OPEN-FILE REPORT 07- 06

Author's Notes

Geologic Map of the Garo Quadrangle, Park County, Colorado

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Geologic Map of the Garo Quadrangle, Park County, Colorado

Description of Map Units, Stratigraphy, Structure, Mineral Resources, Water Resources, and Geologic Hazards

by

Robert M. Kirkham, Karen J. Houck, Neil R. Lindsay, and Stephen M. Keller

View looking east across the southern part of the Garo quadrangle. U.S. Highway 285 (in foreground) cuts through the eastern foothills of the Mosquito Range, which are underlain by Pennsylvanian sedimentary rocks. The meandering South Fork of the South Platte River flows from left (north) to right (south). The informally named Lone Hills are the partially tree-covered hills in the distance. Broad, gently southward-sloping terraces underlain by late to middle Pleistocene alluvial deposits lie between the river and the Lone Hills.

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 Colorado Department of Natural Resources is pleased to present the Colorado Geological Survey's Open-File Report 07-06, *Geologic Map of the Garo Quadrangle, Park County, Colorado.* Its purpose is to describe the geologic setting of this 7.5-minute quadrangle. Consulting geologists Robert Kirkham and Karen Houck, field assistant Neil Lindsay, and volunteer Stephen Keller conducted field work for the project during the summer and fall of 2006.

This mapping project was funded jointly by the U.S. Geological Survey through Agreement No. 06HQAG0045 of the STATEMAP component of the National Cooperative Geologic Mapping Program, which is authorized by the National Geologic Mapping Act of 1997, and also by 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. Geologic maps produced by the CGS through the STATEMAP program are intended as multi-purpose maps useful for land-use planning, geotechnical engineering, geologic-hazards assessment, mineral-resource development, and ground-water exploration.

Vince Matthews
State Geologist and Division Director

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INTRODUCTION

GEOGRAPHIC SETTING

The Garo 7.5-minute quadrangle lies in the western part of South Park, a high-altitude intermontane valley in central Colorado. The map area covers approximately 57 square miles in Park County and is south of the town of Fairplay and west of the town of Hartsel (fig. 1). U.S. Highway 285, Colorado Highway 9, and numerous county-maintained and unimproved public and private roads provide access to most of the quadrangle. The quadrangle is named for the townsite of Garo, which used to be an important stop along the now-abandoned Denver, South Park, and Pacific Railroad (Simmons, 2002).

The foothills of the Mosquito Range are in the western part of the quadrangle (fig. 1). The northwest-southeast-trending ridge in the southeast part of the quadrangle is referred to by the local residents as the Lone Hills. Red Hill, which is a narrow, elongate ridge that extends for tens of miles across South Park, crosses the northeast part of the quadrangle. This ridge is also referred to as the Dakota hogback, because the erosion resistant Dakota Sandstone underlies the hogback ridge. A small part of the western flank of Reinecker Ridge occupies the northeast corner of the quadrangle. Elevations range from a high of about 9,600 feet above mean sea level in the foothills along the western edge of the quadrangle to a low of about 8,900 feet in the southeastern corner of the quadrangle. Except for the foothills of the Mosquito Range and the Lone Hills, most land in the quadrangle slopes gently south or southeast.

Several perennial streams cross the quadrangle. Trout Creek and the Middle Fork of the South Platte River are in the northeast part of the quadrangle. Fourmile Creek, High Creek, and the South Fork of the South Platte River are in the central and western parts of the quadrangle. For brevity, the two forks of the South Platte River are often called simply the Middle Fork or South Fork. The Middle Fork passes through the Dakota hogback in a water gap near the townsite of Garo.

Most land in the quadrangle is either privately owned, administered by the U.S. Forest Service or Bureau of Land Management, or owned by the Denver Water Department. Most of the latter's property was recently acquired from the Colorado State Land Board.

SCOPE OF WORK

Geologic mapping of the Garo quadrangle was undertaken by the Colorado Geological Survey (CGS) as part of the STATEMAP component of the National Cooperative Geologic Mapping Program. This geologic map is one of several recently completed geologic maps in this region that were prepared by the CGS as part of the STATEMAP program (fig. 2). Other recently completed geologic maps in the region include: the Jones Hill quadrangle (Widmann and others, 2007); Fairplay East quadrangle (Kirkham and others, 2006); Fairplay West quadrangle (Widmann and others, 2006), Alma quadrangle (Widmann and others, 2004a); Como quadrangle (Widmann and others, 2005); Breckenridge quadrangle (Wallace and others, 2003); Copper Mountain quadrangle (Widmann and others, 2004b); Castle Rock Gulch quadrangle (Wallace and Keller, 2003); and Buena Vista East quadrangle (Keller and others, 2004).

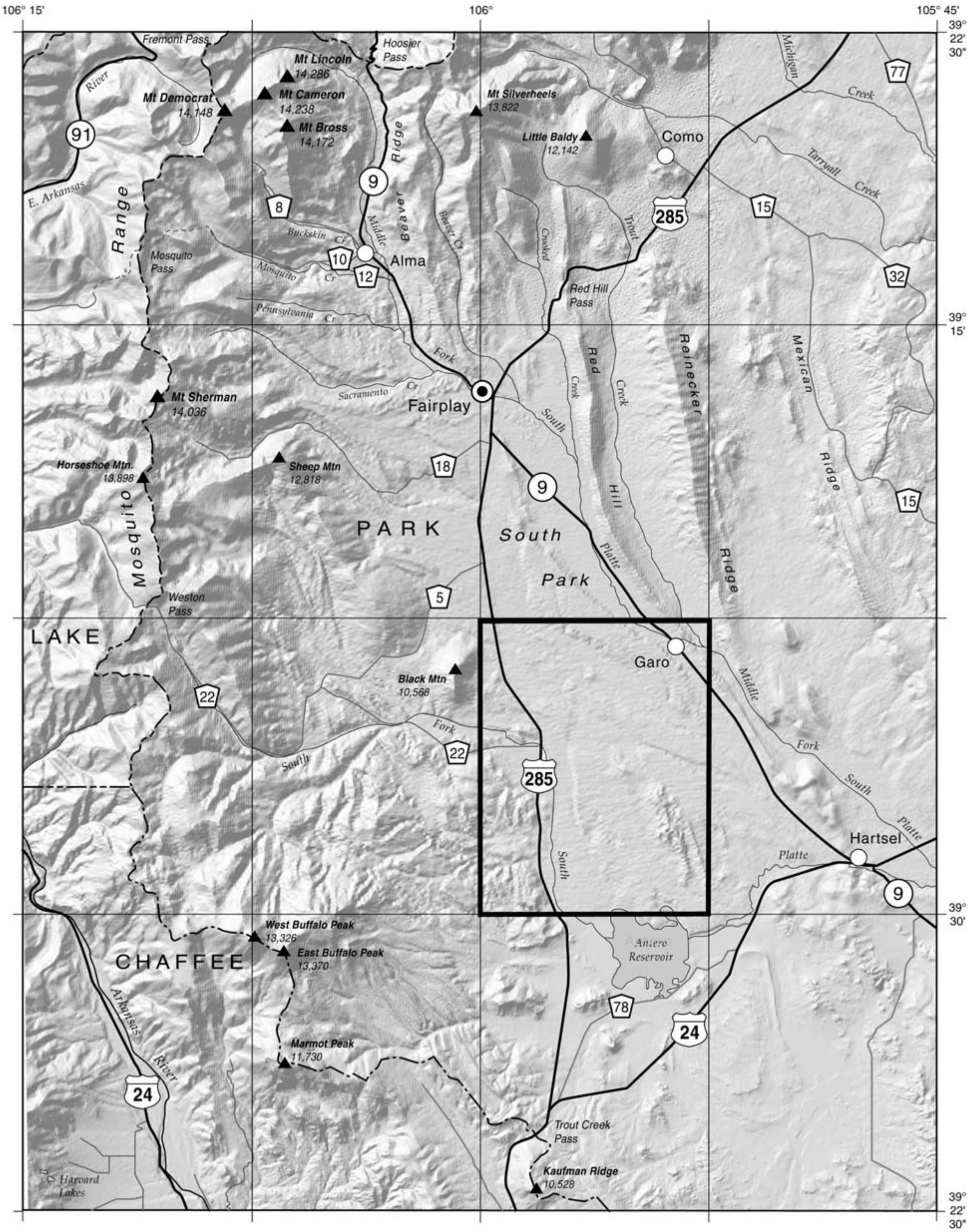

Figure 1. Shaded relief map of the project area and adjoining areas. The thick black line outlines the Garo quadrangle.

Mr. Kirkham was responsible for mapping the Tertiary, Mesozoic, and some of the Paleozoic bedrock, as well as the Quaternary deposits. Ms. Houck, Mr. Lindsay, and Mr. Keller conducted detailed stratigraphic studies of the Minturn and Maroon Formations to establish the contact between the two formations, correlated limestone beds in those formations, and mapped some of the Paleozoic bedrock.

Field work was conducted during the summer and fall of 2006. Geologic information and ground control collected in the field were plotted on 1:24,000-scale color aerial photographs flown for the U.S. Forest Service in 1997. Geographic coordinates for the ground control and geologic data points were determined using hand-held GPS receivers. The annotated aerial photographs were scanned, geo-referenced, and imported into ERDAS Imagine OrthoBase, where they were photogrammetrically corrected and rendered in 3D. Line work was traced directly from stereo pair images of the aerial photographs in ERDAS Imagine Stereo Analyst and exported as ESRI shapefiles into ArcGIS.

PREVIOUS STUDIES

Numerous prior published geologic maps and reports address all or parts of the Garo quadrangle. These include the regional 1:500,000-scale geologic maps of Colorado by Burbank and others (1935) and Tweto (1979), the 1:250,000-scale geologic map of the Denver 1^{o} x 2^{o} quadrangle by Bryant and others (1981b), and the 1:125,000-scale geologic map of Stark and others (1949). Moore and others (2001) showed the generalized surficial geology of the Garo quadrangle on their 1:250,000-scale map of the Denver 1^{o} x 2^{o} quadrangle. The 1:24,000-scale map of Lozano (1965) covers most of the quadrangle. Several geologic maps of areas adjacent to or near the Garo quadrangle were published by the Colorado Geologic Survey and U.S. Geological Survey at scales of 1:24,000 and 1:62,500 (fig. 2).

The geology and origin of South Park were described by Stark and others (1949), De Voto (1961; 1971; 1972), and Sawatsky (1964; 1967). The Pennsylvanian and Permian stratigraphy and structure of the region were discussed in many prior studies (for example, Brill, 1952; De Voto, 1965a, 1965b, 1980). Clement and Dolton (1970) provided a summary of the oil and gas exploration in South Park during the 1960s and 1970s. Hembre and TerBest (1997) and Steyaert and Wandrey (1997) discussed the petroleum potential of the area. Shoffner (1974) and Raynolds (2003) focused on the South Park Formation. Fatti (1974), Beggs (1977), Durani (1980), and Treviño and Keller (2004) reported on geophysical studies of the South Park basin. Willmarth (1959) described the Garo uranium-vanadium-copper deposit.

TERMINOLOGY, NOMENCLATURE, AND METHODOLOGY

The divisions of geologic time and the age estimates of their boundaries are shown in figure 3. Grain-size terminology for sedimentary deposits (both bedrock and surficial deposits) follows the modified Wentworth grain-size scale (Ingram, 1989). This classification system defines three basic size clasts on the basis of grain-size diameter: gravel is larger than 0.08 inches in diameter (2 mm), sand is 0.08 to 0.0024 inches in diameter (2 to 0.062 mm), and mud is smaller than 0.0024 inches in diameter (0.062 mm). Pebbles, cobbles, and boulders are differing sizes of gravel; sand sizes ranges from very fine to very coarse; and mud is divided into clay and silt sizes. The terms pebbles, cobbles, and boulders are commonly used by many geologists for large diameter rounded grains deposited in fluvial and beach environments (for example, Jackson, 1997); however, we use these terms only to describe the size of the gravel, not the genetic origin.

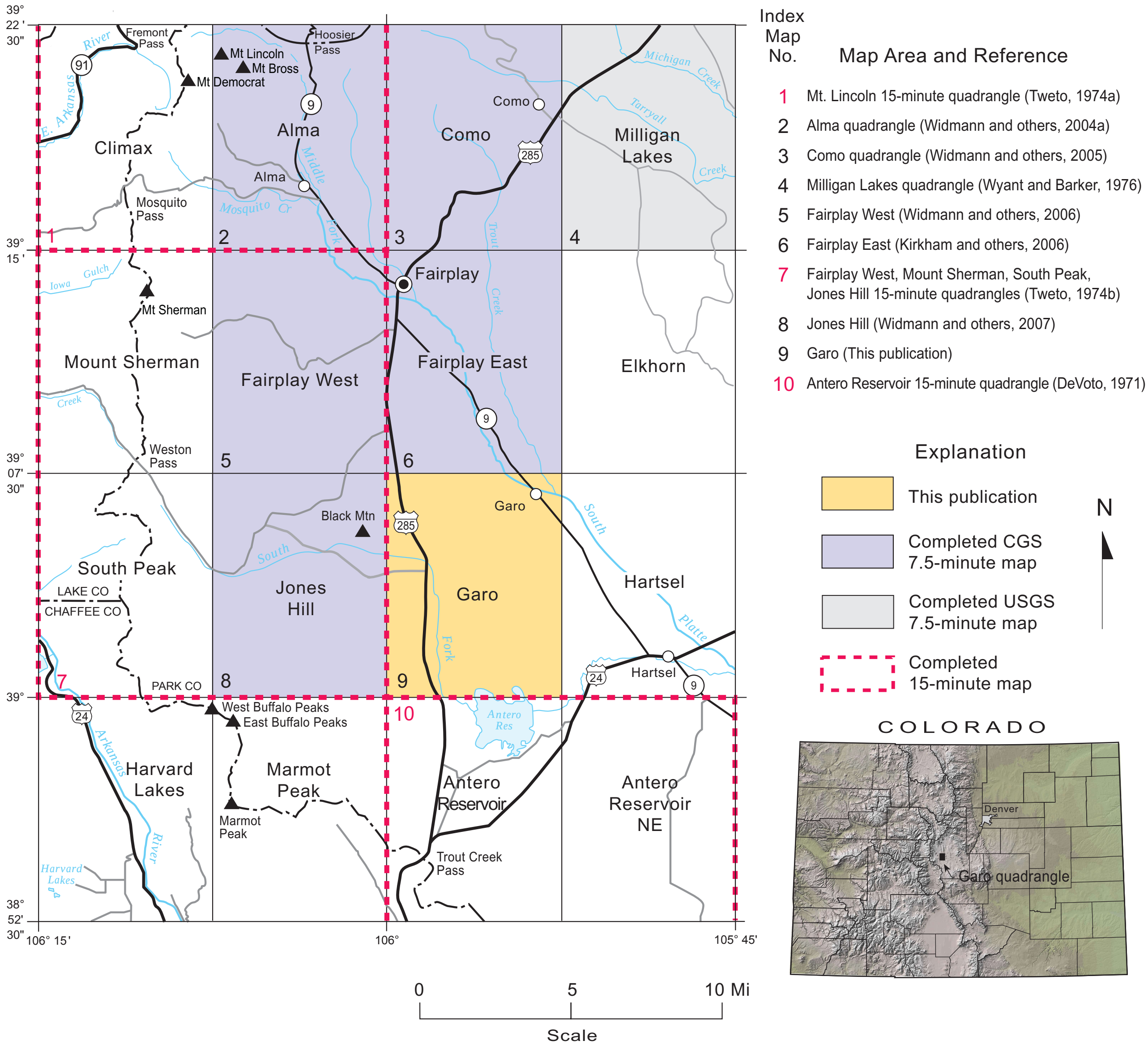

Figure 2. Location map of the Garo quadrangle, and status of geologic mapping in adjacent areas.

