OPEN-FILE REPORT 07-03

Geologic Map of the Signal Peak Quadrangle, Gunnison County, Colorado

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State of Colorado

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Department of Natural Resources

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by
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Colorado Geological Survey
Department of Natural Resources
Denver, Colorado
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Description of Map Units, Structural Geology, Mineral Resources, Water Resources, and Geologic Hazards

by

Allen Stork[1], James C. Coogan[1], Robert Fillmore[1], Holly Brunkal[1],
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Front piece - View of Signal Peak from the south with Tomichi Creek in the foreground. The cliff forming outcrops above U.S. Highway 50 in the middle distance are Dakota Sandstone and Burro Canyon Formation overlying Morison Formation. On the skyline Signal Peak is mostly Fish Canyon Tuff overlain by Carpenter Ridge Tuff.

This mapping project was funded jointly by the Colorado Geological Survey and the U.S. Geological Survey through the National Geologic Mapping Program under STATEMAP Agreement No. 06HQAG0045.

FOREWORD

The purpose of Colorado Geological Survey Open File Report 07-03, *Geologic Map of the Signal Peak Quadrangle, Gunnison County, Colorado* is to describe the geologic setting, mineral and water resources, and geologic hazards of this 7.5-minute quadrangle located in western Colorado. Field work for this project was conducted during the summer of 2006 by consulting geologists Allen Stork, James C. Coogan, Robert Fillmore and Holly Brunkal, and field assistants Joe Nicolette and Andrew Payton.

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, Agreement No. 06HQAG0045, and the Colorado Geological Survey (CGS) 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

LOCATION

The Signal Peak 7.5' quadrangle is located east of the town of Gunnison in central Gunnison County, Colorado. The quadrangle contains portions of both the US Highway 50 and Colorado Highway 114. The main drainages include Tomichi, Cochetopa and Cabin Creeks. The quadrangle lies on the southeastern margin of the Piceance Basin between the Sawatch and Gunnison uplifts and also lies north and east of the volcanic centers in the West Elk and San Juan Mountains (fig. 1).

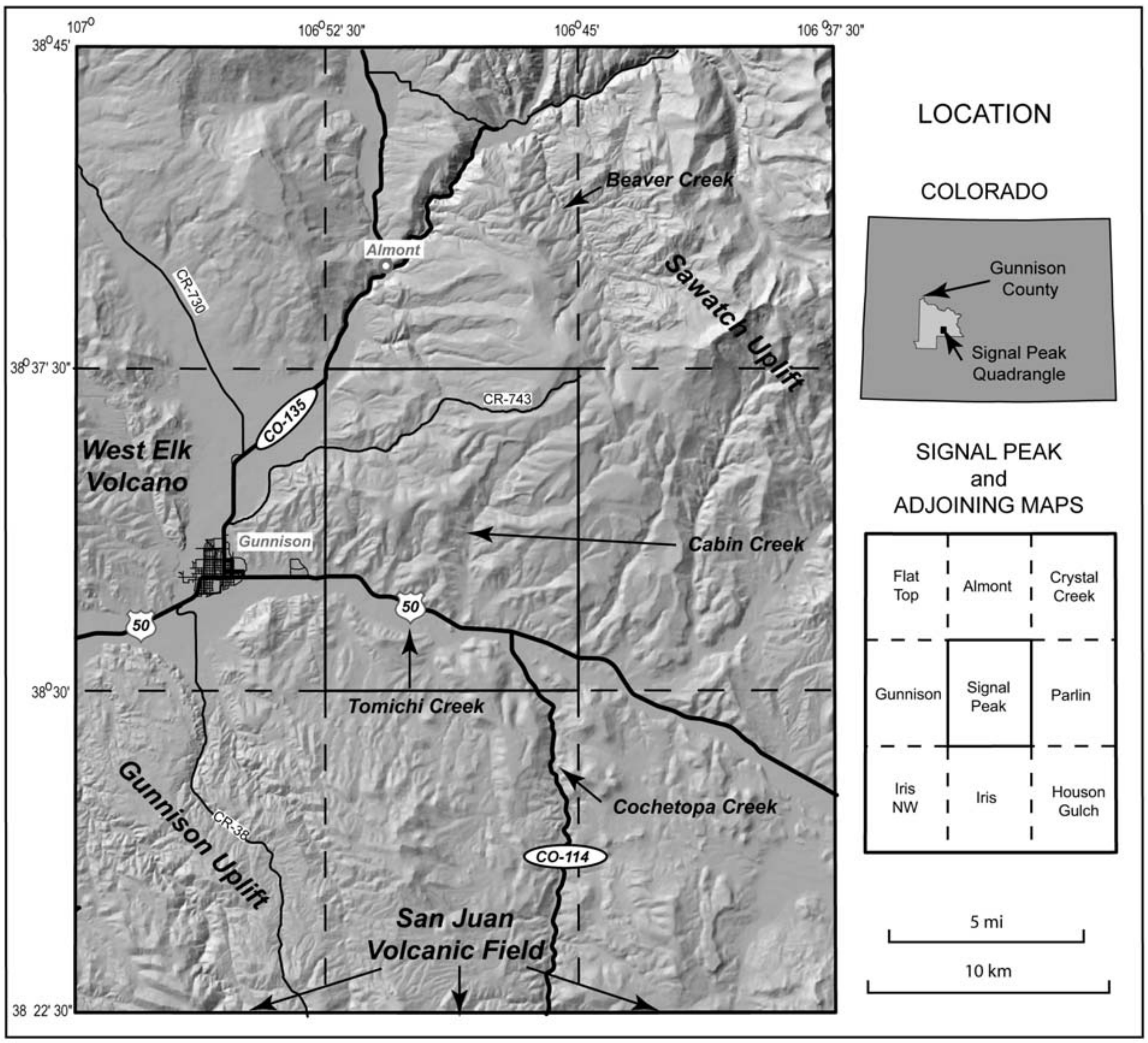

Figure 1. Shaded relief map showing the Signal Peak quadrangle and surrounding area.

Previous geologic work in the Signal Peak 7.5' quadrangle includes unpublished field studies by the Western State College Geology Department and regional-scale mapping by Tweto and others (1976) and Ellis and others (1987). The adjacent Houston Gulch (Olson 1976a), Iris NW (Hedlund and Olson, 1974), Iris (Olson, 1976b), Almont (Coogan and others, 2005) and Gunnison (Stork and others, 2006) quadrangles have been mapped at a scale of 1:24,000. The adjacent Crystal Creek and portions of adjacent Parlin quadrangles (Dewitt and others, 2002) have been mapped at a scale of 1:30,000.

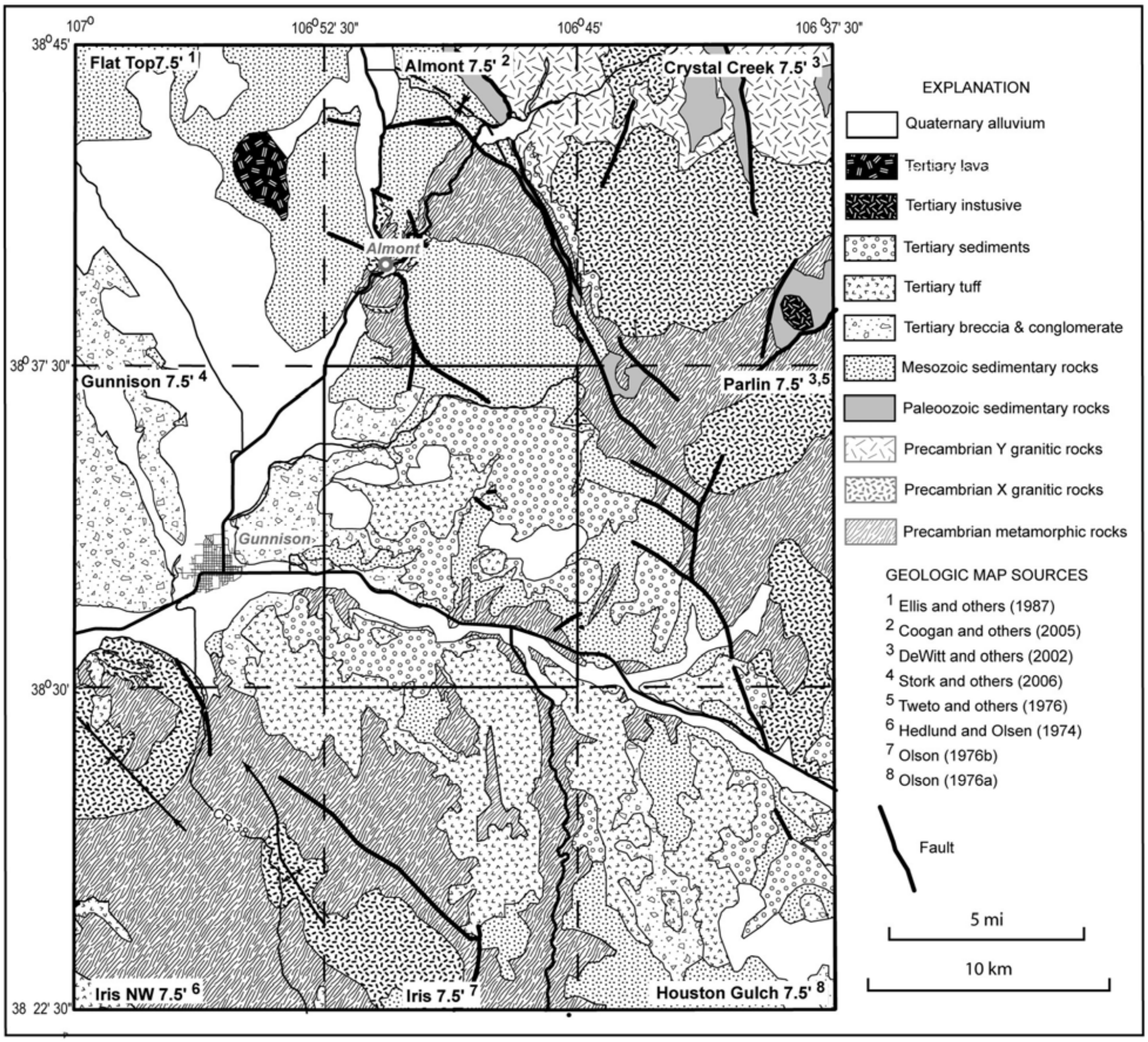

Figure 2. Generalized bedrock geologic map for the area surrounding the Signal Peak quadrangle. Modified from Tweto (1979) with data from DeWitt and others (2002), Coogan and others (2005) and Stork and others (2006).

