the granodiorite (Xgd). Keller and others (2004) mapped a large swarm of east-west- to northeast-trending bodies of quartz diorite in the Trout Creek/Triad Ridge area. They suggested that the quartz diorite and granodiorite might be co-magmatic because of conflicting cross-cutting relationships.

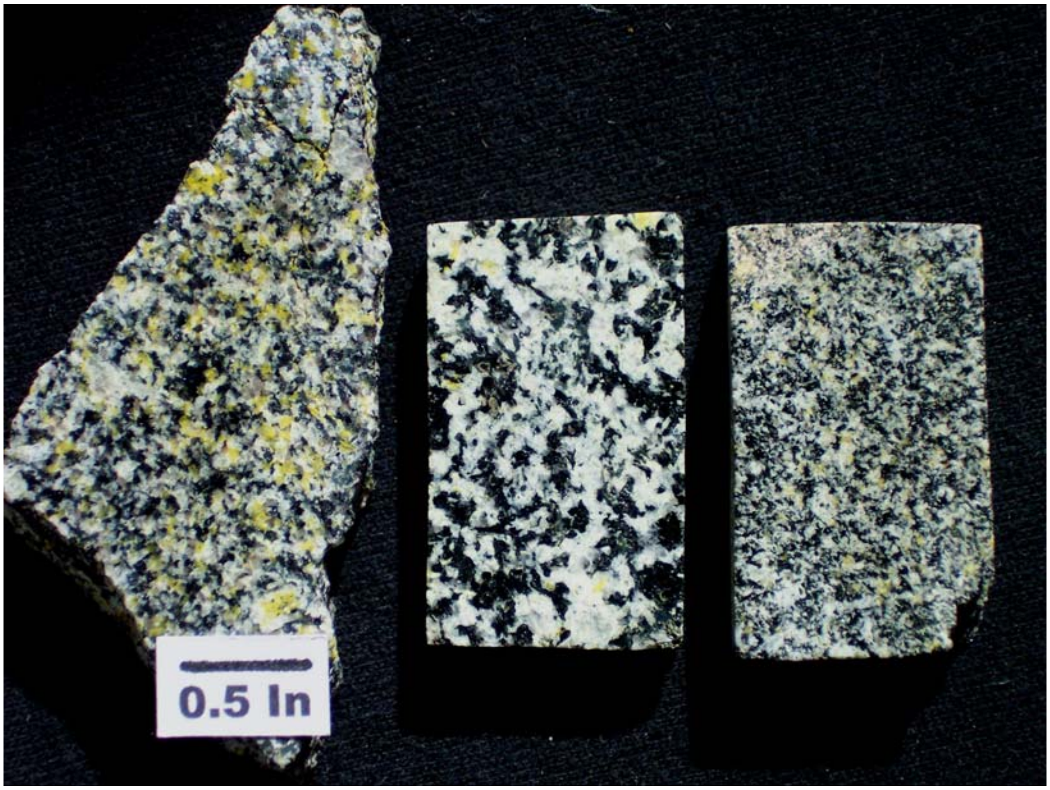


Figure 28. Varities of quartz diorite (Xqd) from the east side of the rift: left – fine-medium-grained, K-feldspar-rich hornblende-biotite granodiorite; middle – medium-grained, hornblende-biotite quartz diorite; right – fine-grained, hornblende-biotite quatz diorite from border (all stained for K-feldspar).

The main mass of quartz diorite (Xqd) on the east side of the rift and in the northeast corner of the Buena Vista West quadrangle occurs in a northeast-trending, elongated body (about 4,500 feet long and 1,000 feet wide) that extends from the Arkansas River northeast of Buena Vista to the east boundary of the quadrangle. The body continues for another 4,000 feet in the northwest corner of the Buena Vista East quadrangle (Keller and others, 2004). Field relationships suggest that the quartz diorite intrudes the granodiorite (Xgd) unit. This is supported by the distribution and shape of the bodies and the finer grain size near contacts. However, the detailed contact relationships between the quartz diorite and the granodiorite are ambiguous and sometimes conflicting. Minor, localized gneissic banding is present in some of the smaller bodies of guartz diorite, immediately adjacent to contacts with granodiorite. In places this gneissic banding is truncated by granodiorite and irregular injections of granodiorite occur along gneiss layers. Some small bodies of quartz diorite are lens-like and appear to be inclusions in granodiorite.

On the west side of the rift, the largest mass of quartz diorite (Xqd) is an irregular, northeast-trending body about 8,000 feet long and 500 to 2,000 feet wide, south of North Fork Cottonwood Creek. A smaller, roughly east-west-trending body occurs on the east slope of Bald Mountain, south of Cottonwood Creek. Numerous smaller bodies and minor areas of mixed float are too small to show on the map. The intrusion of quartz diorite into the biotite gneiss (Xb) and tectonized granodiorite (Xgdf) is suggested by the presence of smaller dike-like bodies. On both the east and west sides of the rift, the quartz diorite (Xqd) is cut by non-foliated pegmatite-granite dikes (YXp and YXg) of the Berthoud Plutonic Suite.

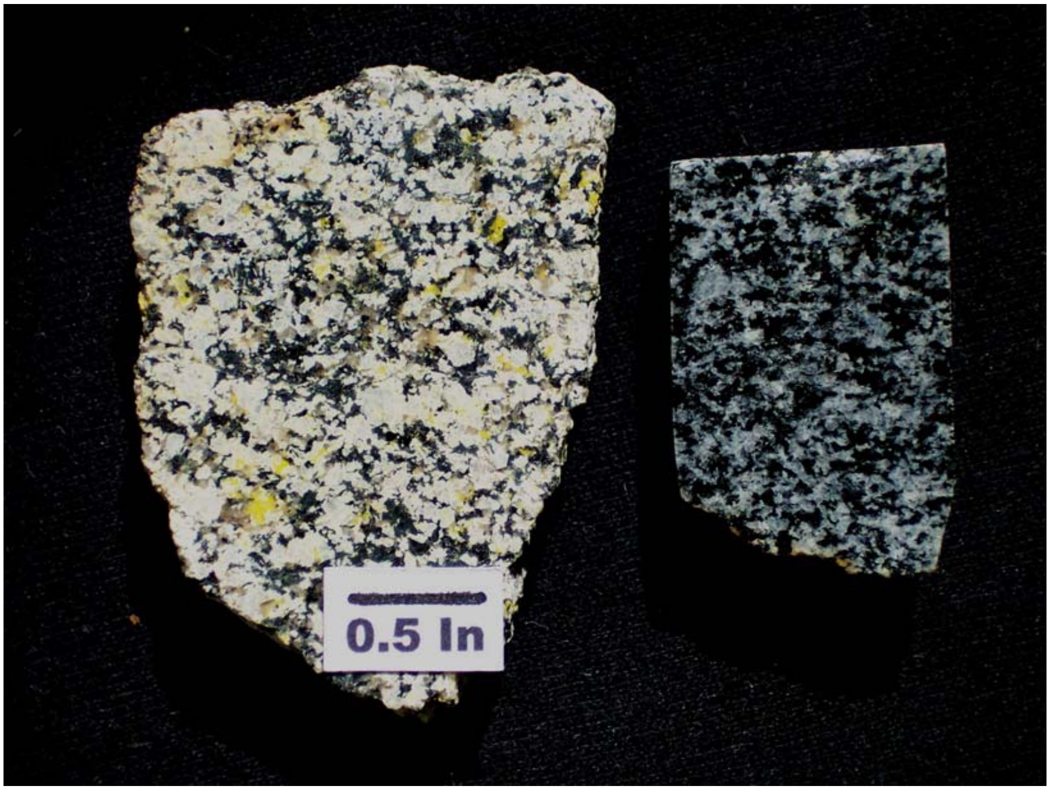


Figure 29. Varities of quartz diorite (Xqd) from the west side of the rift: left – medium-grained, hornblende-biotite quartz diorite; right – fine-grained, weakly foliated hornblende-biotite quartz diorite (both stained for K-feldspar).

The quartz diorite (Xqd) is dark gray and has variable texture and composition. It ranges from fine to medium-coarse grained and is usually equigranular and massive but commonly displays weak to moderate foliation associated with finer grain size near contacts (figs. 28 and 29). Foliation, if present is parallel to the contacts. The quartz diorite locally has irregular gneissic layering at contacts with other Proterozoic units (Xgd, Xgdf and Xb). On the east side of the rift, the foliation in the quartz diorite parallels the biotite foliation and alignment of K-feldspar phenocrysts in adjacent granodiorite (Xgd). The foliation and contacts generally dip moderately to steeply north-northwest. In outcrop, the quartz diorite ranges from massive, to slabby jointed, to locally well-developed, spheroidally weathered. On the west side of the rift, the quartz diorite is massive; in this area, it rarely crops out.

Estimated mineral modes (on hand samples and slabs stained for K-feldspar) of quartz diorite from the east side of the rift indicate about 8 to16 percent quartz, 2 to11 percent K-feldspar, 56 to 65 percent plagioclase, 15 to 22 percent biotite and hornblende, 1 to 2 percent opaque minerals, and trace to 2 percent sphene. Estimated mineral modes of quartz diorite from the west side of the rift indicate about 8 to 12 percent quartz, 0 to 5 percent K-feldspar, 70 to 75 percent plagioclase, 6 to 8 percent biotite, 5 to 7 percent hornblende, and 1 to 2 percent magnetite. It locally has minor red garnet. On the basis of estimated modes, the rocks fall in the quartz diorite field of the IUGS classification (Streckeisen, 1976). Some samples, especially near contacts have estimated K-feldspar contents approaching 10 percent (fig. 28, slab on left) and these rocks would be mineralogically classified as quartz monzodiorite.

Whole-rock chemical analyses of quartz diorite (Xqd) samples from the Buena Vista West quadrangle are given in table 2. A sample from the east side of the rift (sample 04B-271) has a diorite to quartz diorite composition. This analysis is similar (except for variations in Fe and Mg) to two analyses of quartz diorite (Xqd) from the Buena Vista East quadrangle provided by Keller and others (2004). A sample from the west side of the rift (sample 04-425) has a diorite to quartz diorite composition but with lower NaO and higher K_2O than average quartz diorites and diorites. The quartz diorite from the west side of the rift has similar chemistry to the quartz diorite from the east side of the rift, except for higher Fe_2O_3 and CaO and lower MgO. This chemical variation in the quartz diorites is compatible with the variations in mineralogical composition.

The similar appearance, mineralogy, and range of textures in the quartz diorite (Xqd) on the east and west sides of the rift suggest that the quartz diorites are correlative. Further support for this correlation is indicated by the similar relative age relations on both sides of the rift. On the west side of the rift the quartz diorites are younger than the Early Proterozoic gneiss complex (Xb), younger than or contemporaneous with the Early Proterozoic granodiorite (Xgdf), and older than the Early to Middle Proterozoic biotite granite-pegmatite (YXg-YXp). On the east side of rift the quartz diorites are younger than or contemporaneous with Early Proterozoic granodiorite-quartz monzonite (Xgd) and older than the Early to Middle Proterozoic biotite granite-pegmatite (YXg-YXp) intrusions.

Routt Plutonic Suite – Denny Creek Equivalent (1.66 Ga) – A large body of gneissic granodiorite that is part of the Routt Plutonic Suite occurs in the central Sawatch Range and was named Denny Creek Granodiorite Gneiss by Barker and Brock (1965). Its age is estimated to be in the range 1,665-1,675 m.y., and it is slightly older than the Kroenke Granodiorite, another major Routt Plutonic Suite intrusion (Tweto, 1987). The large body of Early Proterozoic porphyritic granodiorite (Xgd) in the southern Mosquito Range, and present in the northeast corner of the Buena Vista West quadrangle, is interpreted to be equivalent to the Denny Creek Granodiorite Gneiss (Keller and others, 2004; and this report). Similar porphyritic granitic rocks (Xgdf) intrude the biotite gneisses in the Sawatch Range in the west part of the Buena Vista quadrangle. They have a penetrative mylonitic deformation fabric and are interpreted to be tectonized equivalents of the granodiorite (Xgd).

Xgd Granodiorite to quartz monzonite (Early Proterozoic?) – Proterozoic biotite granodiorite is the predominant bedrock lithology on the east side of the rift in the northeast corner of the Buena Vista quadrangle. Previous workers have noted compositional variations (granodiorite to quartz monzonite) and textural variations (foliated and non-foliated; equigranular and porphyritic) in this unit (Scott, 1975; Keller and others, 2004). A U-Pb age of 1,672 +/- 5 Ma on similar granodiorite in the Cameron Mountain quadrangle (Bickford and others, 1989) puts it in the Routt Plutonic Suite of Tweto (1987).

The unit makes excellent, rounded bold outcrops along the east side of the Arkansas River. All the Xgd unit in the northeast corner of the Buena Vista West quadrangle is characterized by coarse- to very coarse-grained, porphyritic textures with large (0.5 to 1.25 inch) K-feldspar phenocrysts (fig. 30). The textures are variable with local massive porphyritic textures to more commonly weak to strong alignment of the elongated K-feldspar crystals. The medium- to coarse-grained groundmass also varies from massive to moderately foliated with alignment of biotite parallel to the elongated K-feldspar crystals.