The term “clast” refers to rock and mineral fragments that are in the gravel size class, whereas matrix refers to surrounding material that is in the sand and mud sizes. In clast-supported deposits, the majority of the material consists of clasts that are in point-to-point contact. Matrix-supported deposits are composed predominantly of material smaller than 2 mm, and most clasts are separated by or embedded in matrix. Terms used for sediment sorting are those of Folk and Ward (1957). Sedimentary rocks are named according to the classification system of Folk (1980). English units are used throughout the report except for microscopic observations, which are described in metric units. The 1983 North American datum is used for all UTM coordinates.

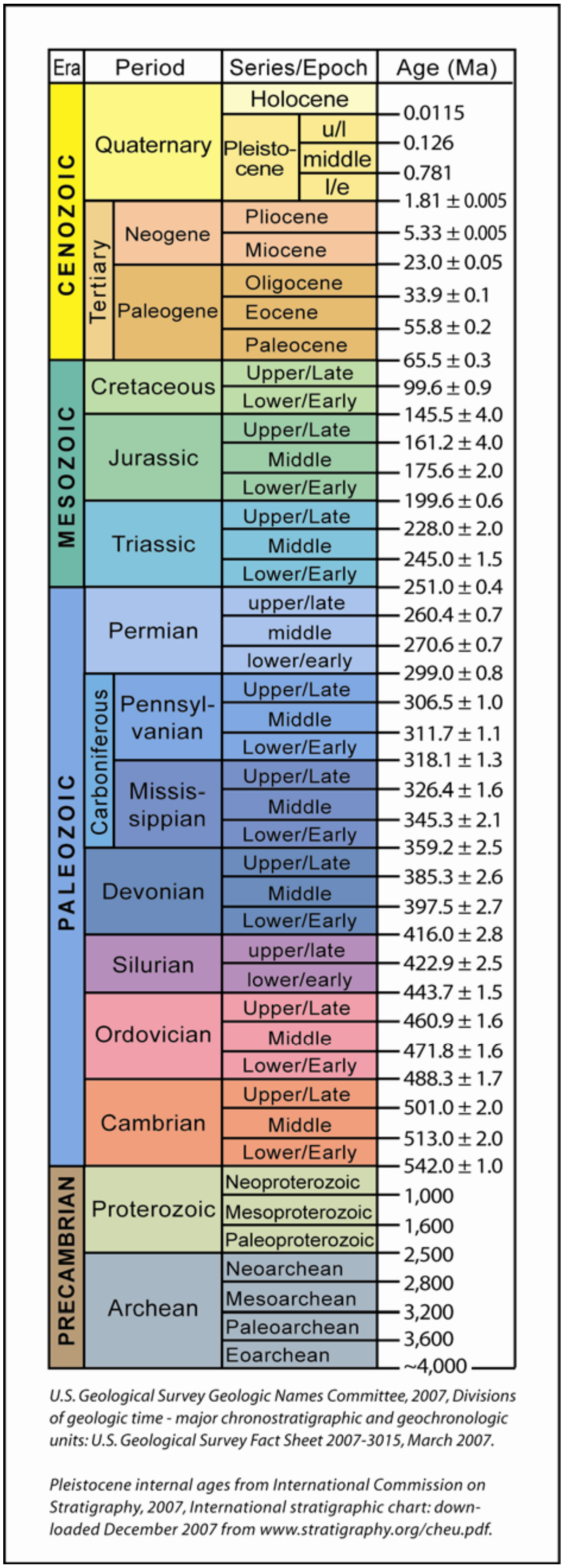

Figure 3. Geologic time scale.

Selected samples were chemically analyzed for major elements. The analytical results are in Appendix A. Locations of the analyzed samples are shown on the geologic map and are also described in Appendix A. The total alkali-silica plot (TAS) of Le Bas and others (1986) was used to classify chemically analyzed volcanic rocks. Two samples from the quadrangle were dated using $^{40}Ar/^{39}Ar$ methods (see Appendix B).

Surficial geologic deposits in the quadrangle are divided into map units on the basis of either genesis or landform and also relative age. Most of the surficial deposits in the map area are not well exposed. The best exposures are in features such as road cuts, eroded stream banks, and excavations at home sites. Due to limited exposures, the physical attributes of the surficial units such as thickness, texture, stratification, and composition are described from observations made at only a few locations, and their origin often is deduced only on the basis of geomorphic characteristics.

Generally, surficial deposits with a minimum thickness of about 3 to 5 feet thick are shown on the map. Surficial deposits associated with distinct landforms such as terraces or playas locally may be thinner than 3 feet. Contacts for many surficial units were located using geomorphic characteristics, and some contacts are gradational. Areas mapped as surficial deposits may include small areas of bedrock that are not depicted on the map. Deposits of residuum are not mapped.

Absolute ages are not available for any of the surficial deposits in the map area. Characteristics such as stratigraphic relations, position in the landscape, degree of weathering, and pedogenic soil development were used to estimate the relative ages of the surficial deposits.

Glacial till and outwash deposited by glacial meltwater are correlated with oxygen-isotope stages wherever possible in this report. Oxygen occurs in two common stable isotopes, ^{16}O and ^{18}O. The ratio of these two isotopes in water is temperature dependent. During cold glacial periods the $^{18}O/^{16}O$ ratio is high, and during warmer interglacial periods the ratio is low. By studying oxygen isotope ratios in thick ice caps and in fossils buried beneath the sea floor, changes in temperature over time can be evaluated (Martinson and others, 1987). An oxygen-isotope stage consists of a lengthy time interval during which the temperature was generally either cold or warm. The modern warm interglacial period is assigned to oxygen-isotope stage one, the last major glacial period (Pinedale glaciation) is oxygen-isotope stage 2, and preceding interglacial and glacial periods are consecutively numbered. The Bull Lake glaciation is usually correlated with isotope stage 6.

Soil-horizon nomenclature of Birkeland (1999) and Machette (1985) was utilized during the project. Concurrent soil mapping by the U.S. Department of Agriculture's Natural Resource Conservation Service aided our attempt to use pedogenic soil development as a tool to determine relative ages of the surficial map units.

Bedrock outcrops and surficial deposits which are less than about 50 feet wide generally are not depicted on the map. Thin but important bedrock units, such as limestone beds, are represented on the map as single lines because they add to the stratigraphic and structural understanding of the geology in the area.

ACKNOWLEDGMENTS

This geologic mapping project was funded jointly by the Colorado Geological Survey and U.S. Geological Survey through the STATEMAP component of the National Cooperative Geologic Mapping Program, Award number 06HQAG0045. The State of Colorado provided funding through the Department of Natural Resources Severance Tax Operational Fund, which is derived from the production of gas, oil, and minerals.

Beth Widmann helped map the geology and interpret the complex structure in the western part of the quadrangle. Jim Shannon described the thin sections from the igneous rocks and patiently answered many questions about the volcanic rocks in the central Colorado volcanic field. Jim Burnell examined and described a thin section from an ash-flow-tuff clast contained in in a conglomeratic limestone bed. Francisco Gutierrez aided our understanding of the evaporite collapse features in the quadrangle. Vince Matthews and Beth Widmann participated in a constructive field review of the mapping project. The map and report benefited from the review comments of Cal Ruleman. Jane Ciener was the technical editor of the map and report. Tom Neer, with Digital Data Services, prepared the digital geologic map for publication. Cartographic work for figures 1 and 2 was performed by Larry Scott.

Numerous landowners and/or property managers gave us permission to conduct field work on their land. They include Scott Sanderson, Mich Buyers, Dave Neukirch, Jo Ann McIver Mills, Gary Spivak, Mike Morris, Bob Meyer, Dan Miller, John Cooney, Jim and Tim Tracey, Dennis Kist, Ted Magaletti, Raphael Esparza, Pete and Kit Spahn, and Mike Suljak. We especially appreciate the cooperation of the Denver Water Department and its employees, including Susan Steele-Weir, Amy Turney, Eric Hibbs, and William George, and also the Campground of the Rockies and its managers, Debbie and Paul Gentry, for allowing access onto their properties.

DESCRIPTION OF MAP UNITS

SURFICIAL DEPOSITS - Surficial deposits are organized into five groups on the basis of their genesis. The genetic groups are human-made deposits; alluvial deposits; mass-wasting deposits; alluvial and mass-wasting deposits, undivided; and lacustrine deposits.

Human-Made Deposits — Earth materials placed by humans

af **Artificial fill (historic)** — Unsorted sand, silt, gravel, or rock fragments locally used as fill along a now abandoned railroad. Maximum thickness about 25 feet.

mw **Mine waste (historic)** — Unsorted sand, gravel, silt, and organic debris at now inactive peat mines in the High Creek fen, along High Creek near the east edge of the quadrangle, and in a small unnamed drainage northwest of Antero Reservoir in the south-central part of the quadrangle. Some of the deposits have been partially or completely reclaimed.

Alluvial Deposits — Sediments transported by flowing water and deposited in fluvial channels and flood plains and in glacial outwash plains and outwash fans. Alluvial deposits locally include significant amounts of organic material.

Qa1 **Alluvial unit one (Holocene)** — Mainly poorly sorted, clast-supported, unconsolidated, sandy gravel of all sizes, gravelly sand, silty sand, and sandy silt in modern channels, flood plains, and adjacent low-lying terraces that are approximately 5 feet or less above modern channels. Deposits in alluvial unit one usually are stratified and may have cut-and-fill channels. Beds of organic-rich sediment or peat are locally present. Most gravel clasts within the unit are fresh and sound, with little or no or decomposition. Clasts typically are subround to subangular, although a few are round or angular. Only weakly developed pedogenic soil horizons have formed on deposits of alluvial unit one. The unit probably was deposited during oxygen isotope stage 1, probably during episodes of Holocene neoglaciation or flooding. Thickness of the unit is estimated to range from about 3 to 15 feet thick but could be greater in places.

Qao **Alluvium and organic-rich sediment (Holocene and upper Pleistocene)** — Unit consists of variable amounts of gravelly alluvium, organic-rich clayey silt, and peat (fig. 4). The silty beds may include windblown sediment. The unit accumulated in the poorly drained upper reaches of tributary drainages in the south-central part of the quadrangle and in the High Creek fen. Estimated maximum thickness is about 15 feet.

Qa2, Qa2y, Qa2o **Alluvial unit two (upper Pleistocene)** — Alluvial unit two contains stratified, poorly sorted, clast-supported, sandy cobble and pebble gravel, gravelly sand, silty sand, and sandy silt that was deposited by glacial meltwater. Most clasts are subround to subangular and are unweathered or very slightly weathered. Locally, the unit is subdivided into two subunits. Subunit Qa2o is older than and usually slightly higher in the landscape than subunit Qa2y. Extensive deposits of alluvial unit two are preserved in the valleys of the Middle Fork and South Fork of the South Platte, High Creek, and Fourmile Creek. Deposits of alluvial unit two also are preserved in a paleovalley of the Middle Fork that is on the west side of the Dakota hogback in an area south of the Middle Fork's water gap through the hogback (fig. 5). A small outwash fan with well preserved channel geomorphology is underlain by deposits of alluvial unit two on the east side of the hogback.

Streams are incised about 5 to 15 feet into alluvial unit two. Pedogenic soils formed in alluvial unit two have weakly to moderately well developed Bw horizons, absent or very weak and thin argillic Bt horizons, and very thin calcareous Cca horizons with stage I to weak stage II carbonate morphology (fig. 6). Exposures of subunits Qay2 and Qa2o are insufficient to determine whether there are significant differences between the soils developed on the two subunits. Stratigraphic relationships between alluvial unit two and the late Pleistocene tills northwest and west of the quadrangle (Widmann and others, 2004a; 2006; 2007), along with soil development and clast weathering, suggest alluvial unit two was deposited during the Pinedale glaciation (oxygen isotope stage 2), which extended from about 13 to 35 ka. Subunit Qa2o may be early Pinedale in age, and Qa2y may be late Pinedale.

The base of alluvial unit two is not exposed in the quadrangle. According to driller's logs from water wells, the thickness locally may exceed 120 feet, although the lower part of the alluvium penetrated by these wells may consist of buried deposits of alluvial unit three.

Figure 4. Organic-rich deposits of unit Qao in the High Creek fen. Hummocky topography probably due to disturbance related to peat mining. "Popcorn" texture may be due to expansive clays (montmorillonite?). View is to southeast from about UTM coordinates 416080 m E, 4328390 m N.