GENERAL GEOLOGY

The oldest rocks in the Signal Peak quadrangle are Precambrian metamorphic and igneous rocks exposed at lower elevations (geologic time divisions used in this report are shown in figure 2). Paleoproterozoic metamorphic rocks include biotite quartzite, biotite-quartz schist and amphibolite. The only exposed Paleoproterozoic igneous rocks are foliated granites exposed in the far northwest corner of the quadrangle.

Paleozoic rocks are absent as the result of Ancestral Rockies uplift of the area during the Middle Pennsylvanian through Permian.

Mesozoic sedimentary rocks directly overlie Precambrian rocks in the quadrangle. From oldest to youngest, these include the Upper Jurassic Junction Creek Sandstone, the Upper Jurassic Salt Wash and Brushy Basin Members of the Morrison Formation, the Lower Cretaceous Burro Canyon Formation, the Upper Cretaceous Dakota Sandstone, and the Upper Cretaceous Mancos Shale. Uppermost Cretaceous and lowermost Tertiary rocks were eroded and/or never deposited because of uplift of the Gunnison area during the Laramide Orogeny.

Oligocene volcanic and sedimentary deposits unconformably overlie Precambrian metamorphic and igneous rocks and Mesozoic sedimentary rocks throughout the quadrangle. The Oligocene volcanic sequence includes from oldest to youngest: the debris flows of the West Elk Breccia and bedded tuff of East

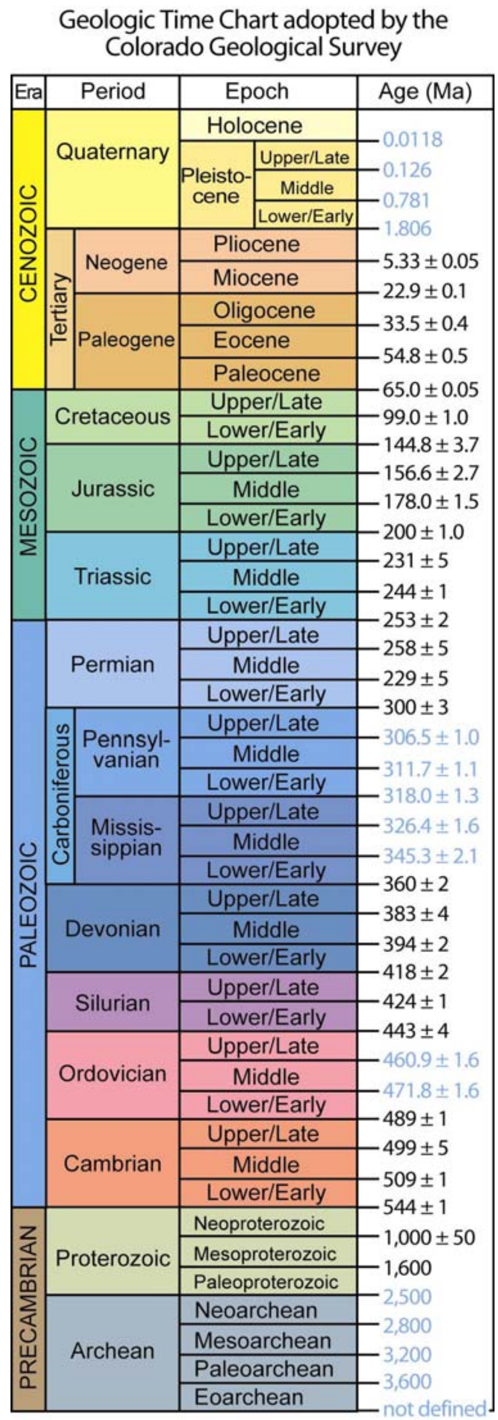

Figure 3. Geologic time chart used for this report. Numerical ages shown in black are from the Geological Survey of Canada (Okulitch, 2002); ages shown in blue are from the International Commission on Stratigraphy, (2005).

Elk Creek erupted from the West Elk volcanic center; the Blue Mesa and Sapinero Mesa Tuffs erupted from western San Juan centers; and the Fish Canyon and Carpenter Ridge Tuffs erupted from central San Juan centers. Thick gravel deposits intertongue with all of the Oligocene volcanic units. These gravel deposits come from two sources: a highland to the northeast and a highland to the south, both uplifted during Laramide time.

Surficial deposits include mass-wasting, alluvial, and human-made deposits.

SCOPE OF WORK

The present study focuses on geologic mapping of the Signal Peak 7.5-minute quadrangle. Field work was undertaken during the summer and fall of 2006. Geology was mapped on the USGS Signal Peak Digital Orthophoto quadrangle (1:12000- scale) and supplemented in the field and laboratory with U.S. Forest Service color aerial photographs (1:24,000-scale) taken in September and October 1997. Map unit contacts were compiled on the Signal Peak Digital Orthophoto quadrangle using ArcGIS. The map is printed on the Signal Peak 7.5 minute topographic map. The cultural features of the topographic base map were last revised in 1979. Thus, roads, quarries, and buildings constructed after 1979 are not on the map base. Igneous rock names are based on IUGS standards (LeMaitre, 1989).

The major issues affecting map quality include the generally poor exposure of fine-grained sedimentary rocks (Morrison Formation and Mancos Shale) and unconsolidated volcanic ash (Tuff of East Elk Creek and portions of the Sapinero Mesa and the Fish Canyon Tuffs), which are commonly completely covered by a colluvium. Also, areas topographically lower than the unconsolidated Tertiary gravel and the welded Carpenter Ridge Tuff are commonly covered by a thin veneer of colluvial debris from these units that makes mapping the bedrock difficult.

ACKNOWLEDGMENTS

Field and office discussions with Bruce Bartleson and Don Graham helped to improve the map. Our field assistants Joe Nicolette and Andrew Payton had major responsibility for sections of the map and greatly improved the quality of our mapping. Special thanks are extended to Peter Lipman (USGS, Emeritus) and Bruce Bartleson (Western State College of Colorado, Emeritus) who provided thorough reviews of the report. Jane Ciener (USGS) acted as our technical editor.

DESCRIPTION OF MAP UNITS

SURFICIAL DEPOSITS

HUMAN-MADE DEPOSITS

af **Artificial fill and disturbed surfaces (latest Holocene)** -- Unsorted sand, silt, gravel, or rock fragments, that may contain construction material deposited as spoils from quarrying operations, road construction, and as landfill. This unit contains the disposal cell for the Gunnison Uranium Mills Tailings Remedial Action (UMTRA) project (UMTRA, 1992)

ALLUVIAL DEPOSITS

Qa **Stream and flood-plain alluvium (Holocene)** -- Sand, silt, clay, and gravel in channels and flood plains; composition depends on source area; maximum thickness unknown. Five kilometers to the west in the adjacent Gunnison quadrangle Qa is up to 40 m (130 ft) thick (UMTRA, 1992).

Qt_1 **Stream terrace alluvium (upper Pleistocene)** -- Sand, silt, clay, and gravel in terraces above flood plains. In the northwest, this terrace is 6 m (20 ft) above the flood plain and correlates with the **Qt_1** terrace mapped in the adjacent Almont and Gunnison quadrangles (Coogan and others, 2005; Stork and others 2006). Two charcoal samples from the Wilson Pit gravel quarry (Almont quadrangle, Section 4 T. 50 N., R. 1 E.) have yielded C^{14} ages of 47.7 ± 1.2 Ka and 49.1 ± 1.5 Ka (unpublished data) for sediments preserved in the **Qt_1** terrace. The original depth of the samples is uncertain because of the quarrying operation; however, the first sample was from the base of the reddish B horizon (?) 10 cm below the disturbed surface. The second sample was taken 15 m west of the first sample, 1.5 m below the base of the B horizon.

Qt **Stream terrace alluvium (upper Pleistocene?)** -- Sand, silt, clay, and gravel in terraces above alluvium on side tributaries; terrace 0-3 m (0-10 ft).

Qf **Alluvial-fan deposits (Holocene to upper Pleistocene)** -- Mostly poorly stratified and poorly sorted sand, silt, and gravel deposited mainly by a combination of debris flow and alluvial processes at the mouths of drainages; generally less than 12 m (40 ft) thick.

Qdf **Debris-fan deposits (Holocene and upper Pleistocene)** -- Mostly poorly stratified and poorly sorted sand and gravel that is commonly angular; deposited mainly by rockfall and sheetwash at the base of steep slopes; generally less than 12 m (40 ft) thick.

MASS-WASTING DEPOSITS

Qc **Colluvium (Holocene and upper Pleistocene) --** Poorly stratified sand, silt, and gravel that caps hilltops and gentle to moderate slopes; deposited by a variety of processes, including slopewash and soil creep; composition depends on local bedrock; generally less than 6 m (20 ft) thick.

Qce **Eolian colluvium (Holocene) --** Poorly stratified sand and silt that accumulated in drainages on the lee side of ridges; initially deposited by eolian processes and modified by variety of processes, including slopewash and soil creep, with minor fluvial reworking; 0 to 6 m (0 to 20 ft) thick.

Qls **Mass-movement deposits, undivided (Holocene and upper Pleistocene)** -- Includes slides, slumps, and flows, as well as colluvium and talus mapped on and adjacent to steep slopes where several mass-movement processes contribute to the deposit; composition varies from poorly sorted clay to boulder-sized material depending on local source terrain; generally characterized by hummocky topography, head and internal scarps, and chaotic bedding in displaced bedrock; morphology is subdued with age; thicknesses are variable from 0 to 12 m (0 to 40 ft) thick.

Qlso **Mass-movement deposits (Pleistocene?)**—Older slides, slumps, and flows whose surface has been reworked by fluvial and eolian process but still exhibit hummocky internal morphology; commonly originate in clay-rich bedrock of the Cretaceous Mancos

Shale and Jurassic Brushy Basin Member of the Morrison Formation; these deposits have been cut into by the Holocene flood plain; up to 20 m (65 ft) thick.

Qef **Earthflow deposits (Holocene? to Pleistocene?) –** Large-scale earthflows exhibiting internal flow or hummocky morphology; originate in clay-rich bedrock of the Cretaceous Mancos Shale and downslope from unconsolidated Quaternary deposits; up to 6 m (20 ft) thick.