Estimates of mineral modes of representative hand samples and two slabs (stained for potassium feldspar) indicate about 25 to 30 percent quartz, 30 to 35 percent K-feldspar, 25 to 30 percent plagioclase, 5 to 8 percent biotite and opaque minerals, and 1 to 2 percent sphene. The Xgd in the northeast corner of the Buena Vista East quadrangle is predominantly granite B of the IUGS classification (Streckeisen, 1976). The proportion of K-feldspar phenocrysts is variable from about 15 to 40 percent, and because almost all of the K-feldspar occurs as phenocrysts, the rocks with lower phenocryst content shift from granite B field into the granodiorite and quartz monzodiorite fields of the IUGS classification (fig. 30). One sharp contact between two phases of the granodiorite with different K-feldspar phenocryst contents was observed. This contact provides the best support for the large K-feldspar crystals representing original phenocrysts or megacrysts in the granodiorite and suggests that the large Proterozoic Xgd intrusive body in the southern Mosquito Range is made up of multiple intrusive phases.

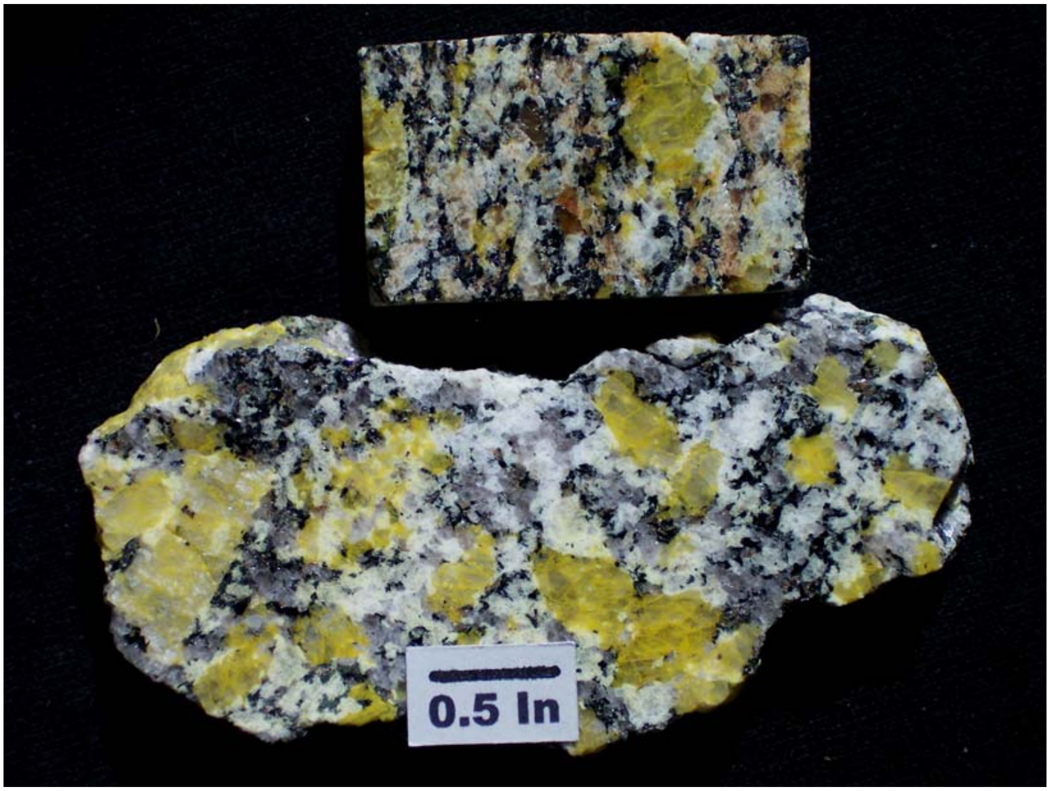


Figure 30. Varities of Proterozoic granodiorite (Xgd) from the Buena Vista West quadrangle: top- moderately foliated, mafic-rich granodiorite; and bottom- non-foliated, quartz and K-feldspar-rich, porphyritic biotite quartz monzonite (both stained for K-feldspar).

The alignment of elongated K-feldspar crystals could, in part, represent primary flow alignment of phenocrysts. However, the local development of parallel, metamorphic foliation of biotite in the matrix, consistent regional orientation of aligned K-feldspar crystals and their parallelism to younger Proterozoic intrusions (YXg and Xqd) and metamorphic foliation overprints, suggests that the alignment of elongated K-feldspar crystals is predominantly a metamorphic foliation. The local occurrence of large K-feldspar crystals in biotite granite (YXg) and quartz diorite (Xqd) immediately adjacent to contacts with granodiorite (Xgd) is sometimes ambiguous. Some of these large K-feldspar crystals appear to be inclusions, or xenocrysts of K-feldspar derived from the granodiorite. However, the size and distribution of some of these K-feldspar crystals suggest that some are porphyroblasts of K-feldspar formed during metamorphic overprinting.

Xgdf Granodiorite augen gneiss (Early Proterozoic?) – Early Proterozoic biotite granodiorite to granite augen gneiss occurs as irregular masses in biotite gneiss (Xb) on the west side of the rift and the western part of the Buena Vista West quadrangle. The augen gneiss is mainly characterized by large (0.5 to 1.5 in.) K-feldspar augen that range from relic subhedral-euhedral pheno-megacrysts to stretched porphyroblasts in a matrix of variable composition ranging from biotite granite to biotite granodiorite (fig. 31). The other main characteristic is the presence of a penetrative mylonitic deformation fabric. In one variant of the unit the augen consist of small, stretched lenses (or mini-boudins) of less deformed granitic material in a matrix of recrystallized, mylonitized granite. Less deformed and recrystallized variants of this unit are similar to and correlative with the Proterozoic granodiorite (Xgd) on the east side of the rift. The more deformed variants are similar to the foliated granodiorite (Xgdf) unit of Keller and others (2004); these variants were interpreted to be Proterozoic tectonized zones in the granodiorite (Xgd).

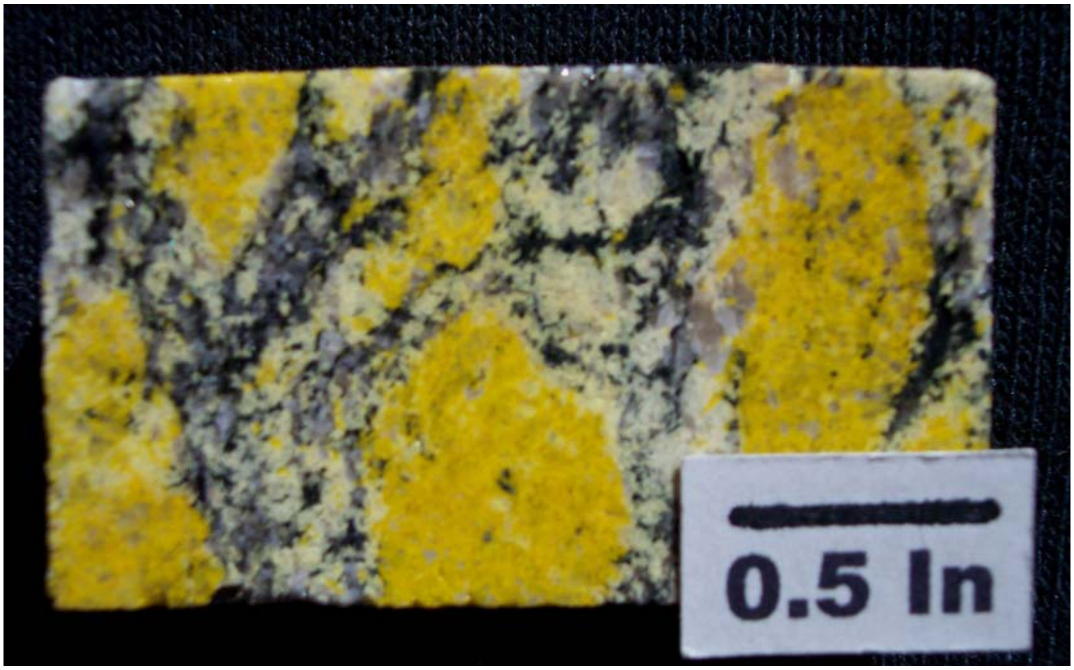


Figure 31. Digital image of Proterozoic quartz monzonitic augen gneiss (Xgdf) showing K-feldspar augen in foliated matrix (stained for K-feldspar).

The largest bodies of granodiorite augen gneiss are in the Mercury Creek and Deep Creek area where they are associated with the largest bodies of quartz diorite (Xqd). The distribution and contact relations of the Xgdf and Xqd units with the biotite gneiss (Xb) are complex. In general, Xqd appears to be the youngest and occurs as dike-like bodies at contacts with Xgdf and Xb units. The granodiorite augen gneiss bodies typically have the appearance of being the oldest because of the more penetrative deformation fabrics, in comparison to the Xb unit. The granodiorite augen gneiss (Xgdf) on the west side of the rift is considered to be correlative with the granodiorite (Xgd) unit on the east side of the rift and both are considered to be correlative with the Denny Creek (1.66 Ga) suite of intrusives and meta-intrusives. The local development of stronger penetrative deformation fabrics in the granodiorite augen gneiss, than in surrounding biotite gneiss may be related to focused ductile deformation occurring shortly after the granodiorite bodies were intruded.

Early Proterozoic layered biotite and felsic-hornblendic gneiss complex (1.74 Ga) – Early Proterozoic gneisses dominate the Precambrian bedrock on the west side of the Arkansas Valley in the western part of the Buena Vista West quadrangle. The average age for the protolith of the gneiss complex in Colorado is about 1,800 Ma and metamorphism of the gneisses peaked at about 1,740 Ma (Tweto, 1987). Two main groups of gneissic rocks have been recognized: (1) biotite gneisses largely derived from sedimentary rocks; and (2) felsic and hornblendic gneisses largely derived from volcanic and related intrusive rocks (Tweto, 1987). Tweto (1987) summarized the distribution of the two groups of gneisses and showed the area on the west side of the Buena Vista West quadrangle as consisting of biotite gneisses (Xb). However, he stated that many small bodies of felsic and hornblendic gneisses occur in the broad east-west belt of biotite gneisses. This study shows that the sequence of gneisses in the Buena Vista West quadrangle is a complex mixture of the two gneiss groups.

Xb Biotite-garnet felsic and biotite-hornblende intermediate gneiss and amphibolite (Early Proterozoic?) – The early Proterozoic layered gneiss complex is present north of Cottonwood Creek, north of the Mount Princeton pluton, and as a large outlier on Bald Mountain on the south side of Cottonwood Creek. The west extension of this unit into the Mount Harvard 15-minute quadrangle was mapped and described by Brock and Barker (1972) as a "complex of layered gneisses”. Scott (1975) mapped the same rocks and described biotite-, garnet- and sillimanite-bearing gneisses as "migmatitic gneiss." Fridrich and others (1998) made the first attempt at mapping and subdividing various units within this package of Proterozoic rocks. The biotite gneiss (Xb) unit of this report is the same as the Scott (1975) Xgnb unit and is equivalent to the Xb unit of Keller and others (2004) on the east side of the rift.

The Proterozoic rocks include three main gneiss units that are complexly interlayered and intermixed and were not subdivided in this study. The predominant unit is a sequence of biotite-garnet (+/- sillimanite) felsic gneiss with well-developed gneissic layering and moderate foliation (fig. 32). They are light gray to pink and generally fine to medium grained with thin gneissic layering on the order of 0.25 to 1.0 inches. They consist of variable amounts of K-feldspar, plagioclase, quartz, and biotite. Red to light-pink garnets from 0.01 to 0.5 inches in diameter are usually conspicuous and generally developed in the biotite-rich layers. Biotite-garnet granite and pegmatite are common as concordant segregations and cross-cutting bands. Locally some interlayered, fine-grained amphibolites occur in this unit. The aluminous composition and regular, thin gneissic layering suggest a predominantly meta-sedimentary protolith.


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Figure 32. Outcrop of biotite-garnet felsic gneiss (Xb) from west side of Arkansas Valley graben, Buena Vista West quadrangle. Note irregular gneiss layering and minor amphibolite bands (black).

The second Proterozoic gneiss unit is a sequence of biotite-hornblende-garnet intermediate gneisses (fig. 33). They are medium to dark gray, generally fine to medium grained, with well-developed gneissic layering and weak to moderate foliation. They contain variable amounts of plagioclase, K-feldspar, quartz, hornblende, biotite, garnet, and rare actinolite. Fine-grained biotite-hornblende amphibolite is common in this unit as concordant layers in the gneiss. The amount of biotite in the amphibolites is variable from none in equigranular amphibolites to moderate in foliated amphibolites and appears to be related to a retrograde metamorphic overprinting. The intermediate gneiss also contains concordant biotite granite and pegmatite segregations and cross-cutting bodies. The composition and textures of this gneiss sequence suggest a predominantly meta-volcanic or mixed meta-volcanic/meta-sedimentary protolith. The distribution of the felsic and intermediate gneiss units varies from discrete outcrop/float areas to zones of complex interlayering of the two units. There are suggestions of relatively large, mappable areas of the felsic and intermediate gneisses, but no systematic patterns emerged during mapping. In local areas the felsic gneisses become migmatitic. In these areas, the gneissic layering becomes irregular and disrupted by folding and faulting and multiple injections of remobilized granitic to pegmatitic material locally display ptygmatic folding.