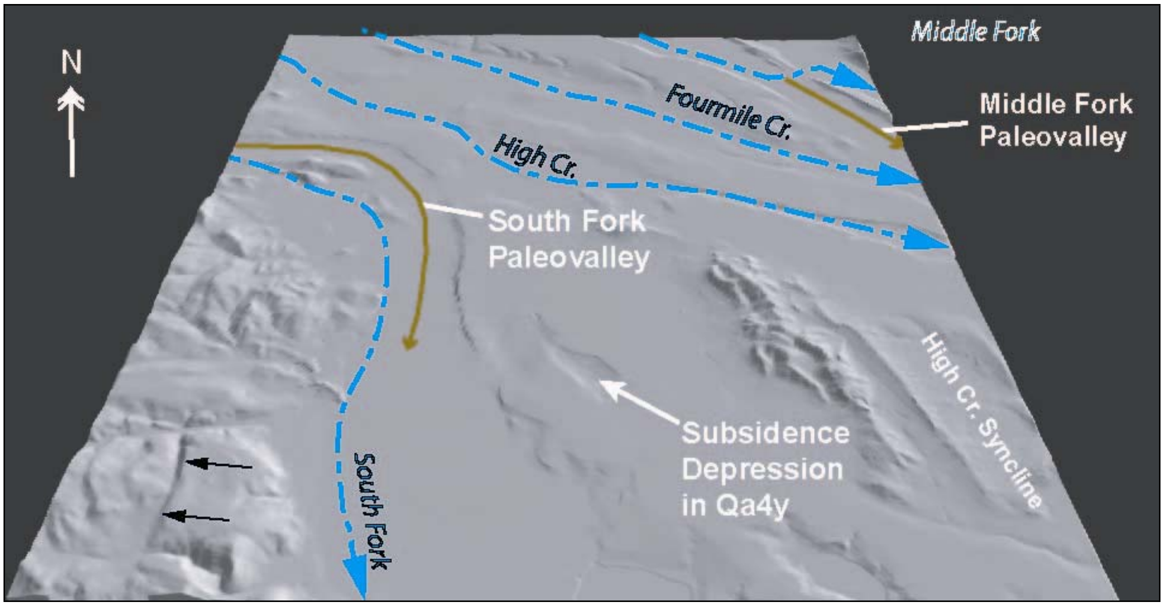

Figure 5. Shaded relief DEM of the Garo quadrangle, looking north. Dashed blue lines represent approximate locations of the South and Middle Forks of the South Platte River, High Creek, and Fourmile Creek. Locations of the Middle Fork paleovalley and South Fork paleovalley shown by brown lines. The water gap cut through the Dakota hogback is located where the river swings through the ridge in the upper right corner of the image. West flank and part of the east flank of the High Creek syncline is apparent in the lower right corner. The large subsidence depression in the center of the image formed in a terrace underlain by deposits of subunit Qa4y. Note the prominent north-south-trending, west-facing escarpment in the lower right (denoted by black arrows), which may be a fault-line scarp.

Figure 6. Exposure of alluvial unit Qa2y, and the pedogenic soil formed on it, in a pit on the west side of Highway 285 located approximately at UTM coordinates 414160 m E, 4330190 m N.

Qa3 Alluvial unit three (upper middle Pleistocene) — Sediment in unit Qa3 is similar to that contained in unit Qa2, in that it was deposited as outwash from melting glaciers, but it is older and usually higher in the landscape than unit Qa2. Deposits of alluvial unit three were recognized in the valleys of the South Fork of the South Platte River, High Creek, and Fourmile Creek. Along the western edge of the quadrangle, a relatively thin veneer of unit Qa3 on the north side of the South Fork is underlain by the evaporitic facies of the Minturn Formation. These outwash gravels are pockmarked by sinkholes that follow bedding in the underlying evaporitic bedrock. About 1 mile east of the western edge of the quadrangle, the terrace deposits of alluvial unit three fill the floor of a paleovalley that is separated from the South Fork by small hills of bedrock (see geologic map and fig. 5). A veneer of light-gray, white, or light-brown fluffy precipitate as much as 6 feet thick conceals unit Qa3 in much of the paleovalley (fig. 7). Nearly all of the precipitate dissolves in dilute hydrochloric acid. X-ray diffraction analysis of a sample collected from the outcrops shown in figure 7 indicates most of the material is gypsum, although significant calcite and minor quartz also are present (R.F. Wendlandt, 2007, written communication).

Figure 7. Light-gray to white precipitate consisting mostly of gypsum with significant amounts of calcite and very minor quartz overlies unit Qa3 in the South Fork paleovalley. View looking east from approximately UTM coordinates 416570 m E, 4325500 m N.

Typically, the original depositional surfaces associated with alluvial unit three are about 10 to 40 feet above adjacent streams, although the distal ends of some deposits of Qa3 appear to extend beneath adjacent younger alluvial deposits. Gravel clasts contained within unit Qa3 typically are slightly or moderately weathered. Pedogenic soils formed on deposits of unit Qa3 commonly have moderately well-developed argillic Bt horizons with blocky or sometimes very weak prismatic structure and stage I carbonate morphology and Bk horizons that have stage II to very weak stage III carbonate morphology. In Fairplay West quadrangle (Widmann and others, 2006) alluvial unit three locally grades to terminal moraines correlated with the late middle Pleistocene Bull Lake glaciation, which occurred during oxygen isotope stage 6. The weathering characteristics of deposits of alluvial unit three and the pedogenic soils formed on them suggest a late middle Pleistocene age, although some deposits of alluvial unit three may have been deposited during oxygen isotope stage 4.

The thickness of alluvial unit three is poorly constrained. In the paleovalley of the South Fork at the west edge of the quadrangle the unit is as thin as a few feet. Elsewhere the base is not exposed, and the thickness is unknown. In and immediately north of the northwest part of the quadrangle, driller's logs from water wells report thicknesses for alluvial deposits in excess of 120 feet. The lower part of the alluvium penetrated by these wells may consist of buried deposits of alluvial unit three.

Qa4y, Qa4o Alluvial unit four (middle Pleistocene) — Alluvial unit four was deposited as glacial outwash and is similar in character to alluvial unit two, except remnants of alluvial unit four are preserved higher in the landscape than alluvial unit two, many of the Laramide intrusive and Precambrian clasts within the alluvial unit four are moderately to strongly weathered, and the pedogenic soils formed on alluvial unit four typically include well developed carbonate-rich horizons. Alluvial unit four is subdivided into two subunits within the quadrangle, Qa4y and Qa4o, chiefly on the basis of relative position in the landscape. Deposits of Qa4o are about 15 to 30 feet higher in the landscape than deposits of Qa4y. We tentatively interpret these elevation differences to be a result of deposition at different times and that erosion slightly lowered the stream valley elevation during the interval between Qa4o and Qa4y deposition. It is also possible that the elevation difference could be due to differences in the amount of vertical subsidence caused by dissolution of underlying evaporite rocks. In two areas within the quadrangle, deposits of Qa4o and Qa4y are adjacent. The terrace risers between the deposits in these areas are not distinct and sharp, which suggests the elevation differences might be a result of differential subsidence.

A large remnant of unit Qa4o caps the broad divide between the valleys of Fourmile Creek and the Middle Fork of the South Platte River. This deposit is contiguous with deposits in the Fairplay East quadrangle that were mapped simply as Qa4 (Kirkham and others, 2006). Widespread deposits of alluvial unit four also are present between Fourmile Creek and High Creek, between High Creek and the Lone Hills, and between the South Fork of the South Platte and the Lone Hills. Lozano (1965) mapped some of the alluvial unit four deposits in the vicinity of High Creek as his upper Antero Formation (our Wagontongue Formation—unit Tw). Our mapping suggests these deposits are entirely alluvial unit four. These gravel deposits are well exposed in a gravel pit, trench excavations, and an eroded bank where the abandoned railroad crosses High Creek (fig. 7). Clast imbrications and bedding indicate these deposits are subhorizontal, not folded by the

High Creek syncline. Large cut-and-fill structures with sloping margins are present in these deposits and could be misinterpreted as tilted bedding.

The large remnant of Qa4o between the Middle Fork and Fourmile Creek is about 120 to 140 feet above those streams near the northern edge of the quadrangle and about 80 feet above those streams at the southern end of the remnant. Other deposits of Qa4o are about 60 to 90 feet above adjacent streams. Deposits of Qa4y are generally 40 to 70 feet above adjacent streams. Pedogenic soils formed on deposits of alluvial unit four are somewhat similar to those on unit Qa3, except that the Bk horizon in Qa4y and Qa4o usually has moderate stage III to weak stage IV morphology (fig. 8).

Figure 8. Stage III to weak stage IV carbonate horizons are typical of alluvial unit four. Photograph shows exposure of unit Qa4y in excavation for leach field of septic system located at approximately UTM coordinates 421920 m E, 4325510 m N. White pipe rests on ground surface.

Thickness of alluvial unit four varies significantly across the quadrangle. In most areas it typically is 5 to 20 feet thick, but locally it is much thicker. For example, in the S ½ of section 1, T. 11 S., R. 77 W. mapping suggests alluvial unit four is over 100 feet thick. Driller's logs of water wells in this area (see files of the Colorado Division of Water Resources) indicate gravel thicknesses of 115 to 135 feet (permit nos. 65356, 234573, and 114578). Exposures and field relationships in the SE ¼ of section 20, W ½ of section 28, and NE ¼ of section 29, T. 11 S., R. 76 W. suggest the thickness of alluvial unit four may exceed 60 feet in this area.

QTg Older gravel deposits (Pleistocene and/or Tertiary) — Deposits of unit QTg are preserved in four areas within the quadrangle, three of which are on or near the western edge of the mapped area and a fourth near the center of the quadrangle. Remnants of unit QTg cap ridges in three locations north of Pole Gulch in the southwestern part of the quadrangle. The remnants lie at different positions in the landscape and are elongated parallel to Pole Gulch, which suggests they are remnants of valley-fill deposits and are examples of inversion of topography. Since the deposits are at different positions in the landscape, they must have been deposited in at least two and perhaps three different paleovalleys at different times. A fourth and topographically higher remnant of unit QTg found to the west in the Jones Hill quadrangle (Widmann and others, 2007) documents the existence of an even older paleovalley.

Deposits of unit QTg in the southwest part of the quadrangle were mapped on the basis of float; no exposures were observed. The float consists of subround to subangular pebbles, cobbles, and minor amounts of boulders up to about 2 feet in diameter. Float from the topographically higher deposits consists mostly of volcanic rock that probably was derived from the volcanic flows preserved on Thunder Mountain and the nearby Buffalo Peaks. Clasts derived from Paleozoic sedimentary rocks are more common in the topographically lower deposits, and clasts derived from Precambrian crystalline bedrock were observed only in the topographically lowest deposits. This may reflect the clast compositions of the underlying deposits, or it could be due to greater disintegration of the Precambrian and Paleozoic lithologies in the higher and older deposits. The QTg deposits north of Pole Gulch appear to be typically 3 to 10 feet thick and perhaps as much as 40 feet thick locally. They range from about 20 to 160 feet above adjacent valley floors.

Two remnants of unit QTg cap ridges in the center and E ½ of section 22, T. 11 S., R. 77 W. Float overlying the deposits consists mostly of subround to subangular quartzite, sandstone, conglomeratic sandstone, chert, fine-grained granite porphyry, and sparse hornblende andesite, gneiss, pegmatite, and granitic rocks. A roadcut into the eastern end of the southerly remnant provides the only exposure of these deposits (fig. 9). These deposits consist of clast-supported sandy and silty pebble and cobble gravel that fills a channel cut into the Minturn Formation. The clasts are composed of Tertiary volcanic, Paleozoic sedimentary, and Precambrian crystalline lithologies. The clasts are imbricated in a subvertical orientation, suggesting the deposit has been tilted to the southeast. A carbonate horizon with weak stage IV morphology has formed on the deposit. Thickness of the deposits in the southerly remnant is about 5 to 10 feet; on the basis of their mapped extent, the deposits in the northern remnant may be thicker.

A single deposit of unit QTg armors the east side of a hill near the northwest corner of the quadrangle. No exposures of the deposit were observed. Float over the deposit consists of subround to subangular cobbles, pebbles, and sparse boulders as much as 1.5 to 2 feet in diameter. The clasts are composed of quartzite, quartz, sandstone, conglomeratic sandstone, limestone, chert, silicified breccia, and rare granitic and gneissic lithologies. The distribution of the deposit suggests it has been tilted to the northeast.

A small deposit of unit QTg caps the crest of Bare Hill near the center of the quadrangle. As at most other deposits of unit QTg, it was recognized only on the basis of float, which here consists of subround to subangular pebbles and cobble up to about 14 inches in diameter. The clasts are composed of sandstone, conglomeratic sandstone, chert,