ALLUVIAL AND MASS-WASTING DEPOSITS

Qac **Alluvium and colluvium (Holocene and upper Pleistocene)** -- Includes stream and fan alluvium and colluvium; Holocene deposits are not incised and are graded to modern flood plains, whereas upper Pleistocene deposits are incised and are graded to upper Pleistocene alluvial fans and terraces; generally less than 6 m (20 ft) thick.

TERTIARY SEDIMENTS AND VOLCANIC DEPOSITS

Tgb **Gravel and breccia deposits (Pliocene? to Oligocene) --** This unit is composed of sub-angular to sub-rounded unconsolidated gravel and breccia. Deposits contain sediment from sand to boulder (up to 15 cm) size. Boulders and cobbles include Tertiary volcanics, Precambrian tonalite and granodiorite, and metamorphic rocks such as amphibolite, biotite quarzite, and biotite-quartz gneiss. The clasts are consistent with a provenance in the Gunnison Gold Belt to the south. These deposits occupy paleo-channels or paleo-alluvial fans that are interbedded with both Tg and Tf along the southern edge of the quadrangle. Gravels not capped by Oligocene tuffs may be younger (Miocene to Pliocene) if deposited in channels that were later eroded though the tuffs. The deposits are 0-18m (0-60 ft) thick.

Tg **Gravel deposits (Pliocene? to Oligocene) –** This unit is composed of sub-rounded to rounded unconsolidated river gravel. Gravel deposits contain sediment from sand to boulder (up to 150 cm) size. Boulders and cobbles include Precambrian granites and metamorphic rocks, Paleozoic and Mesozoic sandstones, and Tertiary volcanics. Extensive gravel deposits continue to the south and east (Olson, 1976a, b). The clasts are consistent with a provenance to the north and east and were deposited in Oligocene drainages that had headwaters near the current Continental Divide (Gregory and Chase, 1994). These gravels mark locations of paleo-Tomichi Creek as it was disrupted by Oligocene volcanism and large alluvial fans from a highland to the northeast. These gravels overlie the West Elk Breccia and are interbedded with the tuffs of East Elk Creek, the Blue Mesa Tuff, Sapinero Mesa Tuff, Fish Canyon Tuff, and Carpenter Ridge Tuff. Gravels not capped by Oligocene tuffs may be younger (Miocene to Pliocene). The deposits are 0-75 m (0-250 ft) thick south of Tomichi Creek and thicken to the northeast where more than 120 m (400 ft) of gravel is preserved.

Tc Carpenter Ridge Tuff (Oligocene) **–** The Carpenter Ridge Tuff is a non-welded gray to densely welded red-brown rhyolitic ash flow tuff containing 2-5% phenocrysts of plagioclase, sanidine, and biotite. The partly welded tuff has conspicuous pumice fragments (up to 4 cm). The age of this tuff is estimated as 27.55 Ma based on the current Ar/Ar calibration that dates the Fish Canyon Tuff at 28.02 Ma (McIntosh and Lipman, personal communication 2006). The Carpenter Ridge Tuff has a maximum preserved thickness of 60 m (200 ft).

Tf Fish Canyon Tuff (Oligocene) **–** The Fish Canyon Tuff is a light-gray non-welded to dark-gray-brown densely welded dacitic ash flow tuff. The tuff contains 35-40% phenocrysts of plagioclase, sanidine, biotite and hornblende, with lesser amounts of quartz and titanite. The age of this tuff is 28.02 Ma based on the current Ar/Ar calibration (McIntosh and Lipman, personal communication 2006). The Fish Canyon Tuff has a maximum preserved thickness of 150 m (480 ft).

Ts **Sapinero Mesa Tuff (Oligocene) –** The Sapinero Mesa Tuff is a gray or pink non-welded to partially welded rhyolitic ash flow tuff containing 2-5% phenocrysts of plagioclase, sanidine, and biotite. In the scattered outcrops, welding decreases from west to east with dark-gray to pink partially welded tuff in the south and pink non-welded tuff to the north and east. The partially welded tuffs can have conspicuous 1-2 cm light-gray pumice fragments. Bove and others (2001) report an average sanidine Ar/Ar age of 28.19 ± .06 Ma. The Sapinero Mesa Tuff has a maximum preserved thickness of 60 m (200 ft).

Tb **Blue Mesa Tuff (Oligocene) –** The Blue Mesa Tuff is a red-brown densely welded rhyolitic ash flow tuff containing <5% phenocrysts of plagioclase, sanidine, and rare biotite. This unit is only found in the southwest corner of the map area in discontinuous outcrops interbedded with gravels. Bove and others (2001) report a sanidine Ar/Ar age of 28.40 ± .07 Ma. The Blue Mesa Tuff has a maximum preserved thickness of 6 m (20 ft).

Te **Bedded tuff of East Elk Creek (Oligocene)** -- This unit contains interbedded tuff, tuffaceous sandstone, and siltstone. The unit is white to light-green-brown. Individual ash beds contain abundant white angular pumice lapilli (up to 5 mm), and smaller pumice fragments are common in the tuffaceous sandstones. This unit is typically covered by colluvium from stratigraphically higher gravels and welded tuffs in the Signal Peak quadrangle. However, the unit is well exposed in several prominent white cliffs up to 40 m (130 ft) high on the north side of Blue Mesa Reservoir, where the unit was mapped as a tuffaceous conglomeratic facies of the West Elk Breccia by Hedlund and Olson (1973). The unit is younger than a biotite-bearing pumice clast dated by biotite Ar/Ar at 30.7 ± .4 Ma (Stork and Panter, unpublished data). This unit is 0-6 m (0-20 ft) thick.

Tw **West Elk Breccia (Oligocene) –** The West Elk Breccia is predominantly a brownish-gray volcanic breccia and tuff breccia with minor interbedded tuff, tuffaceous sandstones and conglomerate. Breccia beds are poorly sorted, matrix supported, coarsely stratified, and probably were emplaced as volcanic mud and debris flows. Clasts in the breccia include andesite, dacite, and rhyolite up to 2 m in diameter. Reworked clasts of older West Elk Breccia are up to 4 m in diameter. Some breccias have clasts of Precambrian granite and metamorphic rocks and Paleozoic and Mesozoic sedimentary rocks in an ashy matrix, which were derived from paleo-Gunnison and Tomichi stream gravels. Basal breccias exposed near the vent and a late cross cutting dike from West Elk Volcano have been dated to 30.5 ± .8 Ma by Coven and others (1999). This unit thickens markedly across the quadrangle from zero where it pinches out in the near Cabin Creek to at least 100 m (320 ft) on the western edge of the quadrangle. Gaskill and others (1981) report a maximum thickness for the volcaniclastic facies of the West Elk Breccia of approximately 550 m (1800 ft) to the northwest.

Twg **Gravel of the West Elk Breccia (Oligocene) –** This unit is composed of well-rounded, unconsolidated river gravel that forms discontinuous lenses within the West Elk Breccia. Gravel deposits contain clasts from sand to boulder (up to 1.5 m) size. Boulders include Precambrian granites and metamorphic rocks, Paleozoic and Mesozoic sandstones, and Tertiary volcanics. Individual lenses of gravel are up to 15 m (50 ft) thick.

MESOZOIC SEDIMENTARY ROCKS

Km **Mancos Shale (Upper Cretaceous) –** Mancos Shale exposures in the Signal Peak quadrangle consist of dark-gray to gray fissile shale and mudrock with rare, thin, tan sandstone and calcareous sandstone. The Mancos Shale underlies extensive areas of surficial Quaternary mass-movement and alluvial deposits in the northern half of the quadrangle. The widely separated distribution of small Mancos Shale outcrops in the Signal Peak quadrangle precludes mapping of the individual members of the formation that were identified by Coogan and others (2005) in the Almont 7.5' quadrangle to the north (figure 1).

Kd **Dakota Sandstone (Upper Cretaceous) --** The Dakota Sandstone is dominated by yellow-brown to gray sandstone with interbedded conglomerate and mudstone. Sandstone is quartz arenite with a minor component of chert grains. Chert and quartz pebble conglomerate marks the base, but conglomerate locally is absent where there are no scours. Three distinct parts are recognized in the map area. The lower third consists of resistant interbedded fine- to coarse-grained sandstone and pebble conglomerate that fills channel scours up to 3 m (10 ft) deep into underlying strata. This part is dominated by trough and low-angle cross-stratification with minor horizontal stratification. The middle part of the Dakota consists of a recessive zone of thinly bedded, brown and gray, carbonaceous, laminated, fine- to medium-grained sandstone, siltstone, and thin, silty coal horizons. Black carbonaceous clots and plant-stem impressions are abundant. The upper third of the Dakota consists of a resistant yellow-brown to gray sandstone that is overlain by medium-bedded bioturbated siltstone and interbedded gray to black silty shale. The Dakota Sandstone records a marine transgression. The basal third was deposited in braided streams. The middle part represents a swampy shoreline environment and the uppermost Dakota was deposited in a sandy, tide-influenced shallow marine environment. The most complete exposure of the Dakota Sandstone lies on the east edge of the map area, where it reaches a maximum thickness of 37 m (120 ft). The Dakota is 20 m (65 ft) thick in the Gunnison River Canyon immediately northwest of the map area (Coogan and others, 2005). Thickness of the Dakota varies with the depth of basal scours into underlying strata, and most variations are attributed to the lower fluvial part of the formation. The Dakota has a sharp unconformable contact on the Lower Cretaceous Burro Canyon Formation. The upper contact with the overlying Upper Cretaceous Mancos Shale is gradational and records a continued sea level rise into a deep marine environment.

Kbc **Burro Canyon Formation (Lower Cretaceous) –** The Burro Canyon Formation consists of basal cliff-forming sandstone and conglomeratic sandstone that are interbedded with thin intervals of slope-forming varicolored claystone and mudstone in the upper part of the formation. The basal conglomeratic sandstone ranges from 0 to 12 m (0 - 40 ft) thick and consists of crossbedded chert pebble conglomerate that grades upwards into coarse- to fine-grained sandstone. The maximum thickness of the Burro Canyon Formation is 24 m (80 ft), however the thickness varies greatly because the Burro Canyon Formation scours deeply into the underlying Brushy Basin Member of the Morrison Formation. The formation is unconformably overlain by the Upper Cretaceous Dakota Sandstone.