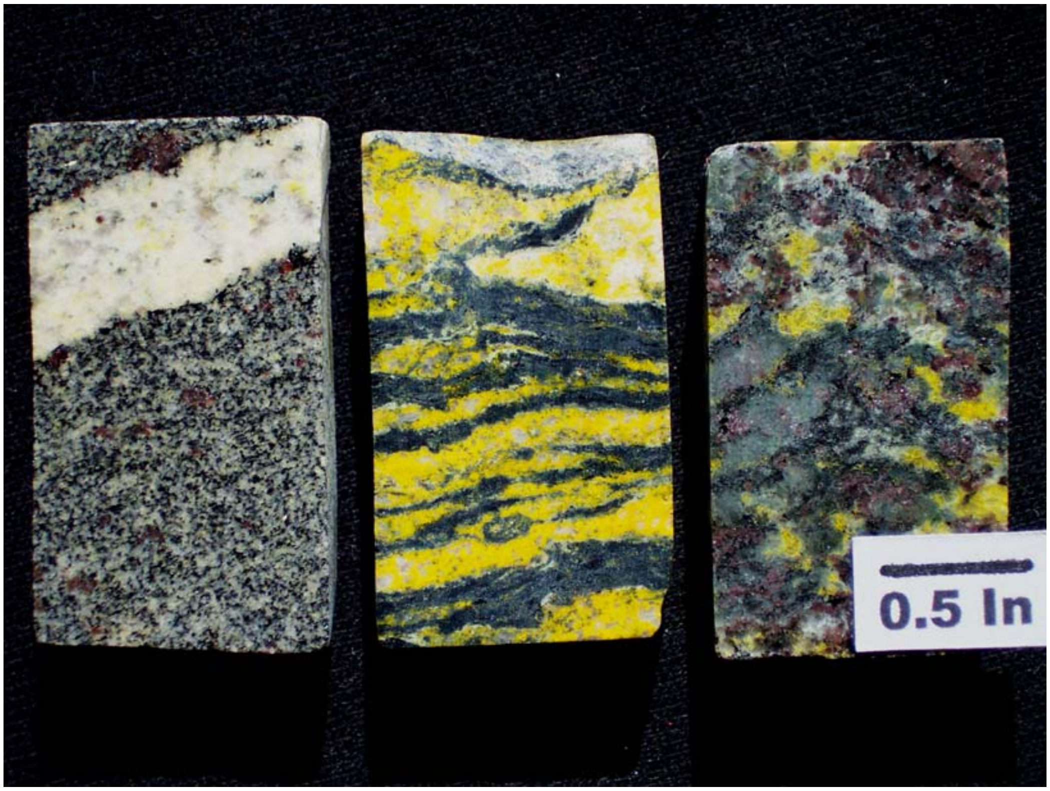

Figure 33. Varities of intermediate gneisses from the Buena Vista West quadrangle: left – plagioclase-garnet-biotite gneiss; middle- chlorite-actinolite mylonitic gneiss; right – coarse-grained garnet-biotite gneiss (all stained yellow for K-feldspar).

The third gneiss unit is less abundant and consists of a sequence of fine- to medium- grained biotite granite gneisses. They are characterized by a more felsic composition, consisting of K-feldspar, plagioclase, and quartz, with no hornblende or garnet and only minor biotite. In general, the gneissic layering is much less well developed and less regular than in the felsic and intermediate gneisses. With lower biotite contents the rocks are generally weakly foliated. Coarser granitic and pegmatitic segregations are common and amphibolite layers are rare to absent. There is some interlayering of the granite gneiss and felsic and intermediate gneisses. The granite gneiss is locally transitional with biotite granodiorite-quartz monzonite augen gneiss (Xgdf).

No quartzite or calc-silicate layers were identified that could be used as key horizons in the metamorphic rocks. There are three small areas of concentrated float of a medium- to coarse-grained, mafic to ultramafic, meta-intrusive rock that are probably Early Proterozoic in age. They occur in mixed biotite felsic and biotite-hornblende intermediate gneisses in the range front area between the northern contact of the Mount

Princeton pluton and Red Deer Creek. The bodies are too small to map and probably represent a discontinuous or disrupted dike. A thin section analysis indicates that the rocks consist of coarse orthopyroxene grains and recrystallized plagioclase with abundant accessory ilmentite, magnetite, and apatite. Minor actinolite and abundant biotite appear to be metamorphic. The rocks are meta-norites.

STRUCTURAL GEOLOGY

The rocks in the Buena Vista West quadrangle have undergone repeated structural deformation events since Proterozoic time. Major 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 Late Cretaceous to Eocene Laramide Orogeny (Tweto and Sims, 1963; Tweto, 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 in the Buena Vista 1:62,500 scale quadrangle. Our mapping has confirmed the presence of Quaternary faulting in the Buena Vista West quadrangle.

Proterozoic structural deformation is principally represented by regional metamorphic foliations in the Proterozoic rocks on both sides of the rift. The Proterozoic rocks on the east side of the rift (in the northeast corner of the Buena Vista West quadrangle) are dominated by granodiorite (Xgd) and quartz diorite (Xqd). The granodiorite has local weak to moderate foliations produced by alignment of large, elongated, tabular K-feldspar phenocrysts with a weak to moderate biotite foliation in the matrix. Some of the preferred alignment of K-feldspars could be a primary flow foliation, but it is usually associated with the development of foliation of biotite in the matrix; this biotite foliation is considered to be metamorphic foliation. The quartz diorite bodies also display localized foliation, especially near contacts. Keller and others (2004) suggested that this foliation in the Xqd unit is a primary intrusive foliation and that it is slightly oblique to the tectonic foliation in the Xgd unit in the Buena Vista East quadrangle. Numerous dikes and small bodies of fine grained biotite granite (YXg) are also locally weak to moderately foliated. The regional metamorphic foliations in the northeast corner of the Buena Vista West quadrangle are predominantly east-northeast trending with consistent moderate to steep dips to the north-northwest.

The Proterozoic rocks on the west side of the rift (in the northwest quadrant of the Buena Vista West quadrangle) are dominated by biotite-garnet felsic to intermediate gneisses (Xb). The mafic-rich layers with biotite and/or hornblende are typically moderately foliated, always parallel to the gneissic layering. The quartz diorite (Xqd) bodies are locally weakly to moderately foliated and also have localized zones of gneissic layering. One quartz diorite dike cutting granodiorite has foliation which is oblique to the dike contacts. The oblique orientation suggests that some of the foliation is metamorphic and was superimposed after the dike was emplaced. The granodiorite augen gneiss (Xgdf) commonly displays a more penetrative deformation fabric (locally mylonitic), possibly related to localized intense Precambrian shearing events. These metamorphic and deformation fabrics are predominantly east-northeast trending with moderate northwest dips. Thus, the predominant metamorphic fabrics in the Proterozoic rocks are similar on both sides of the rift.

The Proterozoic rocks on both sides of the rift dispay minor folding. Small folds are present on the east side of the rift, along the small ridge on the west side of Fourmile Creek, about 600 feet north of the Buena Vista West map boundary. There are three 25- to 100-feet thick dike-like bodies of fine-grained biotite granite (YXg) in granodiorite (Xgd). The granite bodies are folded into tight folds with axes roughly oriented S60°W with about a 60 degree plunge. The foliations in the adjacent granodiorite are warped along with the dike contacts. The warping suggests that the folding postdates the metamorphic foliations. Small-scale (inches) folding is common in the Proterozoic gneisses on the west side of the rift. Although present in outcrops, the fold orientations were difficult to measure, other than rough north-south orientation of axes. Peculiar folds occur in the more-deformed gneisses where the folds close on themselves, similar to sheath folds, and/or the folds are sheared off by shears parallel to the fold axial plane. The regional foliation and gneissic layering also appears to be broadly warped into open folds that are roughly oriented north-south with moderate plunges to the north.

Evidence of Precambrian shearing is present on both sides of the rift. On the east side, one east-west (steep south dipping) Precambrian shear zone was traced for about

3,000 feet in the Hop Gulch area, crossing the Buena Vista West and East quadrangle boundary. This fault is characterized by a 1 foot-thick core of mylonitized granodiorite (Xgd) and biotite granite (YXg) and a surrounding zone of brecciated and altered rock (fig. 34). There is a 2,300 ft long, N80°W-elongated body of biotite granite (YXg) that extends east into the Buena Vista East quadrangle (Keller and others, 2004). The alignment and northern contact of this biotite granite body appears to be related to this Proterozoic shear zone. The brecciation is interpreted to be due to Laramide (?) reactivated movement on the fault prior to emplacement of Eocene (?) dacite porphyry dikes (Tdd), which were also locally emplaced along the shear zone. Chlorite, sericite, and epidote alteration and quartz hematite veining may be related to the dacite porphyry. Keller and others (2004) noted north-northeast- to north-northwest-trending faults of probable Proterozoic age on the east side of the rift, in the Buena Vista East quadrangle. They also suggested that some of the numerous northwest-trending faults may be of Proterozoic age.

Figure 34. Proterozoic shear in YXg(?) with semi-ductile shear fabrics and superimposed quartz-hematite veining. From Hop Gulch area, northeast corner of the Buena Vista West quadrangle.

Numerous Precambrian shear zones are present on the west side of the rift. They are generally not well exposed and mostly occur as concentrated float zones from a few feet to over 100 feet wide. The sheared rocks are ductilely deformed tectonites that occur as strongly foliated schists to phyllonites and include biotite, muscovite-sericite, and chlorite schists. The shear foliation and trend of the zones is usually transverse to the surrounding gneiss layering and foliation. Small prospect pits occasionally occur on these shear zones. The shear zones can be accurately plotted where they cross ridge tops, but the narrow zones of schist-phyllonite usually get overwhelmed by other float on hillsides. Consequently, the distribution, orientation, and continuity of these shears zones are poorly understood. Three Proterozoic shear orientations include north-northwest with vertical to moderate southwest dip, north-northeast with moderate northwest dip, and northeast with moderate-steep southeast dip. The indicated trends of the Precambrian shears are similar to, and are sometimes spatially associated with, rift-related faults. The trends suggest that the Precambrian shears may have been locally reactivated during younger deformation events.

Clear evidence of Pennsylvanian and Laramide deformation is lacking in the Buena Vista West quadrangle. Any Paleozoic and Mesozoic sedimentary rocks that were in the area, except for small keel-like, down-faulted slices of Paleozoic sedimentary rocks in the Monarch Pass area (Dings and Robinson, 1957), had been eroded off of the Laramide Sawatch Uplift by Eocene-Oligocene time. Keller and others (2004) suggested that the north-northwest-trending Trout Creek fault (Mosquito-Weston fault of DeVoto, 1971) in the Castle Rock Gulch quadrangle was active during the Pennsylvanian tectonic event that produced the ancestral Front Range and Sawatch uplifts and the Central Colorado trough. They also suggested that north-east-trending faults and folds in the Buena Vista East quadrangle were related to Laramide deformation. There is no evidence of significant northeast-trending faults in the Buena Vista West quadrangle.

Possible Laramide faulting in the Proterozoic rocks on the east side of the graben is indicated by linear, concentrated float zones of a peculiar epidote-matrix breccia (fig. 35). The breccias contain angular clasts and crystal fragments derived from Proterozoic granodiorite (Xgd) and pegmatites (YXp) in a matrix of epidote. Some epidote-matrix breccias occur along broken fault zones exposed along the old Colorado Midland railroad grade in the northeast corner of the Buena Vista quadrangle. It is suggested that other linear float zones of epidote breccia may indicate the location of unexposed faults and that these faults could be identified and delineated by careful mapping of these breccias. The epidote in the faults may be related to hydrothermal alteration associated with the dacite porphyry dikes (Tdd) because epidote is commonly associated with them.

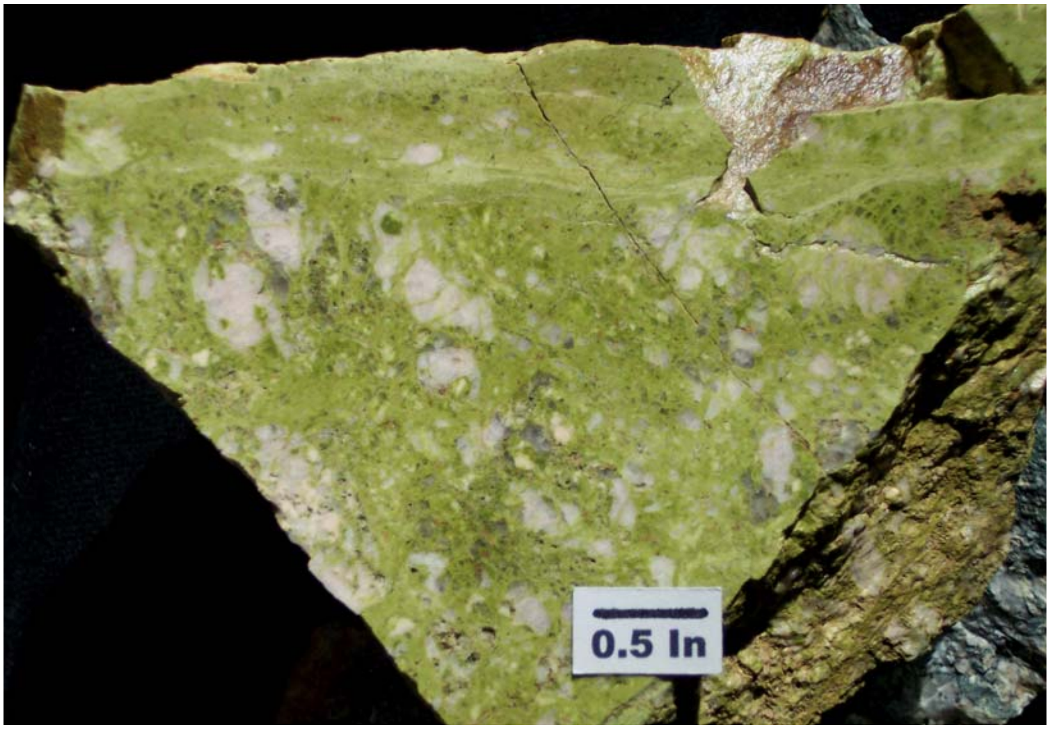

Figure 35. Laramide (?) epidote-matrix fault breccias in Proterozoic rocks on the east side of the rift, northeast corner of the Buena Vista West quadrangle.