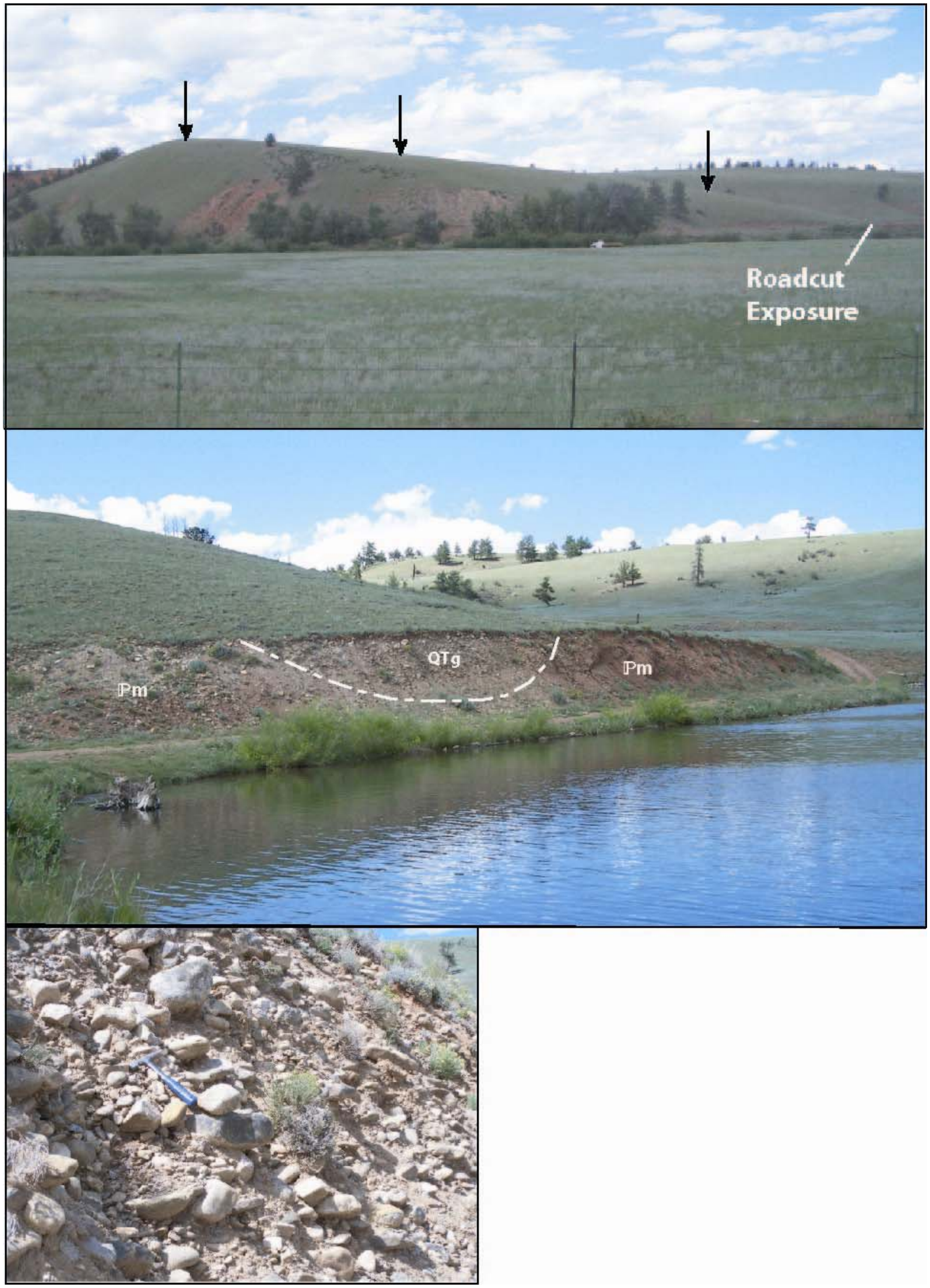

Figure 9. A southeast-tilted deposit of unit QTg caps a ridge on the north side of the South Fork (top photograph; taken from County Road 22 at UTM coordinates 414880 m E, 4325070 m N, looking north-northeast). Black arrows point to the gravel-capped ridge. A channel-shaped deposit of unit QTg is exposed in a roadcut adjacent to one of the fishing lakes on Arrowhead Ranch (middle photograph; location ~415130 m E, 4325500 m N; note: ranch is labeled Johnson Ranch on base map used for plate 1). Channel is cut into Minturn Formation (labeled ℙm). Imbricated clasts within unit QTg are stacked in a subvertical orientation (bottom photograph), which suggests the deposit has been tilted to the southeast.

quartzite, quartz, and granitic lithologies. Scattered gravel clasts are present along much of the hill top, which suggests the gravel cap was previously more extensive that the area mapped as unit QTg.

Ages of the deposits of QTg are poorly constrained. On the basis of their positions in the landscape and the presence stage IV carbonate morphology in one of the deposits, we conclude they probably range from middle or early Pleistocene to late Tertiary in age. As demonstrated by the QTg deposits north of Pole Gulch, not all QTg deposits are of the same age.

Mass-Wasting Deposits – Mass-wasting deposits accumulate on hillslopes and adjacent valley floors. They are transported downslope primarily by gravity. Colluvium and landslide deposits are the principal types of mass-wasting deposits in the quadrangle. The classification system of Cruden and Varnes (1996) is used to describe the type of slope movement.

Qc **Colluvium (Holocene and upper Pleistocene) –** Includes deposits of poorly sorted, sandy or silty, fine to coarse gravel, gravelly sand, and gravelly silt that are on hillslopes or at the foot of the hillslope. Colluvium can be rich in boulders below cliffs and rocky outcrops. As used here, colluvium generally follows the definition of Hilgard (1892) in that it (1) is derived locally and transported only short distances, (2) is not distributed by channelized water flow, (3) contains clasts of varying size, (4) has little or no sedimentary structures or stratification, features which are typically caused by channelized flow of water, and (5) may include minor amounts of sheetwash and debris-flow deposits. Unit Qc may locally include landslide deposits or talus that either are too small to differentiate at the map scale or which are difficult to clearly discern on aerial photographs. Clasts in colluvium typically are angular to subangular, except in areas where the bedrock or surficial deposits in source areas for the colluvium contain well-rounded clasts. Maximum thickness of colluvium is estimated at about 20 feet.

Qls **Landslide deposits (Quaternary) –** Landslide deposits consist of heterogeneous, mostly unsorted and unstratified debris that commonly is characterized by hummocky topography. Only three landslide deposits were identified in the quadrangle. One is located on the east side of the Dakota hogback and south of the Middle Fork water gap. It apparently involves a slope failure in the Benton Group and/or Niobrara Formation. A second landslide deposit is on the west side of Red Hill; it formed in colluvium overlying the Morrison Formation. The third landslide formed on a north-facing slope underlain by the Minturn Formation between the South Fork of the South Platte River and the High Creek fen. In that evaporite subsidence features are prevalent in this area, the landslide deposit may be related to evaporite subsidence. The small landslide deposits on Red Hill probably are about 10 to 20 feet thick, and the one in the Minturn Formation may be slightly thicker.

Alluvial and Mass-Wasting Deposits – Deposits of alluvium and colluvium that are juxtaposed and too small to show individually or have contacts that are not clearly defined are mapped as a single combined unit. Fan deposits are included in this combined category because, in addition to alluvium, they also include significant volumes of debris-flow sediment, which is generally considered to be the result of mass wasting (Cruden and Varnes, 1996; Hungr and others, 2001).

Qf **Fan deposits (Holocene and upper Pleistocene) —** Includes sediment beneath geomorphically distinct fans at the mouths of tributary valleys. In some areas the deposits from adjacent valleys merge to form fan complexes. Fan deposits are chiefly poorly sorted, clast-supported sandy gravel and gravelly sand deposited as alluvium during storm events, but locally they include debris-flow deposits that are composed of matrix-supported, poorly sorted, silty or sandy gravel. Clasts contained in fan deposits are mainly subangular to angular. Maximum thickness of the fan deposits is estimated at 25 feet.

Qac **Alluvium and colluvium (Holocene and upper Pleistocene) —** Unit Qac consists of alluvial sediments in (1) channels, flood plains, and low terraces in tributary drainages and (2) colluvium and sheetwash along valley margins and hillslopes. The alluvial component of the unit is very poorly sorted to well sorted and ranges from sandy pebble, cobble, and boulder gravel to stratified fine sand and silt. Clasts in the alluvial component are subangular to subround. The colluvial part consists of very poorly sorted, unstratified or poorly stratified, gravelly to silty sand, sandy to silty gravel, and gravelly sandy silt. Clasts in the colluvial part are chiefly angular to subangular. The unit may locally include debris-flow deposits, which typically are matrix-supported gravelly silt, and also small landslides or soil slips. Thickness of unit Qac is estimated to range from 3 to 20 feet.

Lacustrine Deposits — Sediments deposited in lakes.

Ql **Lacustrine deposits (Historic) —** Lacustrine deposits exist in the basin in the SW ¼ of section 16 and SE ¼ of Section 17, T. 12 S., R. 76 W. in the southeast part of the quadrangle. The topographic map shows this basin as an arm of Antero Reservoir that fills with water when the reservoir is nearly full. When visited during the summer of 2006, the basin was dry. A shallow pit dug about 2 feet into the floor of the basin revealed interbedded layers of medium-red-brown and medium-gray silty clay and clayey silt with very thin beds of fine sand and thin beds and blebs of dark-gray to black organic-rich clay. Thickness of the historic lacustrine deposits is unknown.

Undifferentiated Surficial Deposits

Q **Surficial deposits, undivided (Quaternary) —** Shown only on cross sections.

BEDROCK

Tertiary Sedimentary and Igneous Rocks

Tw **Wagontongue Formation (Miocene) —** Poorly lithified sedimentary rocks of the Wagontongue Formation fill much of the axial part of the High Creek syncline in the southeast part of the quadrangle. The basal part of the unit is somewhat resistant to erosion and underlies ridges on the flanks of the syncline. Three exposures of the ridge-forming unit were observed in shallow human-made excavations. In these exposures the deposits consisted of mostly massive or weakly bedded sandy cobble and pebble conglomerate with occasional lenses of medium- to coarse-grained sandstone and clayey fine-grained sandstone. The conglomerate clasts are composed of various Precambrian granites and gneisses, hypabyssal intrusive rocks, quartzite, sandstone, conglomeratic sandstone, and sparse andesitic volcanic rocks. Most are subround or subangular. Clasts of igneous and metamorphic rocks are strongly to moderately decomposed (fig. 10).

The upper part of the unit is not exposed. These deposits underlie the topographically subdued area along and immediately adjacent to the axis of the syncline. Because these rocks underlie areas that are topographically subdued relative to the ridge-forming conglomerate beds, it is possible that they are finer grained and more easily eroded. Refer to the chapter on stratigraphy for a summary description of historical nomenclature for this formation, which we correlate with the Miocene Wagontongue Formation. Maximum thickness of the Wagontongue Formation is estimated at 750 feet on the basis of cross section B-B'.

Figure 10. Weakly lithified, silty, sandy, cobble and pebble conglomerate in the Wagontongue Formation exposed in a small excavation at about UTM coordinates 422070 m E, 4321970 m N. View is to east-northeast, parallel to the direction that the beds dip. Small white "plus signs" denote several of the many decomposed clasts in the unit. Note the shingling or imbrication of clasts, which suggest the gravel was deposited by a stream flowing from left to right. Yellow notebook is 5 x 7.5 inches.

Ts Sedimentary rocks (Oligocene?) — Moderately indurated sedimentary rocks of probable Oligocene age crop out in two small areas along U.S. Highway 285. One of these areas is in the SW ¼ of section 26 on the west side of the hill near where the "Rogers Ranch" is shown on the base map. The unit also is exposed in a borrow ditch on the west side of Highway 285 about 1.3 miles north of the Rogers Ranch location. The deposits consist of poorly sorted, light-red-brown, silty, sandy pebble conglomerate and pebbly sandstone with a calcareous matrix (fig. 11). Clasts within the deposit are subangular to subround fragments of sandstone, shale, conglomeratic sandstone, and limestone locally derived from Pennsylvanian rocks. The lateral extent and thickness of these rocks are not known. Unit Ts is inferred to be Oligocene in age, but could be Eocene.

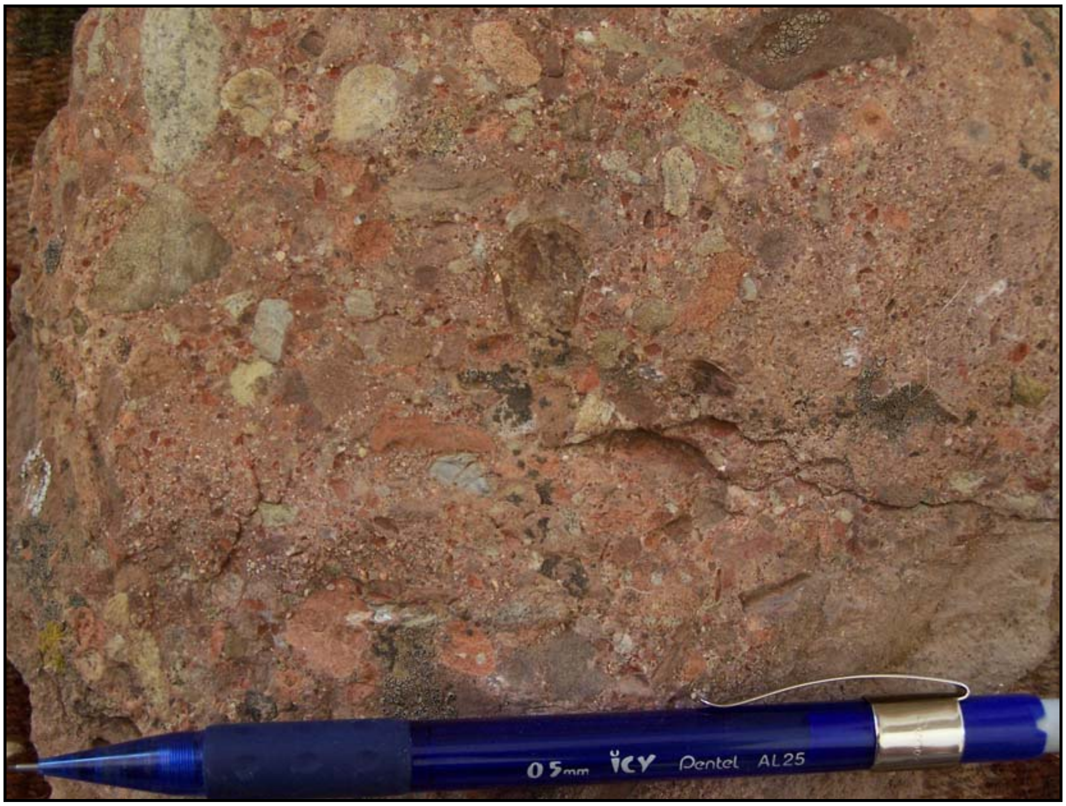

Figure 11. Typical outcrop of unit Ts, consisting of moderately well indurated, silty, sandy, pebble conglomerate. Sample is from a borrow pit on the west side of U.S. Highway 285 approximately at UTM 415740 m E, 4325750 m N.

Antero Formation (Oligocene) — The Antero Formation is divided into two informal members, a tuffaceous member and a lenticular underlying limestone member. Both members are restricted to the High Creek syncline.

Ta Tuffaceous member — The weakly indurated tuffaceous member of the Antero Formation underlies topographically subdued strike valleys on the flanks of the High Creek syncline. It is very poorly exposed in the quadrangle. The deposit was primarily recognized on the basis of float consisting of sparse, small chips of tuffaceous mudstone and tuff. A single good exposure was seen in the bottom of a slot trench located at approximately UTM coordinates 422510 m E, 4320220 m N. The trench was too narrow for the exposure to be closely examined, therefore bedding and other macroscopic characteristics were not observable.

The material in the trench was composed entirely of white to cream fine-grained, crystal-vitric tuff of andesitic composition. It contained abundant small (0.03 to 0.15 mm) crystal fragments composed mostly of plagioclase, hornblende, and biotite, with minor amounts of sanidine and augite. Fresh fragmental glass shards and pieces of pumice and collapsed pumice clasts are present. No rounded detrital grains were noted; however, sparse grains of epidote and the very fine-grained clayey matrix suggest the rock might be slightly reworked.