Morrison Formation (Upper Jurassic)

Jmb **Brushy Basin Member –**The Brushy Basin Member is a heterogeneous assemblage of lithologies and consists of irregular alternations of green siliceous claystone, red silty shale, gray limestone, and sparse lenses of sandstone and conglomeratic sandstone. Beds of all lithologies are less than 1.5 m (5 ft) thick. Green claystone is the dominant rock type and mostly is structureless, although laminations are locally evident. Laminated red silty shale increases in abundance toward the base of the member. Gray limestone is micritic and contains evidence of plant rootlets. Clasts in conglomeratic sandstone lenses are composed predominantly of intraclasts of limestone, green claystone, and red shale. The Brushy Basin Member is the product of a broad low-relief fluvial flood plain. Claystone and shale are flood-plain deposits. Lenticular sandstone and conglomerate bodies were deposited in the low energy river channels that cut across the flood plain. Limestone was deposited in shallow ponds that formed in depressions on the plain, between the river channels. Fossil dinosaur bones of an *Apatosaurus sp.* were recovered from the Brushy Basin Member in Cabin Creek (Bartleson and Jensen, 1988). North of U.S. Highway 50 where the base of the unit is not exposed, the maximum exposed thickness of the Brushy Basin Member is ~ 50 m (170 ft) near the east edge of the Gunnison quadrangle. The Brushy Basin Member reaches up to 70 m (230 ft) thick in the Almont quadrangle to the northeast (Coogan and others, 2005), but this thickness may include up to 19 m (63 ft) of the overlying Burro Canyon Formation, which is largely indistinguishable from the Brushy Basin in that area. The Brushy Basin forms sagebrush-covered slopes and mostly is concealed beneath a thick mantle of colluvium. Where it cannot be recognized by stratigraphic position, it typically is identified by chips of green and red shale in small drainages and gullies. Its recognition is further complicated by its tendency to collapse into landslides, slumps, and debris flows. The Brushy Basin Member conformably overlies the Salt Wash Member of the Morrison Formation in the northern part of the Signal Peak quadrangle and in the Almont quadrangle to the northwest (Coogan and others, 2005). However, the Salt Wash Member is absent over most of the map area and the Brushy Basin Member rests conformably on the Jurassic Junction Creek Sandstone. Locally the Junction Creek is absent and the Brushy Basin lies nonconformably on Precambrian metamorphic rock.

Jms **Salt Wash Member** -- The Salt Wash Member consists of tan fine- to medium-grained sandstone that is confined to thin exposures forming a bench and thin caprock above the Junction Creek Sandstone in the north-central part of the quadrangle. The Salt Wash Member has a maximum thickness of 3 m (10 ft) at the northern edge of the map area and is absent to the south and east. The basal contact with the Junction Creek is locally sharp with low relief scours. Intertonguing relations between the Junction Creek and the Morrison west of Gunnison suggest this contact is conformable.

Jj **Junction Creek Sandstone (Upper Jurassic) --** The Junction Creek Sandstone consists of well-sorted, fine- to medium-grained, yellow-white quartz sandstone. It is mostly crossbedded on a large scale with single sets up to 5 m (15 ft) thick. The formation was deposited in an eolian dune and sand sheet setting. To the northwest in the Almont quadrangle, and to the west, the basal 3 to 5 m (10 - 16 ft) of the formation consists of medium-grained horizontal and wavy-bedded sandstone with abundant quartz granules and pebbles; symmetrical ripples of aqueous origin occur rarely on bedding surfaces (Coogan and others, 2005). These basal strata were deposited in a marginal shallow marine setting. This facies is absent in the Signal Peak quadrangle. The formation nonconformably overlies a long-lived erosion surface of Precambrian igneous and metamorphic rocks. In the southeast part of the Signal Peak quadrangle the Junction Creek Sandstone has a maximum exposed thickness of 25 m (80 ft) and a complete thickness of 27 to 38 m (90 - 125 ft) in the Almont quadrangle to the northwest (Coogan and others, 2005). The Junction Creek Sandstone is correlative with the Bluff Sandstone in southeast Utah on the basis of intertonguing of both of these units with the lower Morrison Formation (O'Sullivan, 1980, 1998; Coogan and others, 2005).

PROTEROZOIC IGNEOUS AND METAMORPHIC ROCKS

Xg **Gneissic granite (Paleoproterozoic?) --** This unit is a pink medium-grained muscovite granite. The rock consists of 20% plagioclase (~An_{30}), 50 % microcline perthite, 25% quartz, 3% muscovite and 2% magnetite. Accessory minerals include biotite, zircon, and apatite. This granite contains a foliation parallel to the surrounding metamorphic rocks and is therefore tentatively assigned a Paleoproterozoic age.

Xq **Biotite quartzite (Paleoproterozoic)** -- This unit is a light- to dark-gray muscovite-biotite quartzite. Quartzite may be massive to well foliated, is very fine-grained, and is commonly finely laminated with dark biotite bands visible in hand specimen. Granoblastic quartz (65-80%) and feldspar (1-2%) make up most of the rock. Very fine-grained muscovite and biotite are either disseminated throughout the rock or occur in fine layers with biotite more abundant than muscovite. Muscovite porphyroblasts are found in some specimens as isolated crystals or in discontinuous schistose layers. These rocks grade locally into thin layers of coarser grained muscovite-biotite schist. These rocks were first described by Navarro and Blackburn (1974). Hill and Bickford (2001) report $^{207}Pb/^{208}Pb$ ages on eight euheral to rounded zircons that are between 1,733 ± 12 Ma and 1,867 ± 7 Ma, indicating deposition after 1,733 Ma.

Xs **Biotite quartz schist (Paleoproterozoic)** -- This unit is predominantly a dark-gray fine-grained biotite quartz schist but also contains dark-gray biotite quartz gneiss and dark-gray biotite quartzite. The biotite-bearing units are dominated by granoblastic quartz, microcline, and plagioclase (albite-oligoclase) with variable amounts (5-50%) of aligned biotite to produce the foliation. Accessory minerals include muscovite, epidote, blue-green hornblende, titanite, and apatite. In general, grain sizes coarsen to the northeast and become medium-grained with muscovite or biotite porphyroblasts. These rocks are equivalent to the quartz-biotite schist of Hedlund (1974) and Hedlund and Olson (1974) and the metasedimentary rocks Olson (1976a, b) and Dewitt and others (2002)

Xa **Amphibolite (Paleoproterozoic) –** This unit is a black to greenish-black fine- to medium-grained amphibolite. The amphibolite is weakly foliated in most places but grades into gneissic structures locally. The amphibolite consists of 35-70% green amphibole, 25-50% plagioclase (andesine An_{30-45}), and smaller amounts of quartz (<5%), chlorite, epidote, biotite, titanite, and apatite. Amphibolites are often cut by quartz or epidote veins. These rocks are equivalent to the amphibolite and hornblende schist of

Hedlund (1974) and Hedlund and Olson (1974), and the amphibolite and metabasalt of Olson (1976a, b).

DEPOSITIONAL HISTORY

INTRODUCTION

Depositional history of the Signal Peak quadrangle begins with Pennsylvanian uplift of the Ancestral Rocky Mountains, an ancient precursor to the modern Rocky Mountains of Colorado. Although this event initiates erosion in the map area, rather than deposition, it sets the stage for subsequent deposition. The Ancestral Rocky Mountains in Colorado consisted of at least two north-northwest trending, high relief uplifts that coincide in location with modern uplifts. The ancestral Front Range Highland lay to the east, in the position of the modern Front Range. This ancestral uplift was bounded on the east by the Denver Basin and on the west by a basin known as the Central Colorado Trough. Farther west was the ancestral Uncompahgre Highland, bordered on the east by the Central Colorado Trough and to the west by the Paradox Basin, which extends into eastern Utah. The Signal Peak quadrangle lies on the east edge of the Uncompahgre Highland. Stratigraphic and structural relations indicate that the west margin of the adjacent Central Colorado Trough lay several miles to the northeast.

The stratigraphic result of Pennsylvanian uplift in the map area is the absence of Paleozoic strata. Their presence a short distance to the northeast marks the relative position of the Central Colorado Trough, into which the detritus eroded from the adjacent mountains was deposited. Although lower Paleozoic rocks (Cambrian-Mississippian) existed in the area prior to its uplift, they were the first to be stripped from the highlands as they rose. In addition to the removal of earlier deposited Paleozoic strata, the Uncompahgre Highland inhibited the deposition of Triassic and Lower-Middle Jurassic strata due to its enduring relief. Based on the presence of these strata to the west, the area of the Signal Peak quadrangle was the last part of the Uncompahgre highlands to be covered by Mesozoic sediments. It was not until the Late Jurassic that the topographic relief was sufficiently reduced to allow the deposition of sediments. The irregular erosion surface on which these sediments were deposited endured from Pennsylvanian to Late Jurassic time, a period of more than 150 million years.

MESOZOIC

Upper Jurassic Junction Creek Sandstone

The Upper Jurassic Junction Creek Sandstone (Jj) consists of well-sorted, fine- to medium-grained sandstone with large-scale cross-stratification, deposited in an eolian dune setting. Cross-stratification shows a northeastward transport direction for these eolian sands (Dick, 2006). The Junction Creek thins eastward across the map area and locally is absent. It pinches out completely several miles east of the Signal Peak quadrangle and to the north near Crested Butte. The Junction Creek correlates with the eolian Bluff Sandstone in southeast Utah. These sandstones were deposited under arid conditions in an extensive dune field that stretched from southeast Utah through southwest Colorado, to the Gunnison area. The dune field likely initiated in southeast Utah and was pushed into Colorado by northeast-directed winds, eventually depositing a thin blanket of sand across the erosion surface of Precambrian rock that was a remnant of the much reduced Uncompahgre Highlands. The Signal Peak quadrangle and adjacent areas mark the depositional limit of the Bluff/Junction Creek dune field.

Upper Jurassic Morrison Formation

The upper Jurassic Morrison Formation consists of sandstone, mudstone, and limestone of continental origin. Two members are recognized in the map area: the basal Salt Wash Member (Jms) and the overlying Brushy Basin Member (Jmb). The Salt Wash Member is present only in the north part of the map area and is dominated by pebbly sandstone deposited in east-flowing, moderate-energy rivers. The overlying Brushy Basin Member occurs across the map area and is composed predominantly of red and green mudstone that encases thick lenses of conglomeratic sandstone and thin lenses of limestone. Mudstone represents deposition during floods on a broad, low-relief flood plain. Sandstone and conglomerate were deposited in lens-shaped channels of low energy rivers that cut the flood plain. Small shallow ponds and wetlands that dotted the extensive flood plain hosted thin discontinuous beds of limestone. The Morrison Formation conformably overlies the Junction Creek Sandstone. Locally, where the Junction Creek is absent, the Morrison lies nonconformably on Precambrian metamorphic rock. The Lower Cretaceous Burro Canyon Formation unconformably overlies the Morrison Formation.