Erosion of the Laramide uplifts which started about 70 Ma continued into Eocene time and culminated in a well-formed, widespread, low-relief erosion surface, the late Eocene surface (Epis and Chapin, 1975; Scott, 1975, Epis and others, 1976 and 1980). The beveling of this surface continued until eruption of the Oligocene Wall Mountain Tuff, which partly buried it (Epis and Chapin, 1975). Shannon (1988) suggested that erosion and modification of the late Eocene surface must have continued until after eruption of the Badger Creek Tuff (about 34 Ma) and possibly to about 28 to 30 Ma when the surface was initially disrupted by Rio Grande rift extension. No positively identified remnants of the late Eocene surface were found in the Buena Vista West quadrangle. The closest remnant is the Trout Creek paleovalley in the Buena Vista East quadrangle. The small patches of possible Tertiary volcanic rocks (Tv) south of Bald Mountain, in the Buena Vista West quadrangle are potential remnants of volcanic rocks that were deposited on the modified late Eocene surface. Shannon (1988) suggested that possible remnants of Tertiary ash-flow tuffs were deposited on the modified late Eocene surface and then down dropped and preserved in the upper Arkansas Valley graben, but no drilling has been deep enough to penetrate them.

The recently recognized tuff of Triad Ridge (new hornblende and biotite ages of 37.49 +/- 0.22 Ma for lower tuff of Triad Ridge) is a major accumulation of ash-flow tuff in the Trout Creek paleovalley (McIntosh and Chapin, 2004). This is important to the discussion of structural geology because the Trout Creek paleovalley has a strong S65°W alignment and trends directly across the rift to Mount Princeton, which is near the center of the northern collapse structure of the Mount Aetna cauldron. Simply on the basis of these spatial relationships, it is suggested (similar to McIntosh and Chapin, 2004) that the lower tuff of Triad Ridge probably came from a caldera source in the Mount Princeton area and that the source was obliterated by the intrusion of the Mount Princeton pluton. Keller and others (2004) discussed evidence for a second paleovalley (also in the Buena Vista East quadrangle) that contains the 30 Ma Nathrop Volcanics, Wall Mountain Tuff, and Tallahassee Creek Conglomerate. It is about 14,000 feet south of, and is sub-parallel to, the Trout Creek paleovalley. These relationships demonstrate that at around 37 to 36 m.y. major nues ardentes were generally flowing west to east, down paleovalleys in the present area of the southern part of the Buena Vista West quadrangle.

It is likely that a westward continuation of the Trout Creek paleovalley contains ash-flow tuffs and has been down dropped and preserved beneath the Tertiary valley fill of the Buena Vista West quadrangle. Therefore, a wedge of Tertiary volcanic rocks is shown on the graben floor along the west side of the rift near the west-southwest projection of the axis of the Trout Creek paleovalley, in the Buena Vista West geologic cross section. The tuff of Triad Ridge and/or the Wall Mountain Tuff is likely preserved in this area.

The Laramide Sawatch uplift persisted until Oligocene time when the northern Rio Grande rift was developed along its eastern flank and split the range into the present Sawatch Range on the west and the smaller southern Mosquito Range on the east (Tweto, 1979). The onset of Rio Grande rift faulting is estimated at about 28 Ma and Rio Grande rift magmatism at about 26-27 Ma (Tweto, 1979).

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 is the surface expression of the Upper Arkansas rift basin. The basin (a structural graben or half-graben) is the northernmost major rift basin of the Rio Grande rift (Chapin and Cather, 1994). The Upper Arkansas axial graben is highly asymmetric with much more uplift and erosion on the western block uplift (Sawatch Range) than on the eastern block uplift (southern Mosquito Range). The Mount Princeton pluton (36.6 Ma) has been breached and deeply incised by erosion; all evidence of an overlying volcanic edifice has been completely removed. The Mount Aetna cauldron (34.4 Ma) has been eroded down to the level of a ring-dike complex with some intracauldron volcanics preserved in the down-dropped block. Thus, there has been several km of uplift and erosion of the southern Sawatch Range (western block) since 37 Ma and 34 Ma. In contrast, the preservation of outflow ash-flow tuffs (of the same age at about 34 to 37 m.y.) and extrusive topaz rhyolites (about 30 Ma Nathrop Volcanics; See Keller and others, 2004 and McIntosh and Chapin, 2004)) in the southern Mosquito Range indicates relatively minor uplift and erosion of the eastern block.

Studies of the western Sawatch block uplift also show interesting asymmetries. Bryant and Naeser (1980) conducted an apatite fission-track uplift study on the Twin Lakes pluton. In a transect across part of the Sawatch Range they found that apatite fission-track ages range from about 30 Ma on the west to 16 Ma on the east. They suggested that the 30 Ma ages could be related to initial reactivation and uplift of the Sawatch Range block, and the younger ages to the east toward the graben represent a maximum time for rapid differential movement between the Arkansas Valley and the Sawatch Range. Tweto (1979) noted that the distribution of 14,000 ft peaks along the eastern margin of the Sawatch Range is significantly displaced from the crest of the Sawatch Range and the Continental Divide. He suggested that the higher elevations and reset apatite ages along the eastern edge of the Sawatch Range were related to westward tilting of the Sawatch Range block.

In the Chalk Creek area, Shannon (1988) found similar evidence of younger apatite fission-track ages of 15 to 24 Ma in a horst block (Collegiate Peaks horst) that includes Mount Princeton and Mount Antero. Four apatites from further west in the Sawatch Range have apatite fission-track ages of 30 Ma or older. He suggested that the Collegiate Peaks horst might continue northward and include Mount Yale and Mount Harvard. Preliminary mapping in 2002 and 2003, showed that the horst block does continue northwestward and includes Mount Yale, but not Mount Columbia or Mount Harvard. It is possible that there may be a series of (en echelon?) horst blocks along the east flank of the Sawatch Range. Shannon (1988) estimated about 2,500 feet of differential uplift of the horst block relative to the rest of the Sawatch Range and a minimum of about 11,000 feet of relative offset from the horst block to the estimated graben floor (using about 4,800 feet of fill along the west side). The recognition of differentially up-lifted horst blocks reduces the need for wholesale, westward block tilting of the Sawatch Range. The northwest and north-northwest-trending faults in the southwest corner of the Buena Vista West quadrangle are the easternmost faults on the eastern edge of the horst block and are offset down to the east. These faults, in at least two places offset the Tmpk-Tmpm contact and drop it down to the east in steps of a few hundred feet to 1,000 feet. Some Tmpk occurs down as low as about 10,400 feet on the south side of Maxwell Creek; this offset indicates that the unit may be offset as much as about 3,000 feet over a horizontal distance of a little over one mile. Some of this apparent offset of the Tmpk unit is probably due to its original shape, a sheet that was draped over the interior of the pluton. The contacts between the Mount Princeton pluton and Proterozoic rocks near Cottonwood Creek and Bald Mountain indicate that this area is close to the eastern margin of the pluton.

The pattern of faulting that is responsible for formation of the Upper Arkansas Valley graben is complicated and not well understood. One problem is that most of the host rocks bounding the graben are Proterozoic rocks that have undergone multiple episodes of deformation and faulting. Trying to determine the age of faulting and reactivated faulting is critical in evaluating when, where, and how much movement may be ascribed to formation of the graben. The northwest-trending faults that predominate in the Proterozoic rocks on the east side of the graben in the Buena Vista East and in the NE corner of the Buena Vista West quadrangle are roughly oriented N50°W, which is oblique to the N20°W orientation of the graben. This N20°W orientation is close to, but still slightly oblique to, the N25° to 30°W orientation of the main fault zones mapped on the west side of the rift in the Buena Vista West quadrangle. It should also be noted that the N20°W trend is close to the N15°W trend of the Laramide Trout Creek fault (Wallace and Keller, 2003), and suggests that Laramide structures may be an important influence on the orientation of rift-bounding faults.

A number of main through-going north-northwest-trending fault zones exist along the western margin of the graben in the Buena Vista West quadrangle. These faults are generally poorly exposed unless they occur in areas with steep topography and are actively being eroded. Examples include the Cottonwood cliffs, near the Cottonwood Hot Springs, which has similar exposures as the Chalk Cliffs in Chalk Creek. Another example is the lower part of Dry Gulch where the stream has recently cut through a till or gravel terrace and exposed a highly faulted window of Mount Princeton quartz monzonite. The roadcuts on Bald Mountain and at the mouth of Red Deer Creek also provide exposures of probable rift-related faults.

The 36 to 37 Ma age of the Mount Princeton pluton indicates that it is younger than the waning stages (about 45 to 40 m.y.) of the Laramide orogeny. Thus, the Mount Princeton pluton records the structural transition from mid-Tertiary caldera eruptions (specifically the 34 Ma Mount Aetna cauldron) to the Oligocene-Miocene initiation of Rio Grande rift faulting. Rift-related faults in the Mount Princeton pluton and the Proterozoic rocks adjacent to the pluton are also characterized, and their identification is enhanced, by the association of hydrothermal features. These typically include chlorite coatings, sericite coatings, quartz druse coatings, epidote coatings and hematite coatings, and slickensided (+/- striated) versions of the same. The benefit is that these coatings occur as float indicators of the presence of a fault, for example where a fault crosses a ridge through a saddle that has no outcrop. Empirical observations indicate that many of the old prospect pits are on fault structures and the pit waste piles often contain slickensided mineral coatings and mineralized fault breccias.

Fault breccias are locally concentrated along the north-northwest-trending faults and are good fault indicators. Most of the faults on Bald Mountain and the low hills to the south and southwest are characterized by iron-oxide cemented breccias. The breccias are common on the prospect dumps and also occur as float concentrations on the surface. The iron-oxide breccias appear to be related to a significant hydrothermal center at Bald Mountain (see Mineral Resources section).

Rift-related faults are predominantly brittle faults that occur in zones with multiple fault orientations (fig. 36). There is some sheeting with sets of similarly oriented faults and fractures. Examination of the faulting in Cottonwood cliffs indicates abundant complex faulting with numerous fault orientations. There are abundant high-angle and low-angle faults, exactly as at Chalk Cliffs (Shannon, 1988; Emslie, 1991). In both areas steeper faults generally post-date and offset the low-angle faults. Even in areas with good exposure, it is impossible to trace individual fault breaks for more than a few hundred feet.

Figure 36. Low-angle, rift-related fault exposed at Cottonwood Hot Springs, Cottonwood Creek, Buena Vista West quadrangle. Note intense fracturing in hanging wall, zeolite-clay alteration in footwall, and discontinuous iron-oxides along fault.

Thin (from about 0.2 to 6.0 inches) bands of microbreccia and fault breccia are locally developed along the main fault planes. Rare thin (less than 0.5 inch) bands of ductile shearing with incipient to weak mylonitic fabrics occur in some fault zones. These bands tend to be irregular and discontinuous because of disruption by younger brittle faulting. The ductile shear bands were first observed in the Chalk Cliffs during the 1980's (Shannon, 1988). Subsequently, Emslie (1991) and Miller (1999) have studied the structure and hydrothermal alteration at Chalk Cliffs. Both of these studies mention ductile shears (Emslie, 1991) or "foliated cataclasites" (Miller, 1999) and interpreted them as related to rift faulting. It appears that both of these studies were conducted without evaluating whether or not the ductile shear bands could be related to an older deformation event, namely collapse of the Mount Aetna cauldron.

During field work for the Buena Vista quadrangle, minor ductile shear bands were noted along rift-related fault zones near the mouth of Dry Creek (fig. 37). These faults are the north-northwest continuation of faults from the Chalk Cliffs about 2.0 miles to the south. Minor ductile shear bands occur in the Cottonwood cliffs and in outcrops of Mount Princeton rocks about 4,000 feet north-northeast of Cottonwood Hot Springs. All of these ductile shears occur in Mount Princeton pluton rocks and none have been observed in Proterozoic rocks. The Chalk Cliffs and Dry Creek localities occur directly adjacent to the Mount Aetna cauldron ring zone (northern collapse structure). At these localities and in the Cottonwood cliffs it is difficult or impossible to rule out that the ductile shear bands are significantly older than the rift faults and were formed during collapse of the Mount Aetna cauldron as ring shears (Trs). The northernmost locality about 4,000 feet north-northeast of Cottonwood Hot Springs is not associated with other ring zone features (ring dikes or intrusive breccias) and may support the idea that some rift faulting was by ductile deformation processes.