To the south, De Voto (1971) reported that the Antero Formation included volcanic and arkosic sandstone, tuff-pebble conglomerate, siltstone, mudstone, and shale in addition to the tuff beds. This suggests unit Ta may contain lithologies other than tuff within the Garo quadrangle. Previous workers (for example, Brown, 1940; Stark and others, 1949; Lozano, 1965; De Voto, 1971) assigned an Oligocene age to the tuffaceous part of the Antero Formation on the basis of paleontological evidence. Recent ^{40}Ar/^{39}Ar dating of tuff beds and tuffaceous sediments in the Antero Formation in the region (McIntosh and Chapin, 2004) yielded ages of about 33.8 Ma (early Oligocene). Maximum thickness of the tuffaceous member is estimated at about 400 feet. It thickens from north to south along the western flank of the High Creek syncline.

Tal **Limestone member** — The limestone member of the Antero Formation locally underlies the base of the tuffaceous member of the Antero Formation. It rests on either andesitic and dacitic volcanic rocks (unit Tad) or sedimentary rocks of the Maroon Formation (unit PIPm). Thin, lenticular limestone beds and siliceous chert-like beds comprise the only lithologies observed in this poorly exposed unit within the quadrangle. To the south, limestone beds also are interbedded with the tuffaceous member (Johnson, 1937b; De Voto, 1971), but none were noted in this stratigraphic position in the very poorly exposed outcrops in the Garo quadrangle. The limestones are white or gray where weathered and tan to medium brown where fresh. They range from lime mudstones to packstones to porous calcareous tufa with mineralized plant fragments. Some beds include rounded ripup clasts suggestive of lacustrine environments. The siliceous chert-like beds may have resulted from silicification of limestone beds or from alteration or dissolution of volcanic ashes that fell into alkaline lakes. In some locations the siliceous beds are at the base of the member (fig. 12). The distinctive algal features reported by Johnson (1937a, b) in limestone beds elsewhere in South Park were not observed in the Garo quadrangle. Thickness of the limestone member is uncertain, but may be a maximum of about 40 feet in the quadrangle.

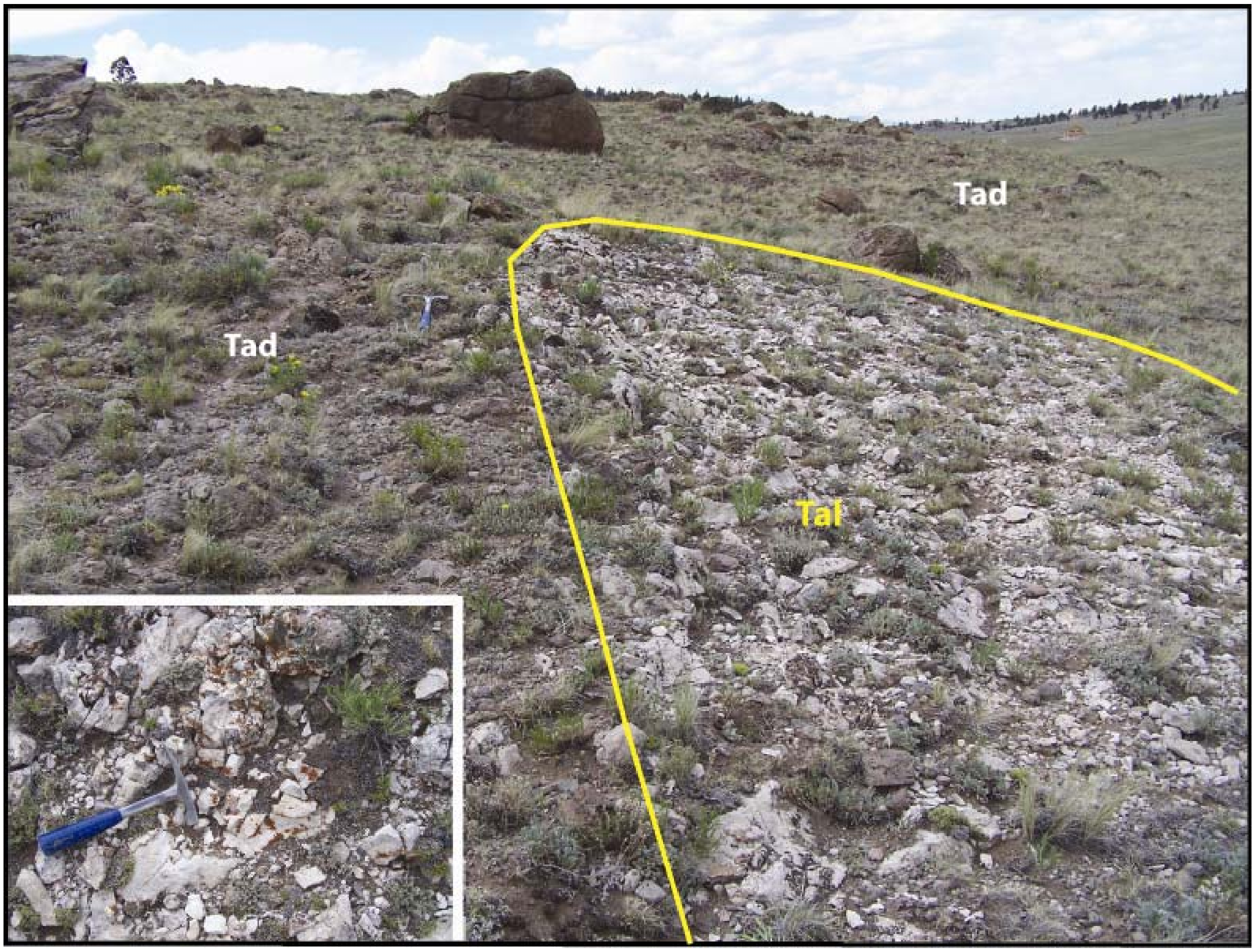

Figure 12. Relatively thin, east-dipping strata in the basal part of the limestone member of the Antero Formation (Tal) form multiple mini-flatiron-like scabs that overlie the andesitic and dacitic rocks of unit Tad. The base of the limestone member is marked by the yellow line. Siliceous chert-like beds (shown in inset photograph) comprise the basal 0.5 to 1.5 feet of the limestone member at this location. View is to north, approximately at UTM coordinates 422760 m E, 4319195 m N.

Ttc Tallahassee Creek Conglomerate (Eocene) — Deposits of coarse-grained conglomerate crop out at the northern end of the Lone Hills. No exposures of this unit were discovered. Its extent was mapped on the basis of large boulders (as much as 6 feet in length) and cobbles composed of Proterozoic intrusive lithologies, andesitic, felsic, and basaltic lithologies, and pegmatite, quartz, and quartzite that litter the ground surface (fig. 13). Some of the more resistant clasts are polished and grooved ventifacts. Although very poorly exposed, the unit appears to be a poorly or moderately lithified conglomerate rich in boulders that overlies the rocks of unit Tad, in which case it probably is correlative with the Tallahassee Creek Conglomerate of Epis and Chapin (1974). It is also possible that the deposits underlie or are intercalated within the andesitic and dacitic volcanic rocks of unit Tad, in which case they would be older than the Tallahassee Creek Conglomerate. Thickness is uncertain, but the unit probably is no more than about 15 to 25 feet thick.

Figure 13. Boulders and cobbles of granitic, gneissic, and volcanic rocks, quartz, pegmatite, and quartzite litter the ground surface in areas underlain by the Tallahassee Creek Conglomerate (upper photograph; view is to east). Granitic boulders are commonly very weathered (lower left photograph). Note the bench-like erosional rim on the left side of the boulder that is subparallel to the ground surface. The more erosion resistant boulders and cobbles on the ground surface in this area are ventifacted (lower right photograph). All photographs in this figure were taken in the SE ¼ of the SW ¼ of section 29, T. 11 S., R. 76 W.

Twm Wall Mountain Tuff (Eocene) — Remnants of the Wall Mountain Tuff are preserved in outcrop only on the flanks of the High Creek syncline. The formation is a devitrified, densely welded, vitric-crystal-lithic ash-flow tuff that often forms prominent outcrops. It has remnant glass shard textures, although the glass is completely devitrified. A glassy vitrophyre is locally present at the base of the unit. Abundant collapsed pumice clasts, some with crystal fragments, comprise 10 to 15 % of the tuff. Phenocryst assemblages include sanidine (12 to 15 % by volume), plagioclase (8 to 10 %), biotite (1 to 2 %), augite (trace to 0.5 %), and accessory magnetite, zircon, and allanite. Feldspar phenocrysts are fresh and occur as relatively large crystal fragments. The proportion of sanidine exceeds plagioclase, but there are considerable large plagioclase crystal fragments. Three whole-rock samples of the Wall Mountain Tuff were chemically analyzed using XRF methods (samples G153, G159, and G178; see Appendix A). Silica content ranged from 67.4 to 70.3 %, and alkali content varied from 8.5 to 9.6 %. Two of the three samples plot in the rhyolite field in the total alkali-silica diagram, and the third plots in the trachydacite field near the rhyolite field (fig. 14).

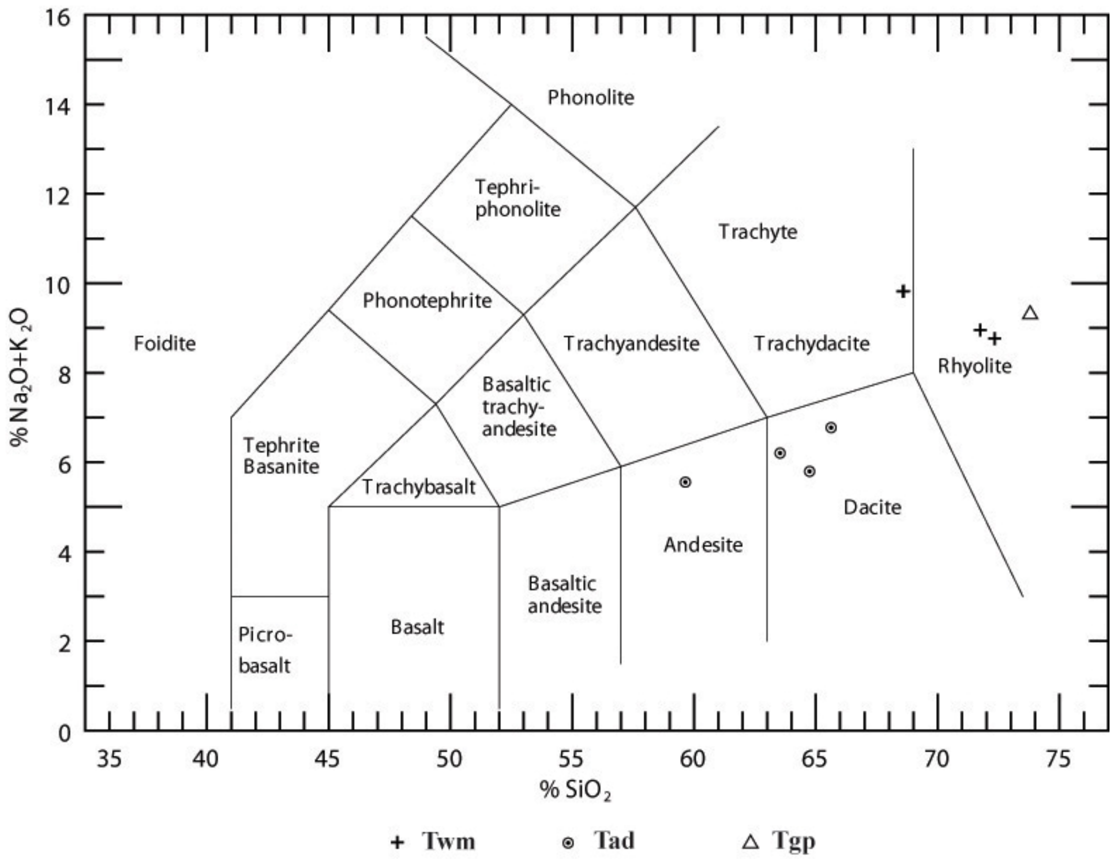

Figure 14. Total alkali-silica diagram of volcanic and selected intrusive rock samples from the Garo quadrangle. The analysis of the intrusive stock (Tgp) is included to allow for comparisons with the chemistry of the volcanic rocks. Classification scheme is that of Le Bas and others (1986). Values are in weight percent and are water and volatile free and summed to 100 %. See Appendix A for the geochemical analyses.

The ash-flow tuff locally crops out on the flanks of the High Creek syncline. Several relatively thick lens-shaped remnants crop on the west flank of the syncline. Each lens-like body of tuff appears to fill a topographic low, perhaps a paleovalley with approximate west-east orientation, and they overlie andesitic and dacitic flows, flow breccias, and lahars of unit Tad. Where thick, the ash-flow tuff remnants usually form prominent cliffs that contrast sharply with the underlying andesitic and dacitic rocks (fig. 15). Since the remnants of tuff are disconnected, it is unclear whether each lens flowed down a separate paleovalley or if the tuff blanketed the area and the upper part of the tuff unit was subsequently removed by erosion from the interfluves prior to deposition of the overlying tuffaceous member of the Antero Formation (unit Ta). On the east flank of the High Creek syncline the ash-flow tuff is very thin or absent, and it rests on sedimentary rocks of the

Minturn Formation. Most of the ash-flow tuff outcrops on the east flank of the syncline are on the adjacent Hartsel quadrangle.