Rivers of the Morrison Formation originated in highlands of the Nevadan orogenic belt in eastern Nevada. This rising mountain belt marked the initiation of a continuous series of mountain building episodes in western North America that persisted through the Cretaceous

Period. The resulting geographic reorganization generated rivers that cut eastward across Utah and Colorado. The Morrison represents a profound change from the earlier westward drainage pattern that was driven by uplift of the Ancestral Rocky Mountains and which endured from the Pennsylvanian to the Early Jurassic. The shift to an east-flowing river system continued to the end of the Cretaceous.

Dinosaurs were an important part of the Morrison ecosystem, and the formation has yielded countless dinosaur fossils throughout western North America. These include the bones of *Apatosaurus* sp. recovered from the Morrison in lower Cabin Creek in the Signal Peak quadrangle (Bartleson and Jensen, 1988).

Upper Cretaceous Burro Canyon Formation

The Lower Cretaceous Burro Canyon Formation consists of a resistant basal unit of conglomerate and sandstone overlain by a heterogeneous assemblage of mudstone, limestone, and sandstone, all of continental origin. In a pattern similar to the underlying Morrison Formation, the basal pebble conglomerate and sandstone marks the passage of energetic north-northeast-flowing rivers (Craig, 1981). The succeeding olive-green shale and limestone represent a low-lying flood plain with ponded water and wetlands. This flood plain was traversed by sluggish rivers represented by lenses of sandstone. The source terrane for the Burro Canyon Formation lay in the Nevadan orogenic belt to the southwest in Arizona and eastern Nevada, where continued mountain-building provided a constant supply of water and sediment. The Burro Canyon rests unconformably on the Morrison Formation and is unconformably overlain by the Upper Cretaceous Dakota Sandstone.

Upper Cretaceous Dakota Sandstone

The three part division of the Late Cretaceous Dakota Sandstone that is recognized in the map area is common to the formation across western Colorado and much of Utah. This regular change records a regional rise in sea level and a westward advance of the shoreline of the Western Interior seaway. As this transgression proceeded, the depositional setting of the Dakota gradually shifted from a fluvial environment to a shallow marine setting. This slow inundation continued with deposition of the deep marine Mancos Shale that overlies the Dakota. This is shown by the gradational contact between the Dakota and Mancos Shale.

The lower third of the Dakota consists of cliff-forming sandstone and conglomerate that locally scours up to 10 feet into underlying strata. Thickness varies laterally with the depth of these erosional scours. Deposits of the lower Dakota are characterized by trough and low-angle cross-stratification with a minor component of horizontal bedding.

This part of the formation represents the distal reaches of east-flowing braided rivers. The source for this drainage lay along the Utah-Nevada border in the highlands of the Sevier orogenic belt. These rivers drained into the Western Interior seaway, a large north-south trending sea with a shoreline that lay in central Colorado. This sea stretched south from the Gulf of Mexico northward to the Arctic inundating the central part of the North American continent.

The middle part of the formation consists of thin silty coal beds, fine-grained sandstone, and siltstone. These strata were deposited in coastal wetlands and coal swamps that developed as sea level rose and the shoreline shifted west into the western Colorado, inundating the earlier rivers.

The upper part of the Dakota is of shallow marine origin and records the continued rise of the Western Interior seaway. Herringbone cross-strata indicate a strong tidal influence. Abundant trace fossils including *Diplocraterion* and *Ophiomorpha* attest to a sandy shoreline setting. The upper part of the Dakota consists of very fine-grained sandstone and siltstone interbedded with black silty shale representing the transition to the deep marine Mancos Shale.

TERTIARY

The Tertiary depositional history of the area is dominated by (1) erosion from the topographic highs to the north, east, and south that were uplifted during the Laramide orogeny; (2) deposition of volcaniclastic aprons from volcanic centers to the south and west that disrupted the established drainage systems and turned the region into a depositional basin; (3) deposition of rocks eroded from the Laramide topographic highs and San Juan volcanic centers in alluvial fans into the basin; and (4) the eruption of voluminous ash flow sheets from central and western San Juan volcanic centers that repeatedly disrupted the fluvial system. This history is recorded in the extensive gravel deposits of the Signal Peak quadrangle that continue both to the south and east (Gregory and Chase, 1994; Olson, 1976a, b) and to the west (Stork and others, 2006; Green, 2002; and unpublished mapping).

Tertiary deposition in the Signal Peak quadrangle started with emplacement of volcaniclastic rocks from West Elk Volcano. Laharic and volcaniclastic sediments, along with similar units erupted from the volcanic centers to the south, blocked prevolcanic paleo-drainages and changed stream gradients to create a depositional center in the region. The main paleo-drainages in the quadrangle are a paleo-Gunnison channel located just north of Lost Canyon (mixed Tw and Twg) and a paleo-Tomichi channel centered on the current position of Tomichi Creek. Eruptions from West Elk volcano established the general course of the Gunnison River and Tomichi Creek at that time and raised base level in the region 180 m (600 ft) (Hansen, 1971; Hedlund, 1974; Hedlund and Olsen; 1973).

The disruptions of paleo-drainages by the volcanism caused extensive deposition of gravels upstream from two distinct source regions. The first source (Tg and Twg) was from the Laramide highlands to the north and east. In the Signal Peak quadrangle, deposition of these units was dominated by a large alluvial fan that coarsens and thickens to the northeast and slopes to the southwest. Boulders and cobbles from this source include Precambrian granites and metamorphic rocks, and Paleozoic and Mesozoic sandstones. Large ash flow sheets from the San Juan volcanic field were repeatedly deposited on this fan. In the Signal Peak quadrangle the Blue Mesa Tuff, Sapinero Mesa Tuff, Fish Canyon Tuff, and Carpenter Ridge Tuff are all interbedded with the Tertiary gravels of this fan and show various depositional or erosional pinch-outs with the gravel. Deposition on this fan continued after deposition of the Carpenter Ridge Tuff but the fan was eventually isolated from its source by headward erosion of Beaver Creek along the main Laramide faults that form the southwest boundary of the Sawatch Range (Coogan and others, 2005; Dewitt and others, 2002). It is possible that these faults may have been reactivated in the Neogene (Coogan and others, 2005).

At the base of this fan complex a paleo-Tomichi channel ran along the southern edge of the map just south of the current position of Tomichi Creek. West-directed paleo-current measurements (Gregory and Chase, 1994) from equivalent gravels to the east show that an axial paleo-Tomichi drainage, which had headwaters near the current Continental Divide, had been established in the topographic low between the older Laramide highland and the emerging San Juan volcanic field. This axial drainage was disrupted by the eruption of the various ash flow sheets but repeatedly reestablished itself within a few kilometers of the current Tomichi Creek.

The second and much less voluminous source of gravel (Tgb) was south of the paleo-Tomichi drainage and deposited material from a mixed Precambrian and volcanic highland to the south. Boulders and cobbles include Tertiary volcanics, Precambrian tonalite and granodiorite, and metamorphic rocks such as amphibolite, biotite quarzite, and biotite-quartz gneiss. These clasts are consistent with a provenance in the Gunnison Gold Belt to the south and are intermixed with mafic and intermediate volcanic clasts from volcanic centers in the San Juan Mountains. In the Signal Peak quadrangle these deposits occupy paleo-channels or paleo-alluvial fans that are interbedded with both Tg and Tf along the southern edge of the quadrangle. In the adjacent Gunnison quadrangle (Stork and others, 2006) equivalent deposits occur in channels at many stratigraphic horizons: between the bedded tuffs of East Elk Creek and the Fish Canyon Tuff; between the Sapinero Mesa and Fish Canyon Tuff; and between the Fish Canyon and Carpenter Ridge Tuffs. The repeated deposition of rock from this source implies a Precambrian highland that was continuously or at least repeatedly exposed above the San Juan volcanics.

STRUCTURAL GEOLOGY

The Signal Peak quadrangle contains a record of at least three phases of mountain building in Colorado that include the assembly of Precambrian basement terranes, the Pennsylvanian through Permian Ancestral Rockies uplift, and the early Tertiary Laramide Orogeny. Post-lower Cretaceous normal faults in the southeastern part of the quadrangle may record an additional episode of anomalous Laramide or late Cenozoic extension. Precambrian metamorphic and igneous rocks in the quadrangle belong to the ~1.74–1.73 Ga Cochetopa succession of metasedimentary and metavolcanic rocks that were deposited in an arc basin setting and subject to upper greenschist to facies metamorphism and attendant polyphase deformation during the Yavapai orogeny (Jessup and others, 2005). The quadrangle is located on what was the eastern flank of the ancestral Uncompahgre uplift active in Pennsylvanian and Permian time (Kluth and Coney, 1981). The Ancestral Rockies history is evident only in the nonconformity that separates the Jurassic Junction Creek Sandstone and Morrison Formation from Precambrian basement rocks, where the regional Paleozoic section was eroded from the Gunnison area during and after Ancestral Rockies uplift. The early Tertiary Laramide Orogeny is represented by the general, gentle northward and westward dip of Mesozoic strata in the southern part of the quadrangle, as well as by Biebel anticline and syncline, Lost Canyon anticline and syncline, and related smaller folds and faults in Jurassic and Cretaceous strata across the northern and central parts of the quadrangle.

PRECAMBRIAN STRUCTURE

The Paleoproterozoic biotite quartz schist and amphibolite map units are complexly folded about two sets of subvertical axes along the southern border of the Signal Peak quadrangle. Structural analysis is limited by exposure to the southeastern part of the quadrangle (figure 4), where a westward-plunging synclinorium is folded by a second generation of lower amplitude southwestward-plunging folds. The early west-plunging fold trend is defined by folding of the dominant bedding-subparallel foliation (figure 4). Stereonet analysis of all foliation measurements for the southeastern quadrangle delineates an overall fold axis plunging 80^{o} toward 266^{o} that is consistent with the largest scale of folding of amphibolite bodies in the core of the synclinorium, the trace of which underlies Tomichi Creek Valley with a hinge zone exposed adjacent to U.S. Highway 50 near the eastern border of the quadrangle (figure 4).