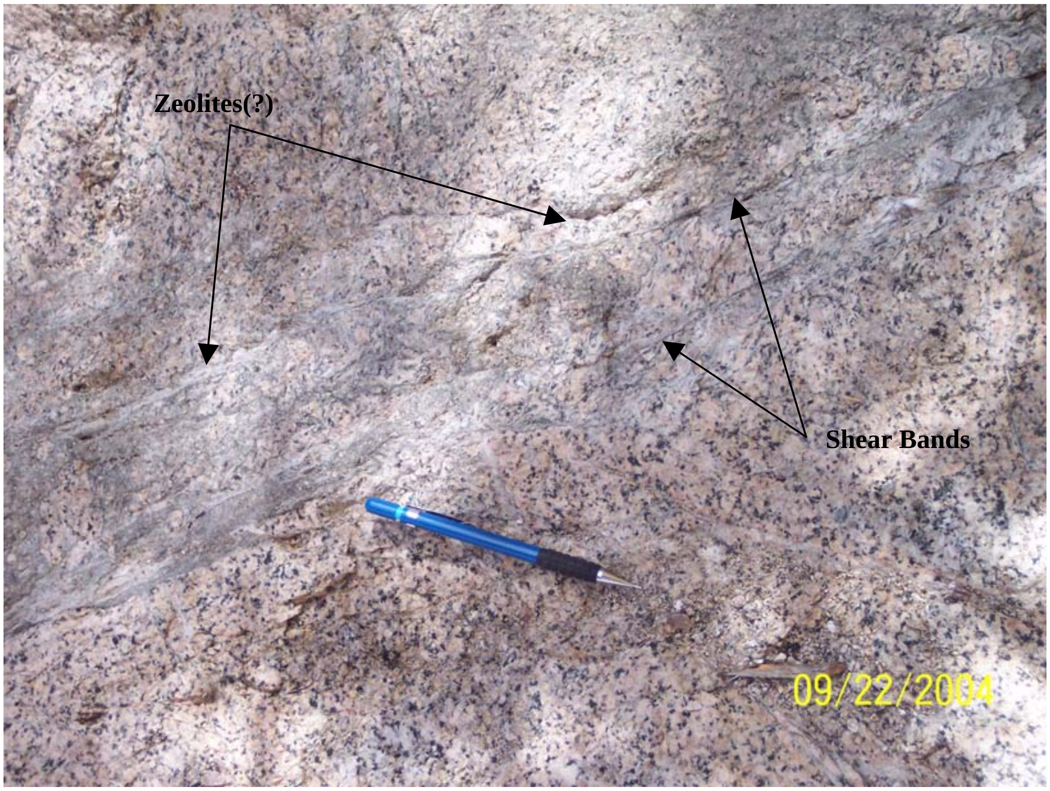

Figure 37. Shear bands with semi-ductile deformation fabrics locally developed along major rift-related fault zones. Shears cut Tmpm in Dry Creek 'window'. White material is zeolite-clay.

Another interesting feature of the western rift boundary is the presence of a series of apparent range-front offsets. These range-front offsets appear to be produced by the slightly oblique relationship of the overall N20^{o}W orientation of the upper Arkansas Valley graben and the N25^{o} to 30^{o}W orientation of the main rift-related faults along the Sawatch Range front. The most studied range-front offset is the one at Chalk Cliffs and the mouth of Chalk Creek (Miller, 1999). Two more range front offsets occur on the Buena Vista West quadrangle. At the south end of the Bald Mountain Proterozoic body near Silver Prince Creek the offset has about 6,000 feet of step over and at North Cottonwood Creek the offset has more than 5,000 feet of step over. No evidence of cross faults was found in either of these areas during this study.

Early on, these range-front offsets were interpreted to be related to cross faults that offset the range-front structures, and cross faults were proposed for Chalk Creek and Cottonwood Creek (Limbach, 1975; and Olson and Dellechaie, 1976). Miller (1999) described the range-front offsets as right-stepping, en echelon fault surfaces. He proposed a model in which the en echelon step is a geometric segment boundary that is actively being breached by formation of a new fault strand developed in the step-over area. This model implies that the rift faults rapidly die out as they enter the Sawatch Range. Preliminary field work indicates that the main faults penetrate deeply into the range. If the same faults that define the range front continue into the range, then it would seem that the amount of displacement must decrease with distance into the range.

The fault strands at the Sawatch Range front have been active into the late Quaternary, as evidenced by fault scarps of progressively greater height on deposits of Pinedale, Bull Lake, and pre-Bull Lake age (table 3). On the basis of estimated ages for the displaced deposits, the vertical slip rate on the range-front fault has ranged from about 0.002 in/yr averaged over the past 650 ka to as much as 0.012 in/yr in the late Quaternary.

Table 3. Heights of fault scarps in various Quaternary deposits on the range-front trace of the Sawatch fault zone.

Unit on upthrown block/ Unit on downthrown block	Fault scarp height (ft)	Fault scarp vertical surface offset (ft)	Approximate time required to create scarp (ka)/ average vertical slip rate (in/yr)
Qfy		5.6	5/ 0.013
Qfp	5.9	8.9, 11.1	15/ 0.008
Qpoo	9.2, 9.8		25/ 0.005
Qac		15.1	15/ 0.012
Qboy		18.4, 16.7	65/ 0.003
Qaco/Qfp		9.8, 16.4, 18.4, 18.4, 22.3	65/ >0.003
Qfo		33.5	35/ 0.011
Qboo/Qboy		35.1	150/ >0.003
Qboo	60.0		150/ 0.005
Qbto		60.0	150/ 0.005
Qk/Qfp		66.9	650/ >0.001
Qk		114.8	650/ 0.002

The structural geology of the interior of the Upper Arkansas graben is less well known, due to a relative lack of detailed subsurface studies in the valley. Zohdy and others (1971) measured a 6 mile-long, east-west electrical resistivity profile across the valley floor about 3 miles south of Buena Vista (Maxwell Park area). Their cross-section (fig. 38) shows that the valley floor is underlain by a series of three thin, tabular, high-resistivity layers; the series thins from about 800 feet thick near the range front to 100 feet thick at the Arkansas River. The upper layer in this series corresponds to the older Bull Lake outwash fan (Qboo) deposited from Maxwell Creek. The other two high-resistivity layers probably represent older coarse-grained Quaternary outwash gravels derived from a similar source. The series thins to a negligible thickness just east of Maxwell Park and then thickens again near the eastern boundary of the Buena Vista West quadrangle.

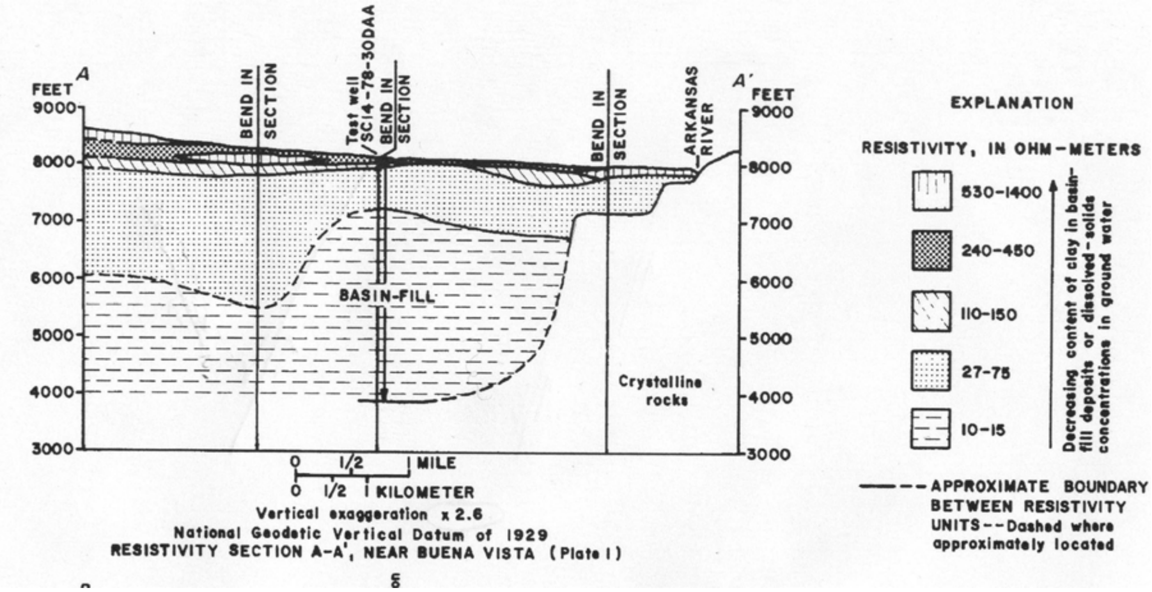

Figure 38. East-west electrical resistivity cross-section across the Upper Arkansas Valley about 3 miles south of Buena Vista. From Crouch and others, 1984, after Zohdy and others, 1971.

The high-resistivity wedge overlies two much thicker (4,000 ft-thick) lower-resistivity units that probably represent the Tertiary Dry Union Formation. A 1,000 foot-deep well on the line of section (eastern margin of Sec. 30, T14S, R78W) penetrated only 20 feet of Quaternary alluvium (Qk) before entering the Dry Union Formation (Crouch and others, 1984). The contact between the two low-resistivity units within the older basin fill drops 1,600 feet down-to-the-west to the west of the deep well and then slowly rises toward the range-front fans. This drop coincides with a west-facing fault scarp on the valley floor, described below. To the east of the well, this same contact declines gently to the east. The structural high in the low-resistivity basin fill strata, and the drastic thinning of the high-resistivity wedge of Quaternary deposits, indicate the deep well in Sec. 30 is located in an intragraben horst block.

On the eastern side of the Upper Arkansas Valley (mainly in the Buena Vista East quadrangle) the resistivity profile indicates crystalline basement rocks at shallow depth. Basement is downdropped to the west along a series of step faults, the largest of which lies about 1 mile west of the Arkansas River.

Partly on the basis of this resistivity data, Tweto (1979) estimated up to 3,800 feet of graben fill near Buena Vista and 4,800 feet of graben fill near Salida. Scott (1975) and Scott and others (1975) suggested that the valley fill was the deepest (greater than 4,800 feet) along the western side of the graben. Keller and others (2004) estimated about 2,000 feet of valley fill on the east side of the rift (in SW corner of the Buena Vista East quadrangle), and postulated that it thickens westward toward the Sawatch Range.

Southwest-facing fault scarps exist on the valley floor 4 miles from the range front (Maxwell Park area) and displace Nebraskan, Kansan, and Bull Lake piedmont alluvium as much as 8.0-10.0 feet (fig. 39). These scarps are continuations of similar west-facing scarps mapped in the Buena Vista East quadrangle (Keller and others, 2004) and are interpreted as overlying a down-to-the-southwest normal fault that is responsible for the anomalies shown on the resistivity profile. This fault comprises the western margin of an intragraben horst, the eastern margin of which is a down-to-the-east normal fault mapped in the adjacent Buena Vista East quadrangle by Keller and others (2004). This horst explains why the oldest valley fill (Dry Union Formation) crops out only near the valley center, where normally the oldest valley fill would be found at the greatest depth.

Figure 39. View of antithetic fault scarp (between arrows) offsetting Kansan alluvium (Qk) by 8.2-9.8 feet in Maxwell Park. View to east along County Road 328. Pickup truck on scarp is 7.2 feet high.

West of the intragraben horst surface, gently sloping Maxwell Park is bounded by opposing fault scarps at the surface and coincides with the lowest deflection of valley fill contacts on the resistivity cross-section. These data suggest that Maxwell Park is underlain by an intragraben graben, which may contain the deepest valley fill in the rift at this latitude.

Overall, the resistivity cross-section and the pattern of surface fault scarps indicates that the Upper Arkansas graben in the Buena Vista West and East quadrangles is composed of a deep western sub-graben beneath Maxwell Park, a central horst (mainly buried), and a shallower eastern sub-graben (in the Buena Vista East quadrangle) that contains the modern Arkansas River. This internal structure is strikingly similar to that of the next major rift basin to the south, the San Luis Basin (Chapin and Cather, 1994).

GEOLOGIC HAZARDS

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

LANDSLIDES

Landslide deposits are relatively rare in the Buena Vista West quadrangle, because the Precambrian and Tertiary intrusive rocks that underlie most of the Sawatch Range are generally too competent for slope failure except where weakened by faulting. We map five definite (unit Qls) and two questionable (unit Qls?) landslide deposits, all in the Sawatch Range north of Silver Prince Creek (table 4).

Table 4. Summary of landslide deposit areas, by map unit.

Map unit	**Description**	**Number of deposits/ lithologies**	**Range of areas (acres)**	**Mean area (acres)**
Qls	Landslide deposit, undivided	5/ Proterozoic biotite gneiss (except 1 in Tmpm)	3.5-76	22
Qls?	Landslide deposit, undivided, questionable	2/ Proterozoic biotite gneiss	10-15	12.5
TOTALS		**7**	3.5-76	20

The mean area of all landslide deposits is 20 acres, with a range from 3.5 acres to 76 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 proximity to rift-related normal faults. Presumably, the rock mass strength in the faulted rock is low enough to permit slope failure of fractured and/or altered rock on steep slopes during times of either elevated water table, strong shaking from earthquakes on the Sawatch fault zone, or both.

Most of the landslides in 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.