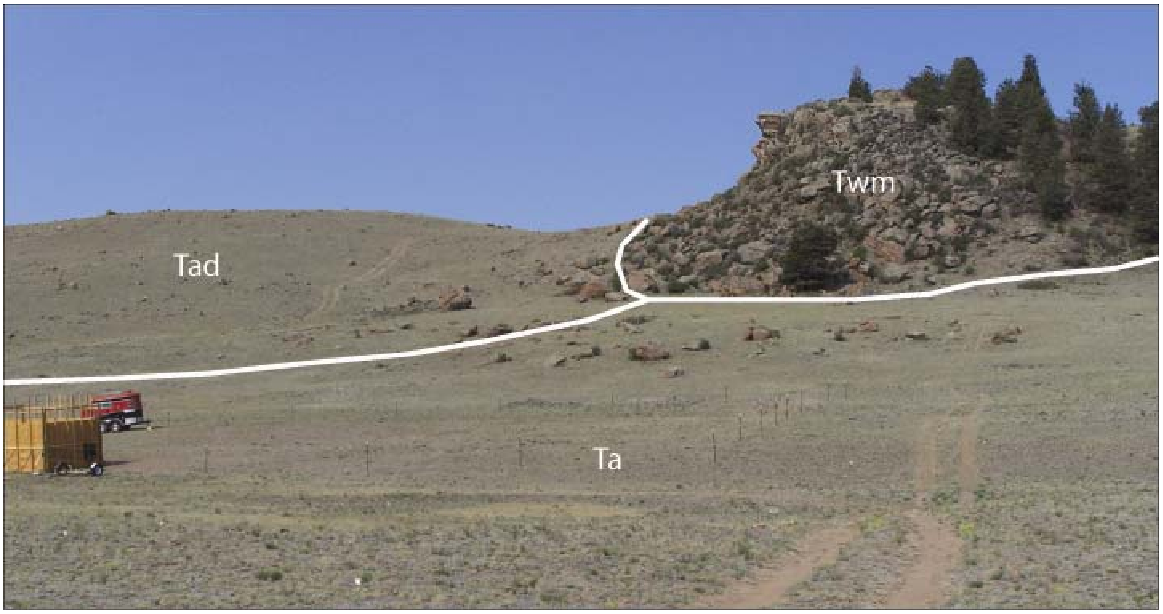

Figure 15. The Wall Mountain Tuff forms the prominent cliff on the right. Rounded hills with scattered boulders to the left (south) of the cliff are underlain by the less resistant andesitic and dacitic flows, flow breccias, and lahars of unit Tad. The valley in the foreground is underlain by the easily eroded tuffaceous member of the Antero Formation. View looking west from approximately UTM coordinates 422550 m E, 4320080 m N. All three formations dip eastward toward the photographer's position.

McIntosh and Chapin (2004) reported an average $^{40}Ar/^{39}Ar$ age of 36.69 ± 0.09 Ma for the Wall Mountain Tuff on the basis of five analyzed samples from elsewhere in the region. The five samples ranged in age from 36.61 ± 0.11 Ma to 36.78 ± 0.21 Ma. Sample G153, which was collected from an outcrop of tuff in the Lone Hills within the quadrangle, yielded an $^{40}Ar/^{39}Ar$ age of 36.93 ± 0.11 Ma (Table 1), which is within the age range of the samples dated by McIntosh and Chapin (2004). The age of the tuff in the quadrangle, along with the similarities in chemistry and phenocryst assemblages, indicates the ash-flow tuff in the Lone Hills is correlative with the Wall Mountain Tuff. Maximum thickness of the Wall Mountain Tuff is estimated at 150 to 200 feet.

Tad Andesitic and dacitic volcanic rocks (Eocene) — A thick sequence of porphyritic andesite and dacite flow breccias, volcanic lahars, and lava flows crops out in the Lone Hills on the west flank of the High Creek syncline. These rocks underlie the Wall Mountain Tuff. The andesitic to dacitic rocks are easily weathered and form very poor outcrops. The best exposures were seen in roadcuts and in isolated boulders scattered across the hills. Petrographically the rocks include the following: hypersthene-biotite-augite-hornblende andesite porphyry and andesite porphyry breccia with glassy groundmass and abundant very fine to fine flow-aligned microlites or with non-glassy aphanitic groundmass; and augite andesite with a glassy groundmass with well-developed flow-layered microlites.

Table 1. Age dates for igneous rocks.

Unit	Samples dated during this study using $^{40}Ar/^{39}Ar$ methods (see Appendix B)		Previously published ages	
	Age	**Material dated**	**Age**	**Material dated**
Twm	36.93 ± 0.11 Ma (sample G153)	sanidine	36.69 ± 0.09 Ma[1]	
Tad	38.59 ± 0.14 Ma (sample G164)	biotite	37.8 ± 1.3 Ma[2]	biotite

[1] average of five $^{40}Ar/^{39}Ar$ ages on Twm in the region; reported by McIntosh and Chapin (2004)
[2] K-Ar age on Tad from southern end of Lone Hills by Bryant and others (1981a); recalibrated by Wilson and Bryant (2006)

Chemically the andesitic and dacitic rocks in unit Tad contain 59.4 to 65.5 % silica and 5.4 to 6.5 % total alkali (Appendix A). On the total alkali-silica diagram of Le Bas and others (1986) the samples plot in the dacite and andesite fields (fig. 14). Lahars (volcanic debris flows) within the unit are matrix-supported, cobbly, pebbly, and bouldery, volcaniclastic mudstones. On the basis of petrographic characteristics and one chemical analysis (G150), the clasts are similar to the flows and flow breccias in the formation. Ventifacts composed of unit Tad are locally common in the float overlying unit Tad on Lone Hill.

An Eocene age is assigned to the unit on the basis of an $^{40}Ar/^{39}Ar$ age of 38.59 ± 0.14 Ma on biotite from sample G164, a dacitic flow breccia in the middle of the unit (see Appendix B). Maximum thickness of unit Tad is estimated at 850 feet on the basis of cross section B-B’ (plate 2).

Tgp **Granite porphyry (Paleocene) —** Granite porphyry crops out in two small areas in the northwestern part of the quadrangle west of Highway 285 and north of the South Fork. Both are probably apophyses of the much larger intrusion at Black Mountain in the Jones Hill quadrangle, which has similar mineralogy and chemistry. Unlike prominent Black Mountain, the bodies of granite porphyry in the Garo quadrangle are only moderately resistant to weathering and form only slightly positive landforms. The rock has a fine-grained, potassium-feldspar-rich, granophyric groundmass consisting of 0.01 to 0.1 mm long crystals. Subhedral phenocrysts of potassium feldspar comprise 2 to 3 % of the rock, about 1 % of the rock consists of quartz phenocrysts, 1 % is plagioclase phenocrysts, and 0.5 % is biotite.

The rock is relatively fresh. The feldspar phenocrysts have weak clay alteration, the biotite grains are partly oxidized, and there are minor amounts of iron oxides along the grain boundaries. One sample of granite porphyry (G314) was chemically analyzed. It contained 72.8 % SiO_2, 4.0 % Na_2O, and 5.1 % K_2O. The sample of granite porphyry had the lowest Fe_2O_3 (0.5 %), CaO (0.7 %), MgO (0.1 %), P_2O_5 (0.02 %), and BaO (0.08 %) of all the analyzed rock samples from the quadrangle (Appendix A). The granite porphyry intrusion at Black Mountain in the adjacent Jones Hill quadrangle, which probably is part of the same intrusive as the granite porphyry in the Garo quadrangle, yielded an $^{40}Ar/^{39}Ar$ age of 60.95 ± 0.15 Ma (Widmann and others, 2007; also Appendix B in this report).

South Park Formation (Paleocene and Upper Cretaceous) — The only member of the South Park Formation that is exposed within the quadrangle is the coarse-grained conglomeratic member (unit Tsc). It is the lowermost member of the formation. Refer to the Stratigraphy chapter for a brief summary description of the stratigraphy of the South Park Formation.

Tsc Coarse-grained conglomeratic member (Paleocene) — The coarse-grained conglomeratic member underlies a very small area on the west flank of Reinecker Ridge in the northeast corner of the mapped area. This weakly lithified unit, which is very poorly exposed in the quadrangle, consists of clast-supported, polymictic, pebble, cobble, and boulder conglomerate and interbedded thin beds of sandstone and siltstone, some of which are volcaniclastic or tuffaceous. Because the boulders and cobbles that comprise the unit are mostly composed of hard, indurated lithologies, the unit is resistant to erosion and is responsible for the relatively high relief of Reinecker Ridge compared to adjacent valleys. In areas underlain by the coarse-grained conglomeratic member of the South Park Formation, the ground surface is strewn with subangular to well-rounded pebbles, cobbles, and, boulders. Boulders 2 to 4 feet in diameter are common in the unit, and boulders as large as 8 feet in diameter were observed on Reinecker Ridge in the adjacent Fairplay East quadrangle (Kirkham and others, 2006), which indicates the member was deposited in a very high-energy environment. Subtle benches and topographic breaks are apparent on the western and eastern slopes of Reinecker Ridge. Cobbles and boulders are rare on these landforms, which suggests they are underlain by thin, lenticular beds of finer-grained clastic and/or tuffaceous strata that are interbedded with the conglomeratic beds.

Some clasts in the conglomeratic member are strongly decomposed and have thick weathering rinds, but others are little affected by weathering and are still very sound. Clast lithologies include various intermediate-composition and felsic intrusive rocks, as well as andesite and basalt, red Pennsylvanian and Permian sandstones, rare hornfels and skarn derived from contact-metamorphosed Pennsylvanian and Permian rocks, rare Dakota Sandstone, and black, cherty pebbles from an undetermined formation. Intrusive rocks are the most abundant clasts, and they also tend to be the largest clasts. Sparse silicified wood is locally present in the member in adjacent areas, but none was noted in the quadrangle. Clasts of Proterozoic crystalline rock were not observed. Andesite clasts are abundant near the base of the member and become increasingly scarce in younger beds. The estimated maximum thickness of the coarse-grained conglomeratic member of the South Park Formation in the Fairplay East quadrangle is 1,300 feet; however, only about the basal 350 to 400 feet of the member is present in the Garo quadrangle.

$^{40}Ar/^{39}Ar$ dates obtained on three clasts from the coarse-grained conglomeratic member in nearby areas help constrain its age (Widmann and others, 2005; Kirkham and others, 2006). The dated clasts ranged from 64.08 ± 0.11 Ma to 66.6 ± 0.5 Ma, which indicates the conglomeratic member is younger than 64 Ma and probably is Paleocene.

Mesozoic Sedimentary Rocks

Kp **Pierre Shale (Upper Cretaceous) —** The Pierre Shale typically consists of medium- to dark-gray, calcareous, marine shale with relatively thin zones of brownish-gray to olive-drab sandstone. The formation underlies the valley floors of Trout Creek and the Middle Fork of the South Platte River downstream of the water gap cut through the Dakota hogback. No outcrops of the Pierre Shale were observed in the quadrangle, because it is concealed by surficial deposits or residuum. Refer to prior publications (for example, Stark and others, 1949; Sawatsky, 1967; Widmann and others, 2005; Kirkham and others, 2006) for more complete descriptions of the Pierre Shale.

In nearby quadrangles Barker and Wyant (1976) and Wyant and Barker (1976) estimated the total thickness of the Pierre Shale at about 6,000 feet. However, an unknown thickness of upper Pierre strata was removed when an angular unconformity was cut across it at the end of the Cretaceous prior to deposition of the South Park Formation. We estimate that only the lower 2,000 to 2,500 feet of the lower part of the Pierre Shale is preserved in the quadrangle. The Pierre Shale conformably overlies the Niobrara Formation.

Kn **Niobrara Formation (Upper Cretaceous) —** The Niobrara Formation, which is poorly exposed in the quadrangle, crops out at the eastern base of Red Hill. In adjacent areas the Niobrara Formation is divided into two members, the Fort Hays Limestone Member and the overlying Smoky Hill Shale Member (Barker and Wyant, 1976; Wyant and Barker, 1976; Widmann and others, 2005). The Fort Hays Limestone Member consists of about 40 to 100 feet of gray fossiliferous marine limestone, and the Smoky Hill Shale Member is a medium- to dark-gray, yellow-weathering, calcareous, marine shale about 350 feet thick. In most places within the Garo quadrangle, the Niobrara Formation is concealed by surficial deposits and residuum, although a fair exposure was observed in a roadcut southeast of the Middle Fork water gap through the Dakota hogback. Exposed strata consist of hackly weathering light-gray limestone that probably is part of the Fort Hays Limestone Member. The Niobrara Formation disconformably overlies the Benton Group.

Kb **Benton Group, undivided (Upper Cretaceous) —** The poorly exposed Benton Group also crops out at the eastern base of Red Hill. Three formations comprise the group in nearby areas (Barker and Wyant, 1976; Wyant and Barker, 1976). In ascending order these formations are the Graneros Shale, Greenhorn Limestone, and Carlile Shale. The Graneros Shale is a dark-gray shale about 300 feet thick; the Greenhorn Limestone includes gray shaly limestone and brown fetid calcareous sandstone with globigerinid foraminifers; and the Carlile Shale is chiefly black shale that is capped by a brown, fossiliferous, fetid, calcareous sandstone called the Juana Lopez Member (Barker and Wyant, 1976; Wyant and Barker, 1976). In the Garo quadrangle the Benton Group is generally concealed by surficial deposits and residuum. The only exposure of these rocks is on the east side of Red Hill, southeast of the Middle Fork water gap through the Dakota hogback. Most of this exposure consists of light- to medium-gray shale, with a thin bed of limestone (fig. 16). Although only a small part of the group is exposed, this is the best outcrop of the Benton strata observed in the Como, Fairplay East, and Garo quadrangles. To the east, Barker and Wyant (1976) and Wyant and Barker (1976) reported a total thickness of about

600 feet for the Benton Group, with the Graneros Shale being about 300 feet thick and a combined thickness of about 300 feet for the Greenhorn and Carlile formations. Widmann and others (2005) described a total thickness of only 250 feet for the entire group. The Benton Group conformably overlies the Dakota Sandstone.

Kd **Dakota Sandstone (Lower Cretaceous) —** Exposures of the Dakota Sandstone are found along the crest of Red Hill, which is a hogback ridge held up by the hard, well-indurated rocks of the Dakota Sandstone. The formation consists mostly of tan or light-gray, coarse- to fine-grained quartzose sandstone, conglomeratic sandstone, and conglomerate, all of which typically weather yellow brown. Sandstone beds are moderately well sorted, and cross-bedding is common. Conglomeratic lenses are prevalent near the base of the unit. They contain subround to round pebbles and granules of chert or quartz; some lenses are arkosic, and angular ripup clasts from the underlying Morrison Formation are locally present. Thin beds of light- to dark-gray, greenish-gray, and light-brown shale occur in the unit, most commonly in the middle part. Well-developed deformation bands are locally abundant (fig. 17). Estimated thickness of the Dakota Sandstone is 175 to 200 feet. The Dakota Sandstone typically disconformably overlies the Morrison Formation, although in the center of the W ½ of section 4, T. 11 S, R. 76 W. a broad channel of Dakota strata appears to be cut into the Morrison rocks.