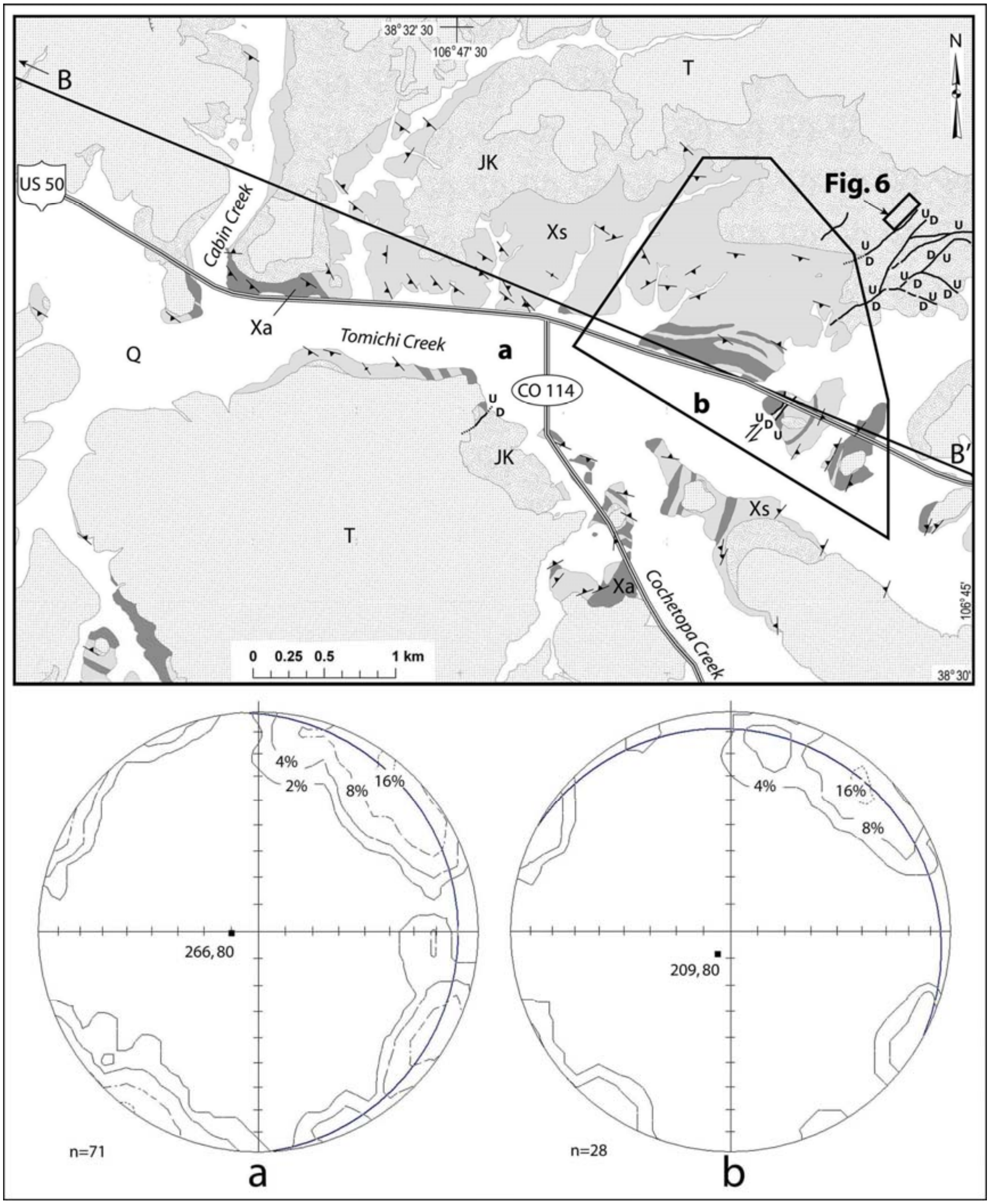

Figure 4. Geologic map and stereonet plots of Precambrian foliation domains of the southeast corner the Signal Peak 7.5' quadrangle. a. Contoured lower-hemisphere equal-area plot of poles to all foliation in southeastern quadrangle (domain a). b. Contoured equal-area plot of poles to foliation in domain b outlined on map. Solid lines on stereonets are best fit great circles through poles and squares are best-fit fold axes. Strike and dip direction of foliation is shown on map. Area of structural analysis of normal faults for Figure 6 shown with related normal faults showing relative displacement (U = up, D = down, half arrows show dextral strike-slip where observed). Map units: Xs = Paleoproterozoic biotite quartz schist, Xa = Paleoproterozoic amphibolite, JK = Jurassic and Cretaceous rocks, T= Tertiary rocks, Q = Quaternary rocks.

Second generation folds represented by a series of shorter wavelength and lower amplitude deflections of amphibolite layers and foliation on the north limb of the main synclinorium north of Highway 50 (figure 4). Stereonet analysis of the north limb domain defines the secondary fold axes as plunging 80^{o} toward 209^{o} (figure 4). The shapes of these secondary folds are projected along their axes into the east half of cross section B-B’ on plate 2 where the cross section traverses the north limb of the larger synclinorium. The two folding episodes observed in the southeastern Signal Peak quadrangle are consistent with the dominant first and weak second generations of steeply plunging folds identified along Iris syncline in the Iris 7.5’ quadrangle immediately south of the Signal Peak quadrangle (Afifi, 1981).

Exposures of the Paleoproterozoic, biotite-quartzite map unit in northern Signal Peak quadrangle generally exhibit more northerly strikes in the northwest part of the quadrangle and more northwestward strikes in the northeast corner of the quadrangle in steeply dipping foliation. These areas represent separate basement structural domains from the southern part of the quadrangle that persist into the southern Almont quadrangle (Coogan and others, 2005). These systematic changes in basement structural trends show a strong correlation to changes in the trends of post-Precambrian folds and faults throughout the Signal Peak, Almont (Coogan and others, 2005) and Gunnison (Stork and others, 2005) quadrangles.

LARAMIDE STRUCTURE

The Paleocene-Eocene Laramide orogeny is represented in the Signal Peak quadrangle by both general tilt domains as well as by discrete structures. The northward dip of Mesozoic strata in the southern part of the quadrangle is the result of tilting on the north flank of the Gunnison uplift, a Precambrian-cored Laramide uplift that continues westward to the Black Canyon of the Gunnison River. North- and northwest-trending folds and faults in Mesozoic strata of the northern half of the quadrangle form the southernmost structures of the Laramide Sawatch uplift trend, which is represented immediately north of Signal Peak quadrangle by basement-cored anticlinal uplifts associated with the Almont, Roaring Judy, and Cement Creek reverse faults in the Almont quadrangle (figure 1). Discrete Laramide structures include a west branch of the Almont fault, the Biebel anticline and syncline above the west branch of the Almont fault, the Lost Canyon anticline and syncline above a buried east branch of the Almont fault, and by a series of small displacement reverse faults and low-amplitude monoclines in headwaters of Lost Canyon Gulch and Cabin Creek in the northeastern corner of the quadrangle (plate 1).

West Branch of Almont Fault

The Almont fault is a steeply west-dipping reverse fault that forms a single south-trending fault trace through the southern half of the Almont quadrangle to where it bifurcates into east and west branches one-half kilometer north of the Signal Peak quadrangle (Coogan and others, 2005). The east branch of the fault is concealed by Quaternary deposits at the south edge of the Almont quadrangle (Coogan and others, 2005) and either remains concealed or reaches its surface termination at the north edge of Signal Peak quadrangle. The east branch of the Almont fault was not mapped within the quadrangle. The west branch of the Almont fault is exposed for one kilometer across the northern border of the quadrangle where it loses stratigraphic throw from where it places Precambrian rocks over Jurassic Morrison strata in the southern Almont quadrangle to where it juxtaposes the upper part of the Morrison Formation against the lower part of the Cretaceous Dakota Sandstone at its southernmost exposure in the Signal Peak quadrangle (plate 1; Coogan and others, 2005). The southern tip of the west branch of the Almont fault is buried beneath Quaternary and Tertiary strata, but the fault is assumed to terminate southward along the axial plane of Biebel syncline. At the deeper structural level of the northern border of the Signal Peak quadrangle, the west branch of the Almont fault precisely parallels the foliation of adjacent Precambrian rocks, a pattern observed along all Laramide faults in the adjacent Almont and Gunnison quadrangles (Coogan and others, 2005; Stork and others, 2006). The along-strike and up-structure correlation between basement foliation, basement faults, and faults and folds in overlying Mesozoic strata indicates that pre-existing Precambrian fabric exerts a primary control on Laramide fold and fault trends in the area.

Biebel Anticline and Syncline

Biebel anticline is an east-vergent asymmetric anticline that is well exposed along Lost Canyon Road in the north-central part of the quadrangle. A detailed study of the geometry and microstructures of Biebel anticline is provided by Wright (1985). The west limb of the anticline averages ~5° west-southwest dip and the steep east limb dips up to 65° to the northeast. Biebel anticline exhibits an angular parallel fold geometry with constant bedding thickness, planar fold limbs, and a sharp ~75 meter-wide hinge zone (figure 5).

Biebel syncline is constrained by the forelimb of Biebel anticline and gently southwest-dipping outcrops of the Mancos Shale and Dakota Sandstone east of Biebel anticline. The hinge zone of the syncline is buried beneath Quaternary and Tertiary deposits in the Lost Canyon Road area, but the location of the synclinal trough is mapped ~30 m east of steeply east-dipping Dakota Sandstone outcrops on the west limb of the syncline on the basis of nearly horizontal dip of the Cretaceous Mancos Shale inferred from a float zone of a thin Mancos sandstone in poor outcrop on the north side of Lost Canyon Road ~30 m east of the mapped trough line. The limited exposure and apparent lack of large stratigraphic offset provides little justification for fault offset across the synclinal hinge at this location. Northward correlation of the synclinal hinge to the west branch of the Almont fault (Coogan and others, 2005) is consistent with development of the Biebel anticline and syncline as fault-propagation folds (Suppe and Medwedeff, 1990), with reverse fault shortening at the Precambrian basement level balanced by fold shortening at the shallower Dakota Sandstone level (plate 2, cross section A-A').