Rock mass strength is also presumed to be low in some areas of the Mount Princeton pluton affected by pervasive hydrothermal alteration (such as the south-facing canyon wall west of Cottonwood Hot Springs (fig. 12) due to the abundant volume of talus produced. However, no discrete landslides are visible on that slope. Evidently the pluton is so uniformly weakened that there are no discrete planes of weakness to form landslide basal shear planes.

FLOODS AND DEBRIS FLOWS

Intense summer rainstorms or rapid melting of deep snowpack during unusually warm spring thaws may cause localized flooding and debris-flow activity. For example, most of the area mapped as Holocene alluvium (Qal) in the quadrangle lies on modern flood plains and is potentially subject to flooding. The 100-year and 500-year flood plains of Cottonwood Creek defined by FEMA in the town of Buena Vista are restricted to map unit Qal.

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, Qf**y) are potentially subject to debris-flow deposition over most of their surfaces. Fans with the highest hazard are those whose drainage basins contain large areas of exposed, altered Tertiary intrusive bedrock with sparse vegetation. One such area is the steep south-facing slope west and north of Cottonwood Hot Springs, in the mouth of Cottonwood Canyon, in the Mount Princeton pluton (map unit Tmpf). This highly altered area spawned a debris flow on 22 July 2002 that deposited up to 15 feet of debris on the highway and trapped a van (http://www.crh.noaa.gov/pub/events/mudslides/mudslides.php, accessed on 25 Feb. 2005). It took 2 weeks to remove all the debris and reopen the highway. The same area spawned another debris flow on Wednesday, 18 Aug. 2004 that buried County Road 306 and forced diversion of all traffic for 4 days (fig. 14). According to Chaffee County Fire Protection Chief Jim Wingert, “The mudslides were all within about one mile of each other ranging from two to 14 feet deep. The water came down fast and the north slope washed out across the road. It looked like a lava flow.” (Chaffee County Times, Aug. 26, 2004 edition).

SEISMICITY

The Buena Vista West 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 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. The most active fault is the Sawatch fault zone, which lies at the base of the Sawatch Range. Fault scarps (thick lines with hachures on the map) up to 8.2 feet high are present in Pinedale-age deposits, and scarps average about 26-59 feet high in Bull Lake-age deposits and up to 115 feet high in Kansan deposits. Trenching investigations at the mouth of Cottonwood Creek and at Eddy Creek (south of the quadrangle) in the late 1970s (Ostenaa and others, 1980; 1981; McCalpin and others, 2002) indicated six surface-rupturing earthquakes have occurred on the fault since about 150 ka, suggesting a recurrence interval of 10 to 40 ka. The most recent of these paleo-earthquakes probably occurred between 4.7 and 8 ka. A moment magnitude (M_w) 6.75 was estimated for the largest paleo-earthquakes on the southern section of the Sawatch Fault (Lettis and others, 1996). (source: http://geosurvey.state. co.us/pubs/ceno/index.asp). In addition, small west-facing fault scarps exist in the east-central part of the quadrangle and displace units Qboy, Qboo, and Qk as much as 8.2 feet. These fault scarps do not displace Pinedale-age deposits and their height in Bull Lake deposits is much less than on the range-front fault, indicating a lower level of activity.

In the event of a M>6 earthquake on the Sawatch fault zone, hazards would include strong ground shaking, shaking-induced ground failure such as liquefaction and landslides, and fault-surface rupture. For the town of Buena Vista (zip code 81211), in any 50 year-long period, there is a 10 percent chance that peak horizontal ground shaking will be stronger than 0.06g (1g= gravitational acceleration), a 5 percent chance it will be stronger than 0.1g, and a 2 percent chance it will be stronger than 0.17g (source: http://eqint.cr.usgs.gov/eq/html/zipcode.html).

The latter estimate (2 percent chance in 50 years) is statistically equivalent to the largest earthquake expected in about 2,500 years. However, the recurrence interval of surface-rupturing earthquakes on the Sawatch fault zone is much longer than 2,500 years (estimated as 10,000 to 40,000 years), so the actual shaking that might occur during a surface-rupturing earthquake would be greater than 0.17g at Buena Vista and much greater closer to the Sawatch fault zone. More precise estimates for any specific site would require a site-specific ground motion study.

The strong shaking may induce landslides and rockfalls in the Sawatch Range and liquefaction of areas containing high water tables (less than 30 feet deep) where the aquifer is mainly sand. The latter condition may exist in parts of the broad flood plain of Cottonwood Creek (map unit Qal) in and near Buena Vista, where water levels in wells stand only 4-20 feet below the surface.

Fault surface rupture during a large earthquake will instantaneously rupture the ground surface and uplift the upthrown side of the fault by 5-8 feet. This movement will displace any structures or facilities sited across the fault trace (typically located beneath the center of the mapped fault scarps), such as roads, canals, pipelines, buried utilities, or houses or barns. Although roads and utilities can be repaired after such an offset, buildings that straddle such a fault trace are typically destroyed by such offsets, so avoiding the fault trace is the only practical solution.

ABANDONED MINED LANDS

Collapse of abandoned mine shafts and tunnels, many of which may be covered by thin surficial material, pose a potential hazard. Some abandoned mines are present in the Buena Vista West quadrangle. Mines with significant underground workings are present in a few areas and abundant small to large (> 6.0 feet deep) prospect pits are scattered over the west half of the quadrangle. At least 16 mines have underground workings and moderate to large waste dumps. The location of the larger mines is shown with the appropriate symbol (adit or shaft) on the geologic map. In general, pits over about ten feet deep and with moderate to large waste dumps are considered to be caved shafts. The location of most of the prospect pits are shown on the geologic map. They range from tiny test pits to medium pits where substantial work was done. None of the abandoned mines have been officially sealed, and most have collapsed or caved by themselves over the years. A few of the larger mines have adits that are still partly open and/or caved shafts that have vertical walled pits greater than ten feet deep. They present potential hazards to humans and animals.

MINERAL RESOURCES

Potential mineral resources in the Buena Vista West quadrangle include construction sand and gravel; placer gold deposits; rare-earth-minerals in pegmatite deposits; precious metals including gold and silver associated with epithermal vein deposits; copper and molybdenum associated with vein and/or porphyry-type deposits; lead and zinc associated with vein deposits; and zeolite minerals. Construction sand and gravel are the only mineral resources that are presently being mined in the quadrangle from sites with active mining permits from the Colorado Division of Minerals and Geology (Guilinger and Keller, 2004). Limited exploration for geothermal energy was carried out during the late 1970's in the Buena Vista West quadrangle. There is little or no recognized potential for oil, natural gas, or coal resources in the quadrangle.

A review of historic metallic mineral mining activities is given in the Vein Deposits section. In addition, a summary of mineralization and alteration in the Buena Vista West quadrangle is provided. This review and summary provide information that can be used to predict where future exploration and mining activities would potentially be located.

SAND AND GRAVEL

Sand and gravel deposits in the Arkansas Valley are presently the most economically significant mineral resource in the Buena Vista West quadrangle. Four gravel pits are currently actively mined, the largest of which is the ACA Products, Inc. pit about 6,000 feet southwest of Buena Vista. Younger and older Bull Lake outwash gravels of the Arkansas River (map unit Qboy/Qboo; see fig. 4) are mined in that pit. Chaffee County sporadically mines sand and gravel from two pits located on the piedmont. The larger Red Deer pit lies 1 mile east-southeast of the mouth of Red Deer Creek in Kansan alluvium (map unit Qk), and a smaller pit lies at the northern end of Maxwell Park (T14S, R78W, Sec. 30) in older Bull lake outwash gravels (map unit Qboo). Hard Rock Paving and Redi-Mix owns a small pit directly north of the Buena Vista trailer park in older Pinedale outwash of the Arkansas River (map unit Qpoo; NW1/4 of sec. 5, T.14S., R.78W). Locations of active and inactive pits in the map area indicate that nearly all of the Quaternary alluvial deposits in the Arkansas Valley are sources of sand and gravel (Keller and others, 2002).

PLACER GOLD

The placer gold deposits at Granite, Colorado (about 15 miles north of Buena Vista) were continuously active from 1860 to 1911 (Henderson, 1926). Placer gold had been discovered by 1897 further south along the Arkansas River, and small and intermittent placer mining operations, with insignificant production up to the present (Dunn, 2003), were located along the river. The district is known as the Arkansas River gold placers district and includes the area from near Granite to Salida. The placer gold in this district is likely sourced from the Granite and Hope mining districts, about 15 miles north of Buena Vista. A search of Bureau of Land Management mining claim records shows no currently active placer mining claims in the Arkansas River gold placers district in the Buena Vista West quadrangle. Sections 31 and 32, T.13S, R.78W (north of Buena Vista) had a large number of placer mining claims that were located in the 1980’s and

1990's, but these have all lapsed. Additional placer claims were located in the same area in 2003 and 2004 and have also lapsed. Records show only two active placer claims in the northeast corner of Section 31, just north of the northern boundary of the Buena Vista West quadrangle.

Additional placer claims were located in 1987 along the Arkansas River in Section 5, T.14S, R.78W just north of Buena Vista. They were invalidated by 1990. Keller and others (2004) described an active, small sand and gravel and gold placer mining operation along the Arkansas River in the Buena Vista East quadrangle.

There is one currently active placer mining claim indicated (BLM mining claim records) to be in the Buena Vista West quadrangle. The Last Chance Gulch claim was located in 2004, in the NW ¼ of Section 21, T.14S, R.79W. However, the location description places this claim on the north side of Cottonwood Creek, above the Cottonwood cliffs and northwest of Cottonwood Hot Springs. Therefore, a problem with the location or claim type is suspected.

PEGMATITE MINERALS

Minor pegmatites (YXp) occur in the Proterozoic rocks in the northeast corner of the Buena Vista West quadrangle. They are relatively small bodies (on the order of tens of feet maximum length) that seem to occur in clusters over areas of about a hundred feet. A few have small prospect pits. The pegmatites consist of quartz, K-feldspar, biotite, and muscovite. One prospect has smoky quartz, which may indicate the presence of radioactive minerals (for example monazite, thorite or coffinite). The pegmatites are related to Proterozoic biotite granite (YXg) bodies and are probably similar to pegmatites in the Buena Vista East and Castle Rock Gulch quadrangles. A number of pegmatites in these quadrangles were mined mainly for potassium feldspar (Keller and others, 2004). The pegmatites comprise the Trout Creek Pass pegmatite district and were also known for rare earth element minerals (Hanson and others, 1992).

Pegmatites are abundant in the Proterozoic rocks on the west side of the rift, but they are small, and relatively discontinuous dike-like bodies. They consist of quartz, K-feldspar, and biotite-muscovite, with local minor magnetite and garnet. In general, the pegmatites in the Buena Vista West quadrangle have little or no resource potential. This is mainly due to their small size and lack of exotic minerals.

VEIN DEPOSITS (METALS)

The Buena Vista West quadrangle contains at least 16 mines with underground workings and moderate to large waste dumps that indicate substantial work was done. However, no official lode mining districts appear to occur in the quadrangle. Records exist of unpatented claims in the Fourmile Creek area just northeast of the northeast corner of the Buena Vista West quadrangle. This area is referred to as the Fourmile mining district, and its described location is about three miles northwest of Buena Vista (Dunn, 2003). Dunn (2003) indicated that production records exist for gold, silver, copper, lead, and zinc for the period 1935 to 1940 for the district.

Significant mining districts (Dunn, 2003) that occur in the region around the Buena Vista West quadrangle include the Chalk Creek mining district (about 15 miles southwest of Buena Vista in the St. Elmo area with gold, silver, copper, lead, and zinc production reported to 1944); the Garfield-Monarch mining district (about 25 miles south-southwest of Buena Vista with lead, zinc, silver, and minor gold and copper production to 1945); the Cottonwood mining district (about 14 miles west of Buena Vista; includes the North Cottonwood district with reported silver, lead, and gold, and the South Cottonwood district with silver; but no significant production reported); the Middle Cottonwood mining district (about 12 miles west of Buena Vista; generally included in the Cottonwood mining district; includes a small group of mines with reported lead and silver production); Browns Canyon mining district (about 16 miles south-southeast of Buena Vista; significant fluorspar production from 1929 to 1950's); and the Granite mining district (about 16 miles north-northwest of Buena Vista; lode gold discoveries in 1867 and intermittent gold and silver production to 1945 with some copper and lead production).

Three patented mining claim blocks are located in the Buena Vista West quadrangle (fig. 40). The largest block, the Maxwell Creek patent group, consists of 15 patented claims above tree line just east and northeast of the summit of Mount Princeton. The claims occur in a roughly north-south trend from Maxwell Creek, southward into the upper part of Dry Creek. The two largest mines in this patent group are the Maxwell Creek adits, located on the south side of Maxwell Creek. The largest mine in the Buena Vista West quadrangle, the Latchaw Mine is located in Dry Creek about 0.5 mile east of this patent group. Chaffee County lode mining claim records indicate that most or all of these claims were originally located in the 1880's and were probably patented by 1900. No indication of recent or current work on theses claims exists.