Figure 16. Outcrop of the Benton Group on the east side of Red Hill at approximately UTM coordinates 424490 m E, 4327660 m N.

Jm **Morrison Formation (Upper Jurassic) —** The Morrison Formation crops out on the hillslope on the west side of Red Hill; however, it is very poorly exposed. In nearby areas the formation is described as chiefly green, red, and gray, commonly bentonitic claystone and interlayered fine- to medium-grained sandstone, siltstone, and limestone that is a total of 200 to 350 feet thick (Stark and others, 1949; Barker and Wyant, 1976; Widmann and others, 2005). The only exposures discovered during the project were in a roadcut on the west side of Colorado Highway 9 north of the Middle Fork's water gap through the Dakota hogback, several feet of mudstone and thin limestone are exposed. The Morrison Formation disconformably overlies the Garo Formation.

Figure 17. Deformation bands are locally well developed in the Dakota Sandstone adjacent to a small fault that crosses the hogback ridge. Photograph taken at approximately UTM coordinates 422550 m E, 4330340 m N. View is to north.

Paleozoic Sedimentary Rocks

Pg **Garo Sandstone (Permian?) —** Good outcrops of the Garo Sandstone exist north of the Middle Fork water gap through the Dakota hogback. According to Simmons (2002), the rock ledges here were used as a natural fort by native Americans. The Garo Sandstone is chiefly light-pink to red or light-gray, fine- to medium-grained, quartz-rich, generally calcareous sandstone. Most beds are moderately well sorted; some have bimodal sizes of sand grains. Quartz grains are generally round or subround; coarser grains are sometimes frosted. Large-scale cross-bedding is locally prominent, as are small round nodules of uncertain origin. The Garo Sandstone is generally less micaceous and more calcareous than the Maroon Formation. Deformation bands are locally common.

Age of the Garo Sandstone is uncertain. Some workers assigned it to the Permian, while others correlate it with the Jurassic Entrada Sandstone. Refer to the Stratigraphy chapter for a summary of these discussions. We utilize the age assignment and stratigraphic relationships of De Voto (1965a, 1965b), who prefers a Permian age for the Garo Sandstone and believes the Garo conformably overlies the Maroon Formation and was deposited synchronously with the uppermost shales of the Maroon in adjacent areas. A complete section of the Garo Sandstone was not exposed in the quadrangle, therefore the thickness is not precisely known. De Voto (1965a) reported a thickness of 62 feet in a measured section located on the east side of Highway 9 about 2 miles southeast of where the highway leaves the eastern edge of the Garo quadrangle. The Garo Sandstone appears to be about this thick in the quadrangle.

PIPm Maroon Formation (Lower Permian to Upper and Middle Pennsylvanian) — The Maroon Formation underlies portions of the northeast and south-central parts of the quadrangle but is concealed by surficial deposits in much of this area. Surface exposures can be seen in and near the Garo mining district, along the western side of the Bare Fault, and at Arrowhead Ranch in the SE ¼ of section 21 and SW ¼ of section 22, T. 11 S., R. 77 W.

Red to reddish-brown laminated siltstone is the dominant lithology in the Maroon Formation in the quadrangle. The siltstone beds crop out poorly; typically they are weathered to red, silty soils. In the NE ¼ and SE ¼ of section 16, T. 11 S., R. 76 W., the siltstones are interbedded with sandstone, conglomerate, limestone, and dolostone. Sandstone and conglomerate beds are pink, arkosic, about 1 to 10 feet thick, and commonly lens-shaped. Sandstones are coarse grained, and many contain granules and small pebbles. Conglomerates contain granules, pebbles, and cobbles of granitic detritus, quartzite, and vein quartz in a coarse sandy matrix. Planar beds and trough cross-beds occur in both the sandstones and conglomerates. Stratigraphically higher exposures in the N ½ of section 16 and the SW ¼ of section 9 have rare sandstone beds and no conglomerate.

The limestone beds are about 0.5 to 3 feet thick, and some, especially in and near the Garo mining district, are partially to completely replaced by silica. The limestone beds typically are more resistant to erosion and crop out better than most other strata in the formation (fig. 18). Most are gray and micritic with white calcite veins, and some are silicified. Some contain stromatolites and intraclasts. The dolostone beds are 1-2 ft thick, gray, and fine to medium grained. Carbonate beds are denoted on the map and cross-sections by the blue lines. Two limestone-rich zones up to 60 ft thick are correlative with the Silverheels and Fairplay limestones in the Fairplay East quadrangle (Kirkham and others, 2006). These limestone zones are further described below.

West of the Bare fault, the sandstones and conglomerates of the Maroon Formation change facies to planar-laminated and ripple cross-laminated fine sandstone. These sandstones are red, pink, green, or gray in color. Medium- and coarse-grained sandstone beds occur rarely in the lower 500 feet of the formation. The limestone beds change facies to calcareous shale or siltstone that is reddish, greenish, or gray in color.

Figure 18. East-dipping gray limestone beds in the Maroon Formation form V-shaped outcrops in this arroyo west of the Garo town site. The two limestone beds, a prominent one in the center of the picture and a much thinner and less obvious one that is best exposed where it crosses the arroyo near the lower left corner of the photograph, contrast sharply with the red-brown clastic beds, which tend to erode more easily. View looking south from approximately UTM coordinates 422130 m E, 4328840 m N.

No complete sections of the Maroon Formation appear in the quadrangle, and the upper contact is not exposed. In the adjoining Fairplay East quadrangle the formation is about 5,300 to 5,600 feet thick (Kirkham and others, 2006). The Maroon Formation is thought to conformably overlie the Minturn Formation (Tweto, 1949; Tweto and Lovering, 1977).

FL **Fairplay limestone member** – The Fairplay limestone member is denoted on the geologic map and cross sections by a bracket labeled "FL" that spans two limestone beds. It consists of gray limestone, red siltstone, and minor fine-grained sandstone in a zone about 60 feet thick. Limestone beds within the member vary from about 0.5 to 2 feet thick. Most beds are stromatolitic (fig. 19); the others are micritic, and some contain intraclasts. The uppermost limestone is sandy and micaceous. In the adjacent Fairplay East quadrangle the top of the Fairplay limestone lies about 1,900 ft above the base of the Maroon Formation.

Figure 19. Algal laminations in the Fairplay limestone member. Outcrop is located approximately at UTM coordinates 423075 m E, 4326690 m N.

SL **Silverheels limestone member** – The Silverheels limestone member is denoted on the geologic map and cross sections by a limestone bed labeled "SL". It consists of gray sandy limestone and reddish, slightly pebbly coarse-grained sandstone interbedded with red calcareous siltstone. The member is about 30 feet thick, but individual limestone beds are less than 1 foot thick. In the adjacent Fairplay East quadrangle the base of the Silverheels limestone member lies about 1,500 ft above the base of the Maroon Formation.

IPm **Minturn Formation (Middle Pennsylvanian)** – The Minturn Formation underlies most of the western, central, and southeastern parts of the quadrangle, but it is concealed by surficial deposits in much of this area. No complete sections of the Minturn Formation occur in the Garo quadrangle, and the lower contact is not exposed. Correlation of partial sections in the adjoining Jones Hill quadrangle suggests a thickness of about 5,500 feet (Widmann and others, 2007). Surface exposures can be seen on and around Bare Hill and in the foothills of the Mosquito Range in the western part of the quadrangle. In the Bare Hill area about 3,000 feet of the Minturn Formation crop out; however, the upper and lower contacts are not exposed. The lower 1,200 feet of Minturn strata exposed in the Bare Hill area are rich in gypsum and gypsiferous clastic sediments. We map these rocks and the evaporite-rich strata along the west side of the quadrangle as an evaporite facies of the Minturn Formation, which is described in a following section.

The upper 1,800 ft of Minturn strata at Bare Hill, which overlie the evaporite facies, are dominated by siltstone, but gypsum beds are absent. Interbedded lithologies are sandstone, conglomerate, limestone, and dolostone. Upward in the section, red colors become increasingly prominent. Sandstone beds are fine to coarse-grained, arkosic, and generally less than 5 feet thick. They are gray, pink, or red in color, and are planar-bedded, planar-laminated, or ripple cross-laminated. Beds of conglomerate and conglomeratic sandstone are 10 to 20 feet thick, pink, trough cross-bedded, and arkosic, and consist of pebbles and granules in a sandy matrix. Limestones and dolostones are 0.5 to 3 feet thick and light to dark gray in color. Most are micritic, but some are moderately to strongly silicified and are red or orange (fig. 20). Intraclasts, detrital sand, and stromatolites were also observed. An especially thick (~9 feet) interval of limestone and dolostone is correlated with the White Quail Limestone Member, which is described below.

Figure 20. Limestone beds in the Minturn Formation are locally partially to completely replaced by chalcedony or chert (approximate location UTM coordinates 413675 m E, 4320910 m N).

In the foothills in the western part of the quadrangle the Minturn strata above the evaporite facies is sandier than in the Bare Hill area, but the sandstone beds are mostly fine-grained. Some beds of medium- to coarse-grained sandstone are present, especially in the southwest part of the quadrangle, but no conglomerate. Calcareous siltstone and shale occur at the stratigraphic positions of the limestones observed in the Bare Hill area, and these are interpreted as lateral equivalents. An especially thick calcareous horizon about 300 feet thick occurs at the stratigraphic position of the Jacque Mountain Limestone Member, which forms the top of the Minturn Formation in the type area north of Leadville. In the Garo quadrangle the Minturn-Maroon contact was placed at the top of this calcareous horizon, which appears to be conformable with overlying strata.

WQL White Quail Limestone Member — Where exposed in the Bare Hill area, the White Quail Limestone Member consists of approximately 10 feet of limestone and dolostone in beds 0.5 to 1 feet thick. The limestone is gray and micritic with white calcite veins and sand- to granule-sized intraclasts. The dolostone is light gray and medium crystalline, giving it a sugary appearance.

RL Robinson Limestone Member — In the Bare Hill area the Robinson Member consists of about 100 feet of very calcareous siltstone with a few thin beds of limestone and sandstone. The siltstone is gray to gray green. The limestone beds are dark gray and micritic, and the sandstone beds are light gray, fine to very fine grained, and calcareous. Quartz grains and mica are the main sandstone constituents.

IPme Evaporite facies of Minturn Formation – The lower 1,200 feet of section in the Bare Hill area consist mostly of gray laminated siltstone and shale with interbedded gypsum, gypsiferous shale, limestone, and fine- to very fine-grained sandstone. Exposed gypsum beds are less than 5 feet thick, dark gray, and coarsely crystalline, with some interbedded shale. Some gypsum beds show evidence of partial dissolution (fig. 21). Gypsiferous intervals are as much as 70 feet thick. The gypsum beds weather to firm, light-gray soils that react vigorously to dilute hydrochloric acid. These soils are dotted with microbial mats and small sinkholes. X-ray diffraction analysis indicates this light-gray soil consists chiefly of gypsum, with small amounts of quartz, a small clay/mica phase (illite or muscovite), and minor calcite (R.F. Wendlandt, 2006, written communication).

Sandstones within the evaporite facies at Bare Hill are gray to tan, generally less than 1 foot thick, and thinly bedded to laminated. Limestones are of two general types: (1) thin beds of gray micritic limestone similar to other limestones in the upper Minturn and Maroon strata and (2) 0.5 to 5 feet-thick beds of massive, vuggy, coarsely crystalline limestone that weathers to a tan color. The vuggy limestones overlie gypsiferous intervals. Commonly they contain sand-sized and pebble- to cobble-sized clasts of angular limestone and/or rounded clasts of quartzite and chert (fig. 22). One of the conglomeratic vuggy limestone beds contains sparse gravel clasts composed of ash-flow tuff, probably of middle Tertiary age. These clasts have groundmasses of either flow-banded glassy matrix or devitrified and altered glass, with phenocrysts of quartz, sanidine, and minor plagioclase (Jim Burnell, 2006, written communication).

Figure 21. Gypsum in the evaporite facies of the Minturn Formation locally is partially dissolved along laminations. Dissolved gypsum is commonly re-precipitated in voids, as seen on the top of this specimen. Gypsum-rich precipitate also overlies outcrops of some gypsum beds, for example on the south and west sides of Bare Hill.

The clasts of ash-flow tuff suggest the vuggy limestone beds may be much younger than the strata with which they are interlayered. The rounded clasts within these limestones probably came from a Quaternary or late to middle Tertiary gravel deposit that once blanketed the area. The clasts may have fallen into a sinkhole that propagated upwards into and perhaps through the gravel deposit. Since the vuggy limestones appear to be interbedded with the Minturn strata, the fallen clasts probably were distributed laterally in a karst feature that followed bedding within the evaporite facies of the Minturn. The gravel contained within the karst feature was subsequently cemented with carbonate and later exposed to the modern ground surface by erosion.

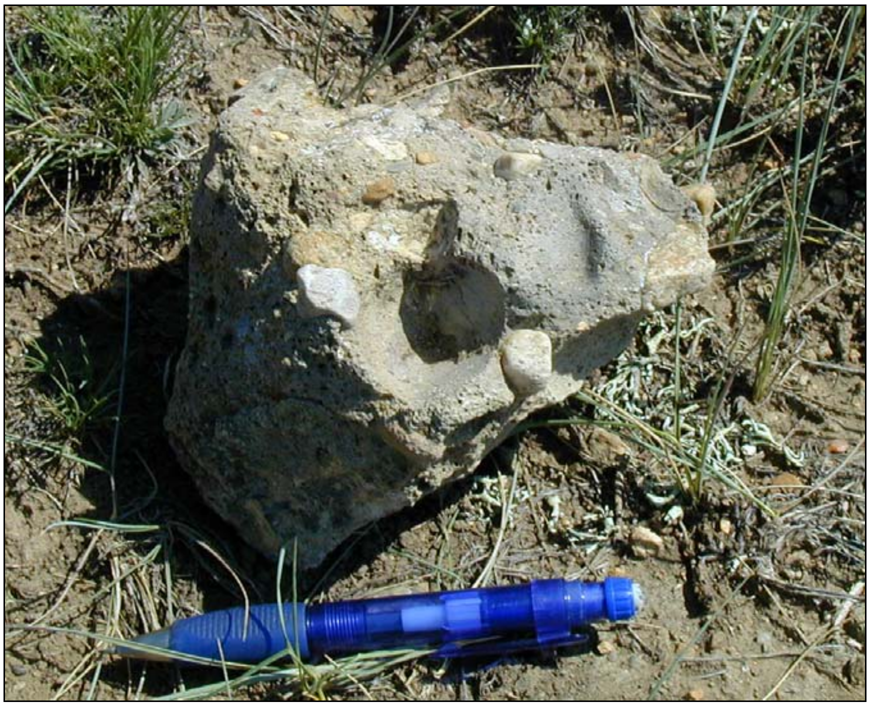

Figure 22. Vuggy limestone with rounded gravel clasts, including a clast of ash-flow tuff of probable middle Tertiary age (clast directly above the shadow). Approximate UTM coordinates 420080 m E, 4328815 m N.