Biebel anticline plunges ~4° to the north-northwest on the north side of Lost Canyon Road. The consistent elevation of the Dakota Sandstone along the interpreted north and south extent of the anticlinal crest indicates that the plunge magnitudes are small along the inferred length of the fold, but changes in plunge direction indicate the presence of low relief culmination and saddle points along the fold crest below the Tertiary and Quaternary cover. The Biebel fold shortening is interpreted to continue southeastward below Tertiary and Quaternary cover to Cabin Creek in the central part of the quadrangle, where two pairs of small amplitude, northeast-vergent, northwest-plunging anticlines and synclines are exposed in faulted and folded outcrops of Precambrian, Jurassic, and lower Cretaceous rocks. The correlation of a continuous fold and reverse fault trend between the northern part of the quadrangle and the Cabin Creek exposures requires that fold orientations change southward from a north to northwest trend. This southward change in fold trend is analogous to a smaller-scale but similar deflection along the trend of Lost Canyon anticline that is located 2 km northeast of the Lost Canyon Road exposures of Biebel anticline and syncline.

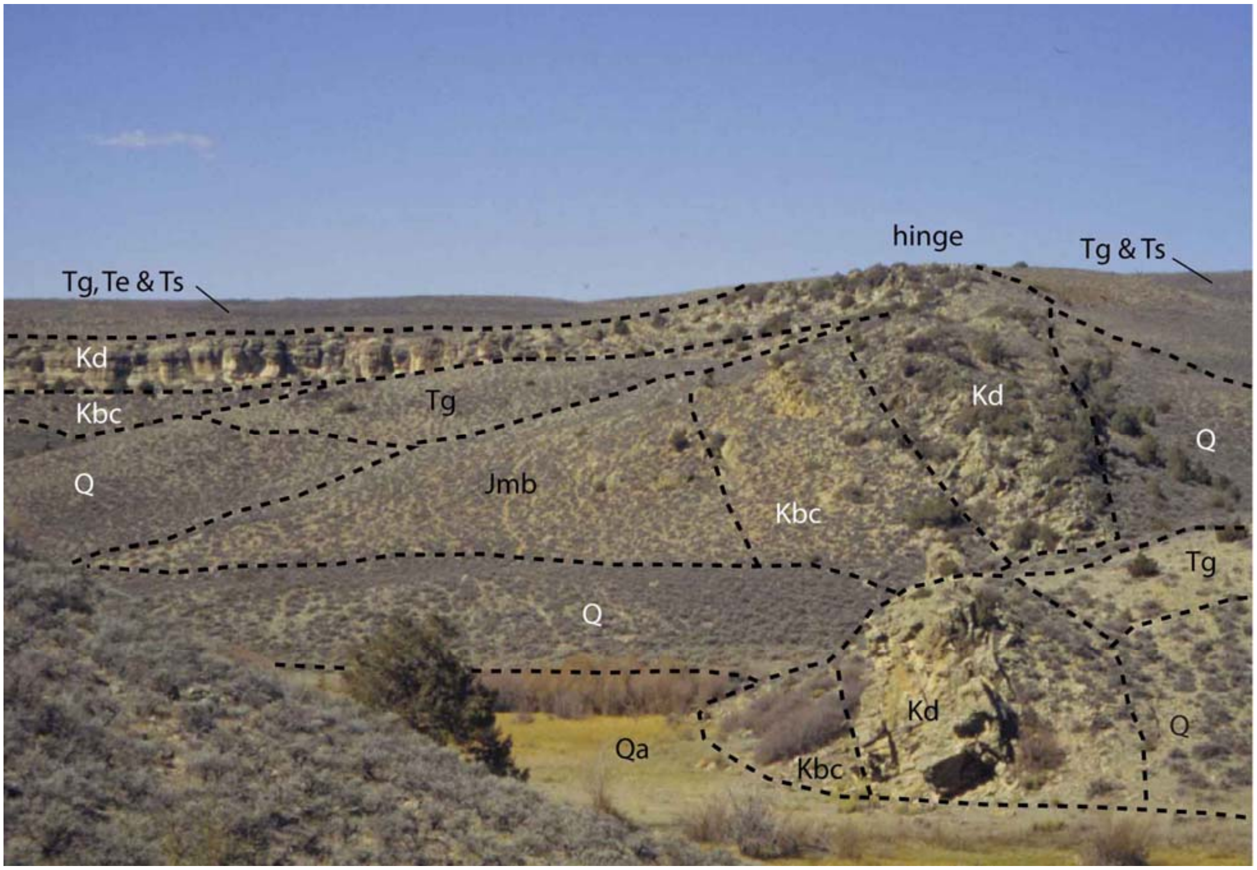

Figure 5. Northward view of Biebel anticline across Lost Canyon Road. Jmb = Brushy Basin Member of Morrison Formation, Kbc = Burro Canyon Formation, Kd = Dakota Sandstone, Tg = Oligocene gravel deposits, Te = bedded tuffs of East Elk Creek, Ts = Sapinero Mesa Tuff, Q = Quaternary mass movement deposits, Qa – Quaternary alluvium. The location of the tight hinge zone is indicated at the crest of the anticline.

Lost Canyon Anticline and Syncline

Lost Canyon anticline and syncline are exposed along the west side of Lost Canyon Gulch near the northern edge of the Signal Peak quadrangle. The 5-15^{o} southwestward-dipping west limb of Lost Canyon anticline correlates northward to the hanging wall of the east branch Almont fault at the south edge of the Almont quadrangle (Coogan and others, 2005), and the subsurface fault tip is inferred to underlie the synclinal hinge of Lost Canyon syncline in the Signal Peak quadrangle. The steep east limb of Lost Canyon anticline is exposed in series of small hogback outcrops of the Burro Canyon Formation and Dakota Sandstone along the west bank of Lost Canyon Gulch for 800 m south of the northern quadrangle boundary (plate 1). The forelimb dip is up 50^{o} eastward, with a local area of nearly vertical beds in the Burro Canyon Formation. The anticlinal crest is exposed along the Burro Canyon – Dakota contact in an area

800 m south of the quadrangle boundary, where dense bedding attitudes constrain a south-southeast plunge of 3.5^{o} toward 155^{o}.

The crest of Lost Canyon anticline is offset 600 m eastward from its position at the north edge of the quadrangle to its position in cross section A-A' near Lost Canyon Road. This offset occurs 1 km south of the quadrangle boundary in an area of extensive Quaternary cover. The area of offset includes a concentration of northeast-trending vertical fractures visible on air photos and northeast-trending vertical deformation bands in sporadic outcrop. These observations are consistent with offset of the crest of the anticline across a northeast-trending distributed sinistral strike-slip zone rather than one discrete strike-slip or tear fault in the hanging wall of the underlying east branch of the Almont fault.

The crest of Lost Canyon anticline is covered by Quaternary deposits south of the offset zone but is constrained by extensive Dakota Sandstone outcrop on the gently dipping west limb and by isolated outcrops of the steep east limb. The west limb dips 5-10^{o} to the southwest, with the east limb dip as high as 60^{o} to the northeast. Like Biebel anticline, Lost Canyon anticline exhibits the narrow hinge (50 – 125m wide), planar limbs, and constant bedding thickness characteristic of an angular parallel fold. The trough area of Lost Canyon syncline is not exposed, but its position is approximately constrained in the subsurface by gently southwestward-dipping Dakota Sandstone outcrops 3 km east of Lost Canyon anticline. These outcrops form the east limb of the syncline and that are projected westward to form the synclinal trough shown in cross section A-A' (plate 2). The northward correlation of the Lost Canyon anticline to the hanging wall of the east branch of the Almont fault (Coogan and others, 2005) is consistent with development Lost Canyon anticline and syncline as fault-propagation folds (Suppe and Medwedeff, 1990) with accommodation of basement fault and sedimentary cover fold shortening that is analogous to Biebel anticline and syncline (plate 2, cross section A-A').

Lost Canyon anticline exhibits a trend of ~135^{o} and minimal plunge adjacent to Lost Canyon Road. The southward change from a north to northwest trend required for correlation of the Biebel folds between the Lost Canyon Road and Cabin Creek exposures mimics the left-stepping pattern and southward change in fold trend exhibited by Lost Canyon anticline in the northern part of the quadrangle.

Small Monoclines and Reverse Faults

Small northwest-trending, west-vergent monoclines fold the Morrison and Burro Canyon Formations in the upper part of Cabin Creek in the northeastern corner of Signal Peak quadrangle (plate 1). The monocline trends are parallel to the trend of two small faults that cut the Precambrian basement through Dakota Sandstone along the north side of upper Lost Canyon near the corners of the Signal Peak and Almont quadrangles (plate 1; Coogan and others, 2005). The faults have small throws (15-40 ft) and are interpreted as steeply east-dipping reverse faults that, along with the adjacent monoclines, accommodated minor Laramide shortening of basement and cover rocks in the northeastern part of quadrangle. These small-scale folds and faults parallel the trend of Precambrian foliation and provide a small-scale example of the common correlation between the trend of Precambrian basement structure and the orientations of Laramide fault and folds.

Relationship between Laramide and Basement Structure

Detailed mapping of Laramide and Precambrian structural trends in the Almont (Coogan and others, 2005), Gunnison (Stork and others, 2006), and Signal Peak quadrangles demonstrates a strong correspondence between the orientation of basement structural trends defined by foliation and intrusive domains and the orientation of Laramide reverse fault and fold trends. Map-scale bends along the Almont, Roaring Judy, and Cement Creek faults of the Almont quadrangle correspond to and closely parallel changes in the orientation of basement foliation and contacts between foliated metamorphic rocks and more competent Precambrian intrusive complexes (Coogan and others, 2005). Similarly, the Gunnison fault of the southeastern Gunnison quadrangle parallels the foliation and intrusive contact along the eastern margin of the Precambrian Gunnison annular complex (Stork and others, 2006). The change from northerly to northwestward trends for Laramide folds and faults in the Signal Peak quadrangle corresponds to changes in the trend of Precambrian foliation from dominanly north-south at the northwestern quadrangle boundary to northwest along the Tomichi and Cochetopa Creek drainages in the southern part of the quadrangle. Although the shallow erosional level of Laramide folds precludes a direct correlation between Laramide fold and fault orientation and underlying basement fabric through most of the quadrangle, the west branch of the Almont fault and monoclines and faults in the northeastern quadrangle provide local corroboration for the close correspondence between Laramide structural and basement fabric orientations.