A small block of three patented claims is present in Mercury Creek. The Mercury Creek claims were originally located in 1897 and immediately went to patent in 1898. A number of mines, some with substantial waste dumps, occur on and around these patented claims. The third block of patented mining claims, the North Fork Cottonwood patent group, is situated on the south side of North Fork Cottonwood Creek and includes three claims located about 1,500 feet north of the Mercury Creek patent block. The North Fork Cottonwood claims were originally located in 1897 and went to patent in 1899. The block has two adits with large waste dumps and one shaft with a medium-sized waste dump. This review indicates that the three patented mining claim blocks which contain some of the larger mines on the Buena Vista West quadrangle were all located early in Colorado's mining history and were probably patented before 1900.

The BLM mining claim records indicate that no active unpatented mining claims exist for the Buena Vista West quadrangle. Indications of only three recent unpatented mining claim groups exist. The first group is the Princeton claims, which were located in 1969 and 1981 and were staked around the northern portion of the Maxwell Creek patent block. They were abandoned in 1992. The second unpatented claim block was located in 1955 and 1969 on Bald Mountain and the areas south and west of Bald Mountain. This unpatented claim block lapsed in 1981 and was re-staked by different owners and the claims lapsed the following year.

During the 2004 field work for the Buena Vista West quadrangle, a number of areas of hydrothermal alteration and associated veins were identified and roughly delineated. These alteration zones are shown on figure 40. The largest area of moderate to strong hydrothermal alteration is an irregular area with a diameter of 6,000 to 7,000 feet centered just south of Bald Mountain. It is hosted entirely in Proterozoic rocks and consists of a roughly 2,000-feet diameter core zone of strong quartz-sericite-pyrite (phyllic) alteration that is just south of the top of Bald Mountain and a surrounding zone of weak to moderate, more structurally controlled phyllic alteration. The core area is a zone of grassy slopes with no trees (vegetation anomaly- kill zone?) and poor rock exposure. Some outcrops of strong phyllic altered rocks occur on the upper switchback roadcuts, and strong phyllic-altered rocks with abundant pyrite occur on a prospect and caved shaft in the core zone. A representative sample from the caved shaft waste dump indicates no elevated precious or base metals and that the phyllic-altered core is essentially barren (table 5, sample 04B-450). There is a small area of concentrated float of an intensely sericite-altered, probable Tertiary porphyritic rock near the caved shaft. The surrounding structurally controlled phyllic alteration zone has numerous prospect pits with iron-oxide cemented fault breccias and quartz veins with minor pyrite. The veins are predominantly oriented northwest with steep northeast dips; northeast to north-northeast orientations also are present with both northwest and southeast dips. Some of the veins in the north, northwest, and west part of the peripheral zone contain magnetite, quartz-magnetite, and quartz-specular hematite.

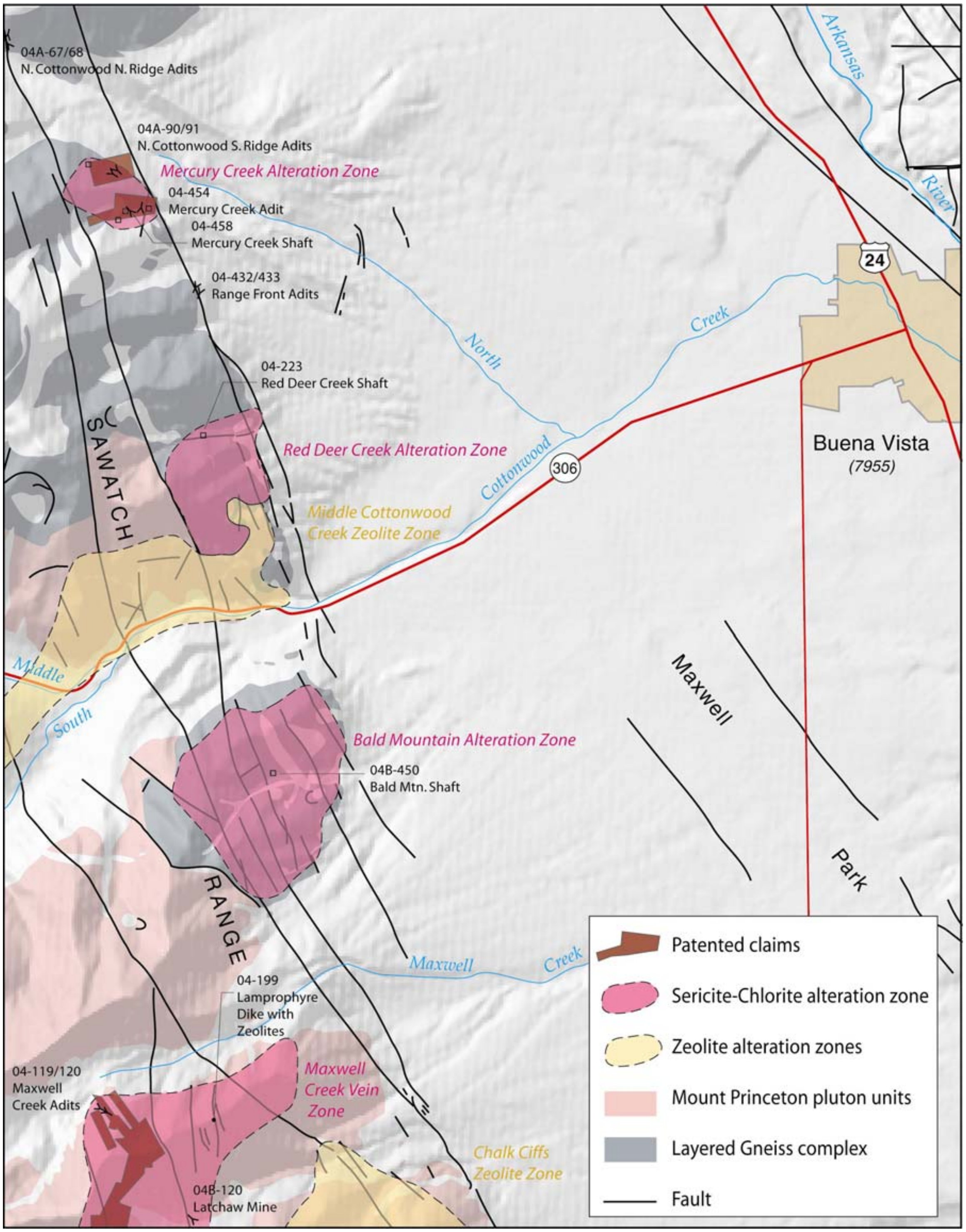

Figure 40. Alteration-mineralization zones in the Buena Vista West quadrangle.

The Bald Mountain alteration zone had unpatented mining claims on parts of it from the 1950's to the early 1980's. However, no evidence exists that any significant exploration work was conducted or that the hydrothermal system was ever drill tested. The style of alteration and mineralization in the Bald Mountain zone is similar to the alteration zone between Middle Cottonwood Creek and Red Deer Creek that is interpreted to be related to the Mount Princeton pluton. The most likely source of the Bald Mountain alteration and mineralization zone is the Mount Princeton pluton, which is interpreted to underlie this area. However, the presence of minor quartz-magnetite veins in the Mount Princeton rocks between Bald Mountain and the Maxwell Creek vein and alteration zone suggests that the zone could be related to an intrusive and hydrothermal system that post-dates the Mount Princeton pluton.

The Maxwell Creek patented claim block has a large irregular zone, about 9,000 feet long, of quartz veins and structurally controlled sericite +/- chlorite alteration (fig. 40). The veins are predominantly oriented north-northwest to northwest with southwest and some northeast dips and with minor north-south and northeast orientations. This vein zone (Maxwell Creek vein zone) contains the largest mine in the Buena Vista West quadrangle, the Latchaw Mine in Dry Creek, and two additional large mines, the Maxwell Creek adits. The vein structures are not exposed at these mines but the orientation of the Maxwell Creek adits and nearby veins exposed on the surface suggest that they have north-northwest orientations. The veins are predominantly hosted in Tmpm and Tmpk subunits of the Mount Princeton pluton. However, the Maxwell Creek adit dumps contain abundant rhyolite porphyry (Trp) dike material that is moderately to strongly sericitized and cut by minor quartz veins; the presence of this dike material suggests that the mineralization is younger than the rhyolite dikes.

The Latchaw Mine has the largest mine waste dump in the Buena Vista West quadrangle suggesting that it has the most extensive underground workings. This mine is not on the patented claim block and no indications of recent (last forty years) unpatented mining claims exist. It is therefore suspected to be related to mining activity around or before 1900. The adit is oriented N60°W and the adit mouth is still open but it is caved inside. The talus near the adit is predominantly Tmpk subunit but the waste dump has mostly Tmpm subunit. There is minor flow-layered rhyolite and a trace of lamprophyre on the dump suggesting that dikes were intersected in the workings. The vein minerals include quartz, pyrite, galena, sphalerite, and chalcopyrite. Vuggy quartz veins with sericite-chlorite alteration halos also occur. There are chlorite-matrix breccias and some mineralized breccias with fragments of galena and sphalerite. Some samples of galena ore are intensely sheared indicating post-mineral movement on the vein zone (fig. 41). A select sample of mineralized material from sorted ore piles indicates high gold (6.69 ppm), silver (154 ppm), copper (1.12 percent), lead (20.1 percent), and zinc (0.38 percent) (table 5, sample 04B-120). These are the highest gold, copper and lead values obtained from mines and prospects in the Buena Vista West quadrangle.

Figure 41. Slab of ductile sheared galena ore with mini-boudins of pyrite from the Latchaw Mine on Mount Princeton, Buena Vista West quadrangle. Sample 04B-120.

The Maxwell Creek adits have similar quartz, pyrite, galena, sphalerite, and chalcopyrite veins and vuggy quartz veins as the Latchaw Mine. Some of the quartz veins have interesting actinolite-chlorite alteration halos. A select sample of ore material from each of the Maxwell Creek adits was composited and analyzed (table 5, sample 04-119/120). The sample has low ore-grade values of gold (1.62 ppm) and silver (17 ppm) associated with copper (0.11 percent), lead (5.8 percent), and zinc (4.5 percent). Field observations and geochemical analyses indicate that the Maxwell Creek vein zone has the strongest precious- and base-metal mineralization in the Buena Vista West quadrangle. The mineralization is younger than the Mount Princeton pluton and is probably syn- or post-rhyolite porphyry (Trp) dikes. The presence of actinolite in the alteration assemblage at the Maxwell Creek adits is unusual. It suggests a relatively high- temperature hydrothermal alteration and perhaps a mafic association (lamprophyre dikes?).

Table 5. Geochemistry of mineralized samples from mines and prospects in the Buena Vista quadrangle, Chaffee County, Colorado. Analyzed by ALS-CHEMEX, Sparks, Nevada- Intermediate Level Geochemical Analyses by ICP (ME-ICP61a) with 4 acid digestion and gold by fire assay with AA finish.

SAMPLE[3]	Au	Ag	Al	As	Ba	Bi[2]	Ca	Cd	Co	Cr	Cu[2]
	ppm	ppm	%	ppm	ppm	ppm	%	ppm	ppm	ppm	ppm
04-119/120	1.615	17	1.12	<50	800	<20	6.95	700	20	20	1050
04-223	0.18	21	1.45	<50	<100	30	0.54	<10	160	90	390
04-409	<0.005	<1	2.6	<50	700	<20	0.69	<10	30	30	70
04-432/433	0.413	25	1.55	540	<100	20	0.1	<10	10	40	240
04-454	1.02	42	3.24	80	100	70	0.27	30	30	20	2190
04-458	0.289	63	3.51	50	500	1260	0.41	<10	20	50	2640
04A-67/68	0.095	112	3.17	<50	300	330	0.07	<10	10	80	170
04A-90/91	1.765	>200	1.13	100	<100	5340	0.3	270	80	10	1830
04B-120	6.69	154	1.02	<50	400	200	0.65	80	20	60	11150
04B-450	0.017	1	6.61	<50	800	<20	0.18	<10	<10	90	50

SAMPLE[3]	Fe	K	Mg	Mn	Mo	Na	Ni	Pb[2]	S	Sr	Ti
	%	%	%	ppm	ppm	%	ppm	ppm	%	ppm	%
04-119/120	1.75	0.4	0.28	2540	40	<0.05	30	58200	4	200	<0.05
04-223	13.6	0.5	0.12	230	70	0.05	70	2100	9.9	20	0.05
04-409	>30.0	0.6	0.54	1970	<10	0.49	20	400	<0.1	100	0.07
04-432/433	>30.0	0.2	0.07	1700	10	<0.05	<10	6190	0.1	<10	0.08
04-454	22.6	0.3	0.5	32400	10	<0.05	10	3300	0.8	40	0.21
04-458	9.48	1.3	0.28	1490	<10	0.36	10	380	1.8	60	0.16
04A-67/68	5.74	1.3	0.1	910	<10	0.24	20	2450	5.5	30	0.1
04A-90/91	>30.0	<0.1	0.14	14300	<10	<0.05	<10	42100	15.6	10	0.05
04B-120	6.01	0.3	0.2	330	10	0.14	10	>100000	8.8	50	<0.05
04B-450	1.84	2.5	0.12	40	30	0.21	<10	380	1.9	40	0.2

SAMPLE[3]	V	Zn[2]	Ag[1]	Pb[1]
	ppm	ppm	ppm	%
04-119/120	20	45600	-	-
04-223	30	220	-	-
04-409	20	400	-	-
04-432/433	40	2090	-	-
04-454	60	3700	-	-
04-458	30	240	-	-
04A-67/68	20	580	-	-
04A-90/91	30	67600	398	-
04B-120	10	3790	-	20.1
04B-450	50	40	-	-

[1] Note extra columns for Ag and Pb for samples that exceeded detection limits.