Along with basement fabric, the Laramide shortening direction exerted a principal control on Laramide fault and fold orientation and geometry. Slickenlines from minor Laramide faults and flexural slip surfaces in Mesozoic strata of the Signal Peak, Almont, and Gunnison quadrangles invariably record a dominant east-northeast slip orientation (mean ~055^{o}) (Coogan, unpublished data; Wright, 1985). This consistent slip direction along both north- and northwest-trending Laramide structures implies a single east-northeast shortening direction for the area. As a result, inherited high-angle Precambrian structural trends should exhibit a dextral component of oblique slip along north-south trends with an increasing dip-slip component along northwest trends and sinistral oblique slip on east-west trends during Laramide reactivation as high angle faults. The pattern of Laramide faulting and folding within the Signal Peak quadrangle is consistent with reactivation of known local Precambrian basement trends subject to east-northeast horizontal shortening and combined dip-slip and dextral oblique slip on the northwest and north-south basement reverse faults that underlie the basement-cored fold trends observed in the quadrangle.

Post Lower-Cretaceous Normal Faults

A series of northeast-trending high angle faults cuts Precambrian through lower Cretaceous rocks adjacent to and north of U.S. Highway 50 near the eastern boundary of Signal Peak quadrangle (plate 1; figure 4). Although the mapped fault planes are poorly exposed through this area, the dip direction, and thus hanging wall and footwall relationships, for two of the faults is evident in roadcuts, and minor fault populations adjacent to a third fault constrain an overall normal sense of slip for the fault system. Minor slip surfaces further indicate a component of right-lateral strike-slip for two of the southeast-dipping normal faults.

Figure 6 is a stereonet plot of kinematic data for eight mesoscopic normal faults that cut the Dakota Sandstone in the footwall of one of the map-scale normal faults shown in figure 4. Fault planes are shown by great circles and slickenlines for each fault are represented by dots along each fault great circle (figure 6). Arrows indicate the downward direction of hanging wall slip that was observed from steps associated with synkinematic Reidel shear surfaces. The stereonet analysis indicates that the mesoscopic faults form a population of conjugate northwest- and southeast-dipping normal faults that are dominated by dip-slip but that also include a component of dextral oblique-slip on southeast-dipping faults. Mesoscopic faulting diminishes northwestward away from the map-scale fault adjacent to the eight measured fault surfaces, consistent with coincident kinematic development of the mesoscopic and map-scale faults, and consistent with interpretation of the map-scale fault as a southeast-dipping normal fault.

An overall normal sense of slip for the map-scale faults is confirmed by exposures of two graben-bounding faults that cross US Highway 50 approximately 1.3 km south-southwest of the mesoscopic faults recorded in figure 6 (figure 4; plate 1). The west- and east-bounding faults of the graben dip southeast and northwest, respectively, in excavations that reasonably limit the distribution of hanging wall and footwall strata across the faults where the fault surfaces are universally obscured by float and soil. A substantial component of normal displacement on both faults is evident from the juxtaposition of the Jurassic Junction Creek Sandstone in the center of the graben against footwall Paleoproterozoic biotite quartz schist and amphibolite across the eastern fault, and against amphibolite across the western fault. Slickensided fault surfaces with unambiguous lineation and kinematic features are rare across the graben system. Slickenlines were observed only in the Junction Creek Sandstone adjacent to the west-bounding fault of the graben. These slickenlines universally plunge shallowly toward the north-northeast and south-southwest, indicating a component of strike-slip along the west-bounding fault zone. Steps associated with Reidel shear surfaces indicate dextral strike-slip on the only two slickenside planes where clear Reidel geometries were observed. Slickenlines on both surfaces plunge less than 5^{o}, which indicates that a component of pure strike-slip was accommodated along these surfaces.

This preliminary structural analysis adjacent to the poorly exposed high-angle faults near the southeastern boundary of the Signal Peak quadrangle indicates that they are normal faults with components of dextral oblique- and strike-slip along southeast-dipping faults. The computed extension direction for the eight faults in figure 6 is 303^{o} – 123^{o}. The age of this extension is only constrained as post-Lower Cretaceous where the faults cut the Dakota Sandstone. Normal faults were not observed cutting the Oligocene or younger deposits in the Signal Peak quadrangle. Determination of the age and significance of this normal fault population requires geologic mapping along the fault trend in adjacent parts of the Parlin 7.5’ quadrangle to the east, as well as further kinematic analysis of mesoscopic faults along the trend to determine whether the faults represent an anomalous extensional or oblique-slip domain within the early Cenozoic Laramide shortening regime or whether they are a local manifestation of regional Late Cenozoic extension associated with Rio Grande Rift and San Luis Valley extension to the east.

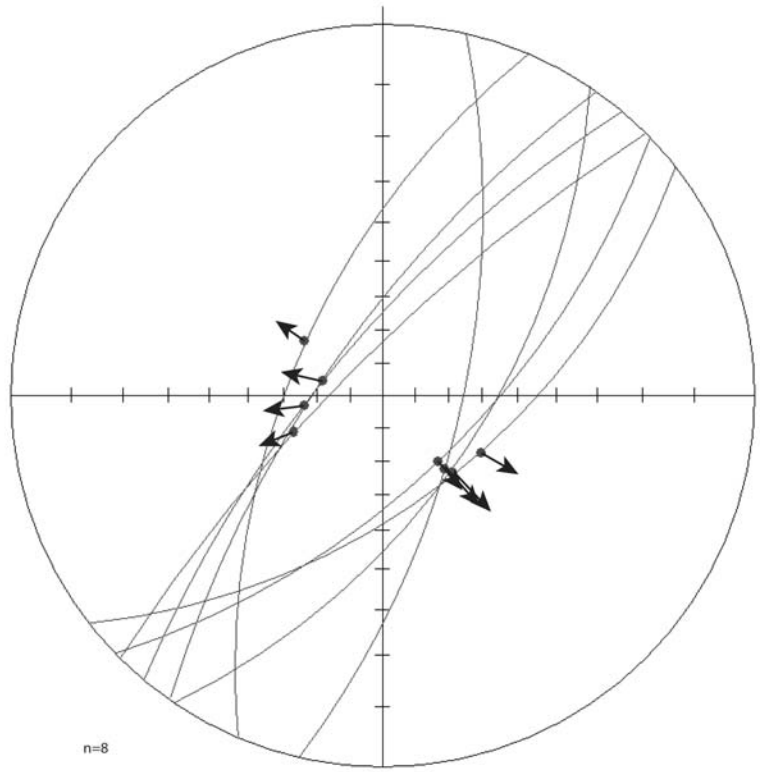

Figure 6. Lower hemisphere equal angle stereonet plot of kinematic data for eight mesoscopic normal faults from the southeastern Signal Peak quarangle. See Figure 4 for location. Fault planes are shown by great circles. Slickenlines are shown by dots. Arrows indicate the downward direction of hanging wall slip determined from Reidel shears.

MINERAL RESOURCES

ECONOMIC MINERALS

There has been no significant mineral production within the Signal Peak quadrangle. Areas to the south, within the Gunnison Gold Belt, have produced base and precious metals from both stratiform and vein deposits within the Precambrian (Streufert, 1999). Within most of the quadrangle potential Precambrian host rocks are deeply buried by overlying Mesozoic sediments and unfaulted Tertiary volcaniclastic rocks. Uranium prospects pits are present throughout the quadrangle and have targeted the Jurassic Morrison Formation, Tertiary volcanic rocks, Tertiary gravels, and mass wasting deposits, but no significant mineralization was found. Uranium was produced from the nearby Cochetopa mining district out of vein deposits along faults (Streufert, 1999).

Significant sand and gravel resources are available from the alluvial deposits (**Qa** and **Qt$_1$**) and potentially from the extensive unconsolidated Tertiary gravel (**Tg**) deposits within the quadrangle. Dimension stone and moss rock for local use have been quarried on a small scale throughout the area from outcrops of Mesozoic sandstones and some of the welded tuffs.

OIL AND GAS

The Signal Peak quadrangle lies at the far southern edge of the Piceance Basin petroleum province and contains a sedimentary sequence that is associated with oil and gas accumulations elsewhere in the state and region (Spencer and Wilson, 1988). The Dakota and Junction Creek Sandstones locally exhibit porosity characteristic of petroleum reservoirs. The Mancos Shale is a known petroleum source rock and low-porosity Mancos sandstone reservoirs produce oil and gas in the northern Piceance Basin (Spencer and Wilson, 1988). However, the deep Tertiary and modern erosion levels throughout the Signal Peak area preclude large-scale oil and gas accumulation in the quadrangle. All potential reservoirs are in communication with surface waters or shallow alluvial groundwater and are essentially flushed of hydrocarbons.

WATER RESOURCES

Shallow alluvium in the Tomichi and Cochetopa Creek valleys forms the principal aquifer in the Signal Peak quadrangle. On a small scale, these gravels provide domestic water from shallow wells for ranches and homes. Springs, such as Biebel Spring, are found near the surface expression of faults and monoclines where aquifers are breached. The Dakota and Junction Creek Sandstones are potential confined aquifers in the region, particularly to the north and west of the Signal Peak quadrangle where these units plunge into the Piceance basin. However, within the Signal Peak quadrangle the small local recharge areas and the discontinuous nature of outcrops on the erosion surface between the Precambrian and overlying volcanic rocks make the extent of the resource difficult to assess. Thick sections of impermeable rocks such as the Mancos Shale, West Elk Breccia, and other Tertiary volcaniclastic units make reliable groundwater development problematic in much of the area. Some domestic wells also produce out of fractured Precambrian rocks.

GEOLOGIC HAZARDS

Areas underlain by alluvium (Qa) along Tomichi and Cochetopa Creeks are historically prone to flooding. Debris flows, mudflows, and sheet flooding may affect areas mapped as fan deposits (Qf), debris fan deposits (Qdf), and alluvium and colluvium (Qac). Historic sheet flooding has occurred where these units are deposited at the mouth of drainages on the north side of Tomichi Creek.

Slopes underlain by the tuffs of East Elk Creek, poorly welded portions of the Fish Canyon Tuff, the Mancos Shale, and the Brushy Basin Member of the Morrison Formation all have the potential for mass movement. Past movement in these units is evident throughout the map area. However, no evidence of active or historical landslide activity was documented during this study and most landslide deposits appear to be stable under present conditions. Rockfall hazards exist on extremely steep slopes beneath densely welded Carpenter Ridge Tuff, the Dakota Sandstone and Burro Canyon Formation. Geologic hazards of the adjacent Gunnison, Flat Top, and Almont quadrangles have been mapped by Soule (1976).

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