[2] Note some high ppm values are converted to percent values in text discussion.

[3] Sample locations are shown on the geology map.

04-119/120	Maxwell Creek adits (119- lower adit; 120- upper adit)
04-223	Red Deer Creek shaft
04-409	Mercury Creek- North ridge prospect
04-432/433	Range Front adits (432- north adit; 433- south adit)
04-454	Mercury Creek adit
04-458	Mercury Creek adit/decline
04A-67/68	North Fork Cottonwood Creek- North ridge adits (67- lower adit; 68- upper adit)
04A-90/91	North Fork Cottonwood Creek- South ridge adits (90- upper adit; 91- lower adit)
04B-120	Latchaw Mine, Dry Creek adit
04B-450	Bald Mountain shaft

The Red Deer Creek alteration zone is a roughly 6,000-feet long zone of weak to moderate sericite alteration hosted in Proterozoic rocks in the range front area between Middle Cottonwood Creek and Red Deer Creek (fig. 39). The alteration zone has minor prospect pits and minor quartz veins. Two quartz vein orientations were roughly east-west with north and south dips. The alteration and veining occur in the area between the Mount Princeton pluton and dikes of Mount Princeton border just south of Red Deer Creek. Thus, the alteration is most likely related to the Mount Princeton pluton, which probably underlies this area. One sample (table 5, sample 04-223) of quartz-hematite and quartz-pyrite veins from a caved shaft with a small to medium sized waste dump in Red Deer Creek is weakly anomalous in gold (0.18 ppm), copper (390 ppm), and zinc (220 ppm) and has low ore-grade values of silver (21 ppm) and lead (0.21 percent).

A small structurally (and stratigraphically?) controlled zone of alteration and quartz veining is associated with the Mercury Creek and North Fork Cottonwood Creek patented claim blocks (fig. 40). This alteration and mineralization zone is about 2,000 feet by 3,000 feet and is hosted in mixed Proterozoic rocks. Mineralization in the Mercury Creek patented claims includes a roughly east-west-trending zone of pyrite and chalcopyrite mineralization associated with strong chlorite alteration and minor quartz veins. The main zone of mineralization on the north side of Mercury Creek appears to be one or more "stratigraphic horizons" that are about 1 to 3 feet thick in the gneiss. Two selected samples of this pyrite-chalcopyrite-chlorite-quartz mineralization (table 5, samples 04-454 and 04-458) have anomalous to low level gold (0.29 to 1.02 ppm), silver (42 to 63 ppm), copper (0.22 to 0.26 percent), lead (380 to 3,300 ppm) and zinc (240 to 3,700 ppm). The distribution of prospect pits in the alteration zone and mineralization in the North Fork Cottonwood Creek patented claim block suggests that transverse (roughly north-south) structurally controlled mineralized structures also cross the ridge between Mercury Creek and North Fork Cottonwood Creek. A sample (table 5, sample 04-409) of quartz-magnetite-epidote veins from a prospect pit on the ridge north of Mercury Creek indicates that they are barren of precious metals and have weakly anomalous lead (400 ppm) and zinc (400 ppm).

The North Fork Cottonwood Creek patented claim block contains two adits with moderate-large waste dumps and one medium-sized caved shaft. The two adits are caved and the orientation of the mineralization could not be determined. However, the distribution of prospect pits at the caved shaft (about 1,000 feet west of the adits) suggests that some of the mineralization is parallel to the gneissic layering in the Proterozoic host rocks, and is therefore similar to ‘stratigraphically-controlled’ mineralization in the Mercury Creek patented claims. The mineralization on the North Cottonwood Creek patented claims consists of pyrite-magnetite-hematite-galena-sphalerite with abundant gossan. Selected samples of sorted ore material from the two adit waste piles were composited into one sample and analyzed (table 5, sample 04A-90/91). This sample gave the highest silver value (390 ppm) obtained from samples from mines and prospects on the Buena Vista West quadrangle. It also has anomalous to low level gold (1.77 ppm) and copper (0.18 percent) and ore grade lead (4.2 percent) and zinc (6.76 percent). The sample is also highly anomalous in Bi (0.53 percent).

Two sets of mines are perpherial to the Mercury Creek alteration-vein zone (fig. 40). Both are hosted in Proterozoic gneisses (Xb) and have similar styles of mineralization and geochemical signatures as the Mercury Creek mines and suggest that this style of mineralization and alteration is probably part of a broader area of mineralization and alteration. Two caved adits with moderate-sized waste dumps occur along the range front (Range Front adits) just south of the mouth of Deep Creek. These adits (one is partly open and the other is caved) are about 4,000 feet southeast of the Mercury Creek mines. A selected sample of sorted gossany material and minor vuggy quartz veins from each dump was composited and analyzed (table 5, sample 04-432/433). The sample contains anomalous to low level gold (0.41 ppm), copper (240 ppm), lead (0.62 percent), and zinc (0.21 percent). The second set of mines includes two adits with large waste dumps on the north side of North Fork Cottonwood Creek (North Fork Cottonwood Creek adits) about 8,000 feet northwest of the Mercury Creek mines. The mineralization includes abundant quartz-sericite-pyrite veins, some vuggy quartz veins, and trace amethystine vuggy quartz veins. Selected quartz-pyrite material from sorted piles on both adit waste dumps was composited and analyzed (table 5, sample 04A-67/68). The sample contains significant silver (112 ppm) and anomalous lead (2,450 ppm) and zinc (580 ppm).

The Mercury Creek alteration and mineralization zone and surrounding peripheral mines and prospects have suggestions of both ‘stratigraphically controlled’ and structurally controlled mineralization. The structurally controlled mineralization has a distinct epithermal character suggested by open-space, typically vuggy quartz veins with associated base-metal and precious-metal (silver-biased) mineralization. It is likely that the structurally controlled vein zones are genetically related to, and may have ‘fed’, the mineralized stratigraphic horizons. The mineralization is probably related to Tertiary magmatism.

Two additional alteration zones are shown for the Buena Vista West quadrangle (fig. 40). They consist of structurally controlled zeolite-clay alteration zones that are hosted in the Mount Princeton pluton. The presence of zeolites is based on a similar appearance to zeolite alteration in the Chalk Cliffs and Cottonwood Cliffs studied by previous workers (Sharp, 1970 and Olson and Dellechaie, 1976) but has not been confirmed with petrographic observations or X-Ray diffraction analyses for this study. Sharp (1970) described two separate zones of zeolite (leonhardite) alteration, each associated with active hot springs at Chalk Cliffs (Mount Antero quadrangle) and at Middle Cottonwood Creek. In contrast, Olson and Dellechaie (1976) interpreted a continuous zone of zeolite alteration that extends from Raspberry Hill (Mount Antero quadrangle) to Middle Cottonwood Creek.

A connection between the Chalk Cliffs and Middle Cottonwood Creek zeolite zones could not be confirmed in this study because of inadequate fault exposures between the two areas. The southern zone of zeolite alteration is associated with rift-related faults exposed in a window through the gravels in lower Dry Creek. This zone is interpreted to be the northern extension of the Chalk Cliffs/Mount Princeton Hot Springs zeolite zone and suggests that zeolitic alteration extends at least 11,000 feet to the north-northwest of the Chalk Cliffs area (similar interpretation as Sharp, 1970). The occurrence of zeolites (optical properties suggest laumontite partly dehydrated to leonardite) in a spessartite lamprophyre dike approximately 16,000 feet northwest of the Chalk Cliffs is interesting and extends the zeolite occurrences even further north and northwest. The zeolites are preferentially developed as a replacement of altered olivine phenocrysts and locally the groundmass plagioclase. Consequently, this occurrence is different than the zeolite coatings and fracture fillings described at Chalk Cliffs and Cottonwood Cliffs (Sharp, 1970 and Olson and Dellechaie, 1976), and may suggest a genetic relationship between some of the zeolites and the lamprophyre magmatism.

The northern zeolite zone is also similar to Sharp's (1970) interpretation and is interpreted to be a 15,000-foot long, northeast-trending zone that extends from the south part of Sheep Mountain in the Mount Yale quadrangle to the range-front area on the north side of North Fork Cottonwood Creek. Zeolite-like alteration was also noted along rift-related faults cutting the Mount Princeton border about 4,000 feet north-northeast of Cottonwood Hot Springs.

GEOTHERMAL ACTIVITY

Geothermal activity in the Buena Vista West quadrangle is manifested by hot springs at the mouth of Cottonwood Creek. Cottonwood Hot Springs is a commercial resort fed by springs with a temperature of 119°F (48°C) and a flow of about 10 gpm (38 L/min) (http://geoheat.oit.edu/directuse/all/dus0049.htm). Temperature of the soaking pools ranges from 94-110˚ F. The water is dominated by dissolved sodium (105 mg/l) and sulfate (110 mg/l), with lesser amounts of silica (57 mg/l) and chloride (30 mg/l). (http://www.cottonwood-hot-springs.com/water.htm).

Sharp (1970) proposed that the thermal springs at Browns Canyon (Nathrop quadrangle) and the hot springs at Chalk Creek (Mount Antero quadrangle) and Cottonwood Creek are controlled by a northwest-trending fault zone that obliquely crosses the rift. The reported temperature of Cottonwood Hot Springs in 1970 was 126° F and the temperature of the Mount Princeton Hot Springs (Chalk Creek) was 183° F (Sharp, 1970).

AMAX Exploration drilled eight geothermal exploration wells in 1979, 240 to 440 feet in depth, west and southwest of Nathrop. Well reports show that all 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. P. Smith, personal communication, 2004).

WATER RESOURCES

Water resources on the Bunea Vista West quadrangle include surface and subsurface ground water.

SURFACE WATER

The largest stream in the quadrangle is the Arkansas River, which flows through the extreme northeast corner of the quadrangle. It is the major, axial drainage of the upper Arkansas Valley 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 feet), 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. Additional flow data were compiled by Crouch and others (1984).

The largest tributary to the Arkansas River is Cottonwood Creek, which flows out of the Sawatch Range and crosses the quadrangle from west to east. In the period 1911-1985 the annual mean streamflow at the gage near Cottonwood Hot Springs (at the range front) 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.

The North Fork of Cottonwood Creek is the second largest tributary in the quadrangle, but it is not gaged. Numerous ditches carry water from the mouth of Cottonwood Creek eastward across the broad valley floor. On the south side these include (from west to east) the Cottonwood Maxwell Ditch, the Wolf and Neerland Ditch, the Arkansas Valley Canal, and the Johnson Ditch. On the north side, the Michigan Ditch extends eastward and also collects water from Deer Creek. Ditches emanate from the mouth of the North Fork of Cottonwood Creek, with the Silver Creek and Mary Bray Ditches on the south side and the McKenna Ditch on the north side.

There are numerous springs in the quadrangle and most are located along mapped faults. The largest spring is Cottonwood Hot Springs, a commercial hot spring on the north bank of Cottonwood Creek 0.5 miles upstream from the range front. The spring is located on a major, north-trending, rift-related fault that parallels the range front. Another group of springs occurs on the eastern margin of the quadrangle, where lower Maxwell and Thompson Creeks intersect a zone of north-northwest trending, down-to-the-west faults.

GROUND WATER

Ground water is an important resource in the Buena Vista West quadrangle, as indicated by the 845 registered water wells recorded by the Colorado Division of Water Resources. The wells are concentrated in the northeastern quarter of the quadrangle, with the highest concentration west of the town of Buena Vista on the distal parts of the Cottonwood Creek and North Fork Cottonwood Creek outwash fans. Most of the wells are shallow (512 are less than 100 feet deep), but 87 are deeper than 200 feet and the deepest well is 560 feet deep. 680 of the wells (80%) have a static water level less than 100 ft below the surface and 483 of the wells (57%) have a static water level of 50 feet below the surface, or less. The wells in the Arkansas Valley generally have yields of 10-15 gpm (gallons per minute), but 134 (16%) have yields less than 10 gpm and 115 (15%) have yields of 20 gpm or greater. On the basis of their depth and yield, and by reference to the resistivity cross section described previously, we infer that most wells produce water from coarse-grained, well-sorted, permeable outwash gravels of Pinedale to pre-Bull Lake age.

The resistivity cross-section (fig. 38) indicates that resistivity decreases with depth beneath the valley and suggests (as do surface outcrops) that the Dry Union Formation is generally much finer grained and probably less permeable than the Quaternary outwash gravels. Given this trend, it is unlikely that future deep drilling for water will result in consistently high-yield wells. However, it is possible that the two sub-grabens, particularly the deeper western one, may contain high-permeability paleochannel deposits from Tertiary or early Quaternary streams that flowed down the axis of the sub-grabens. Such paleochannel deposits would be prime targets for future geophysical surveys and drilling studies of this area.

Scattered wells exist in the Sawatch Range along Cottonwood Creek and produce water from bedrock (Mount Princeton pluton) or from Pinedale till overlying bedrock. Due to the disconnected nature of the fractures, depth to static water varies considerably over short distances. For example, wells in Cottonwood Creek have static levels of 8-76 feet, whereas static levels beneath the crests of Pinedale moraines are as deep as 194 feet. Yields from these wells are likewise rather low and erratic, averaging 3-10 gpm but being as high as 15 gpm in the coarser alluvial deposits.

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