In the foothills of the Mosquito Range and north of the Arrowhead Ranch fault, the gypsum beds thicken and vuggy limestones are more common. In the foothills south of the Arrowhead Ranch fault, sandstone beds are thicker and more numerous, and micritic limestones are better developed. The gypsum beds change facies to gypsiferous shale or pinch out entirely, and vuggy limestones are rare. The sandstones have ripple cross-laminations, mud cracks, plant debris, rain prints, and bioturbation. Some have copper mineralization. Red and variegated colors are present locally.

The micritic limestone beds are generally thicker (up to 8 feet thick) and more varied than at Bare Hill. Some contain intraclasts or chert nodules; others appear to contain algal laminations. The high concentrations of dissolved sodium and chloride in ground water discharging at the spring at the Saltworks Ranch south of the quadrangle (George and others, 1920) suggest halite is present in the evaporite facies at least locally in the subsurface.

PIPmm Maroon and Minturn Formations, undivided (Lower Permian to Middle Pennsylvanian) — This undivided unit is used where poor exposures prevent identification of strata or the contact between the Maroon and Minturn formations.

STRATIGRAPHY

The oldest rocks in the Garo quadrangle are Paleozoic rocks above the Belden Formation and the Coffman Member of the Minturn Formation in South Park. Many names have been applied to these rocks. Johnson (1934) referred to them as the Maroon Formation, partially following the practice of Emmons (1898), who assigned predominantly red strata between the Robinson and Jacque Mountain limestones in the Tenmile District north of Leadville to the Maroon Formation. Emmons assigned strata above the Jacque Mountain to the Wyoming Formation, but Johnson chose not to use this term because he felt that evidence for separating these strata into two formations was not sufficient in the South Park area.

Gould (1935) included Paleozoic strata overlying the Coffman Member in the Maroon Formation. On the west side of the Trout Creek fault, he further subdivided the Maroon into the Chubb Siltstone Member, the Pony Spring Siltstone Member, and the Bath Sandstone Submember. This nomenclature was followed by Stark and others (1949) and DeVoto (1971). Gould also noted the presence of gypsiferous strata in the Chubb Siltstone.

Brill (1952) attempted regional correlations of the upper Paleozoic rocks in the Central Colorado Basin. He correlated the Chubb and lower Pony Spring members with the Minturn Formation and correlated a calcareous horizon above the Bath Sandstone with the Jacque Mountain Limestone. He correlated strata above the calcareous horizon with the Maroon Formation. Chronic (1958) followed this scheme. De Voto (1972) used the Minturn-Maroon nomenclature but drew the contact at the color change from mostly gray to mostly red rocks.

All of these schemes have advantages and disadvantages, but none seem completely satisfactory. The Minturn and Maroon Formations at their type localities are mostly conglomerate (Eldridge, 1894; Tweto, 1949; Tweto and Lovering, 1977), but their equivalents in the Garo quadrangle contain little to no conglomerate. Position of the color change varies from the middle of the Minturn Formation in the Fairplay West quadrangle (Widmann and others, 2006), down to nearly the base of the Minturn Formation in the Jones Hill quadrangle (Widmann and others, 2007), and up to about 1,000 feet above the Jacque Mountain equivalent in the Marmot Peak quadrangle. The Jacque Mountain Limestone remains at the same stratigraphic horizon but is difficult to identify in western South Park, where it changes facies to calcareous siltstone and is overlain and underlain by rocks that look very similar to each other (De Voto, 1971).

The typical lithologies of the Chubb and Pony Spring members and the Bath Submember seem to occur only locally in western South Park (Gould, 1935; Stark and others, 1949). For the present time we have elected to continue to use the Minturn/Maroon nomenclature with the contact drawn at the top of the Jacque Mountain Member, though we acknowledge that this scheme has some shortcomings. As the regional stratigraphic relationships become better understood, it may be beneficial to revise the nomenclature and introduce new terminology.

Though the Minturn and Maroon Formations are challenging to identify and map in the Garo quadrangle, they reveal interesting information about the landscape and geography of the South Park area at the time of their deposition. Previous field studies revealed that detrital sediments in the upper Minturn and lower Maroon strata were carried into northern South Park by rivers flowing from the Breckenridge area toward the south (Taranik, 1974; Widmann and others, 2006; Kirkham and others, 2006). These sediments were shed from the Ancestral Front Range.

In the Jones Hill and Garo quadrangles, detrital sediments in the lower and middle Minturn Formation below the White Quail Limestone Member came from the north-northwest except for one locality. It is not yet known whether these sediments came from the Ancestral Front Range or the Ancestral Sawatch Range. At the other locality, which is in the southern part of the Jones Hill quadrangle, a coarse (pebble and cobble) channel-fill conglomerate of angular arkosic sandstone, siltstone, shale, and dolomite clasts came from the west-southwest. These sediments almost certainly were eroded from a very close source such as the Ancestral Sawatch Range. They appear to be composed of Pennsylvanian sedimentary rocks, and this would indicate uplift of an area that was formerly subsiding and accumulating Pennsylvanian sediments.

Gypsum is also an important constituent of the lower Minturn Formation in portions of the Garo and Jones Hill quadrangles, as was noted by De Voto (1971, 1980) and De Voto and others (1986). We map these strata as the evaporite facies of the Minturn Formation. Gypsiferous strata occur at several horizons, and this implies that the South Park area was repeatedly the site of a restricted sea. The position of the gypsum-bearing strata in the South Park section is approximately equivalent to that of the Wearyman, Hornsilver, and Resolution dolomite members in the Minturn section at Pando (Tweto, 1949). Although no age-diagnostic fossils have been found in the gypsum-bearing strata in South Park, fossils recovered from the Hornsilver Dolomite and an unnamed dolomite below the Wearyman Dolomite in the Minturn and Pando areas indicate a late Atokan age (Tweto and Lovering, 1977, p. 48).

Detrital sediments above the White Quail Limestone Member in the Jones Hill, Garo, and Marmot Peak quadrangles came from the south and east, in the vicinity of Hartsel. Though no age-diagnostic fossils have been found in the White Quail Limestone Member in South Park, it is thought to be Desmoinesian in the Minturn and Pando areas (Tweto and Lovering, 1977, p. 51). This implies that the Hartsel uplift (a part of the Ancestral Front Range) became a source of sediments at that time.

The Garo Sandstone, which crops out on the western side of Red Hill, is stratigraphically above the Minturn and Maroon Formations. The age of the Garo Sandstone and its relationships to underlying formations hase been debated in the literature for decades. Most workers initially considered the Garo to be Jurassic in age and probably correlative with the Entrada Sandstone (for example, Miller, 1937; Stark and others, 1949; Ettinger, 1964). Stark and others (1949) reported unconformities both above and below the Garo Sandstone, which supported that age assignment. De Voto (1965a, b), however, described evidence that the lower part of the Garo Formation interfingers with the uppermost part of the Maroon Formation. He also noted that a sandy dolomitic limestone with a Permian alga previously described by Johnson (1935) lies about 80 feet stratigraphically below the base of the Garo and that the thickness changes in the Garo are mostly a result of facies changes. On the basis of this evidence, De Voto (1965a, b) concluded that the Garo Sandstone is Permian in age, is laterally equivalent to the Maroon, and is overlain by an unconformity but is conformable with the underlying Maroon Formation.

Lozano (1965) did not find the evidence described by De Voto (1965a, b) but continued to use a Permian age for the Garo Sandstone. Most recent studies have returned to the earlier interpretations. Bryant and others (1981b) mapped the unit as the Jurassic Entrada Sandstone. Hembre and TerBest (1997) also suggested the unit was probably correlative with the Entrada, as did Steyaert and Wandrey (1997), who stated that the Garo unconformably overlies the Maroon Formation, but neither publication contains much evidence to support their positions. Until the authors have an opportunity to study the pertinent outcrops near Badger Springs east of the quadrangle, we will use the age assignment and stratigraphic relationships of De Voto (1965a, b), who to date appears to have done the most thorough studies of the formation.

No Triassic strata exist in the quadrangle. The closest Triassic rocks crop out near Boreas Pass at the northern end of South Park (Poole and Stewart, 1964). Either the Triassic strata were never deposited in the mapped area, or they were removed by pre-Late Jurassic erosion. The Upper Jurassic Morrison Formation disconformably overlies the Garo Sandstone, and a thick sequence of Lower and Upper Cretaceous sedimentary rocks disconformably overlies the Morrison, although the erosion surface cut into the Morrison is not planar. The Dakota Sandstone constitutes the basal part of the Cretaceous section and signals the beginning of the transgression of the Western Interior Seaway into the region during the Early Cretaceous. A thick, conformable sequence of Upper Cretaceous marine rocks was deposited over the Dakota in the region. In ascending order, this sequence includes the Benton Group, Niobrara Formation, and Pierre Shale. All the Mesozoic sedimentary rocks, except for the Dakota Sandstone, typically are very poorly exposed in the region. However, parts of the Benton Group and Niobrara Formation are fairly well exposed along the eastern edge of the quadrangle, south of where the Middle Fork cuts through the Dakota hogback.

Only the lowermost part of the South Park Formation crops out in the quadrangle, and it consists of a single member, the Paleocene coarse-grained conglomeratic member (unit Tsc). To the north in the Como quadrangle (Widmann and others, 2005) and in the Fairplay East quadrangle (Kirkham and others, 2006), the conglomeratic member is underlain by the Reinecker Ridge Volcanic Member. This member, however, as well as the lower volcaniclastic member that locally underlies the Reinecker Ridge Volcanic Member, pinch out before reaching the Garo quadrangle. To the north, the conglomeratic member is also overlain by lower Tertiary rocks in the South Park Formation, but these rocks crop out east of the Garo quadrangle, not within it. The nomenclature of the South Park Formation has evolved considerable during the past century. Refer to Kirkham and others (2006) for a description of the evolution of the South Park Formation nomenclature.

To establish a minimum age for the conglomeratic member, igneous-rock clasts contained within the member were dated by Widmann and others (2005) and Kirkham and others (2006). The clasts yielded $^{40}Ar/^{39}Ar$ ages of 64.08 ± 0.11 Ma, 66.4 ± 0.4 Ma, and 66.6 ± 0.5 Ma, which indicate the conglomeratic member is younger than about 64 Ma. To the northeast, the 59.7 ± 2.0 Ma Link Springs tuff member (corrected K-Ar age in Wilson and Bryant, 2006) overlies the conglomeratic member, which suggests the conglomeratic member is entirely Paleocene in age.

The lithologies of clasts within unit Tsc suggest the provenance was to the west or northwest, possibly the Mosquito Range near Leadville and Alma (Wyant and Barker, 1976; De Voto, 1988). De Voto (1988) observed that the conglomerate clasts reflect the erosional unroofing of the Sawatch anticline to the west. The ages of dated clasts from the conglomeratic member are similar to K-Ar ages from Laramide-age intrusions in the Alma and Leadville areas in the Mosquito Range that are petrographically comparable (Bookstrom, 1989; Bookstrom and others, 1987; McDowell, 1971). This also suggests a major source area for clasts in the coarse-grained conglomeratic member of the lower South Park Formation in the Reinecker Ridge area is the Mosquito Range, northwest of the Garo quadrangle.

Granite porphyry intrusions (unit Tgp) in the northwest part of the quadrangle probably are apophyses of the much larger intrusion at Black Mountain in the adjacent Jones Hill quadrangle, which Tweto and others (1974b, 1978) assigned to the middle Tertiary. The granite porphyry intrusion at Black Mountain yielded an $^{40}Ar/^{39}Ar$ age of 60.95 ± 0.15 Ma (Widmann and others, 2007; Peters, 2008), which suggests the granite porphyry intrusions in the Garo quadrangle are Paleocene.

The nomenclature and subdivision of the post-South Park Formation sedimentary and volcanic rocks in South Park also have evolved over the years as various scientists studied them (for example, Johnson, 1937a; Brown, 1940; Stark and others, 1949; De Voto, 1961, 1971; De Voto and others, 1986; Lozano, 1965; Scott and others, 1978; Bryant and others, 1981b; McIntosh and Chapin, 2004). For this study we divide the post-South Park Formation rocks into the following units: (1) a thick basal unit composed of andesite and dacite flows, flow breccias, and lahars (unit Tad); (2) the Tallahassee Creek Conglomerate (unit Ttc); (3) a densely welded rhyolitic ash-flow tuff that locally overlies unit Tad and is correlated with the Wall Mountain Tuff (unit Twm); (4) the Antero Formation, which is younger than the Wall Mountain Tuff and consists of a local limestone member (Tal) and an overlying tuffaceous member (Ta); (5) an uppermost unit consisting of poorly lithified conglomerate and probably finer-grained sediments that we tentatively correlate with the Wagontongue Formation (Tw); and (6) Tertiary sedimentary rocks (Ts), which appear to rest on the Minturn Formation and whose stratigraphic relationships to other Tertiary rocks is uncertain.

In the Garo quadrangle all the post-South Park Formation rocks except for unit Ts are restricted to the High Creek syncline. All these rocks are present in the west limb of the syncline, but unit Tad, the Tallahassee Creek Conglomerate, and the limestone member of the Antero Formation do not crop out in the east limb of the syncline. The Wall Mountain Tuff and tuffaceous member of the Antero Formation are much thinner in the east limb than in the west limb.

The volcanic rocks of unit Tad underlie most of the Lone Hills. Their eruptive source is unknown. An $^{40}Ar/^{39}Ar$ age of 38.59 ± 0.14 Ma was obtained on sample G164, which was collected from a flow breccia in the middle part of the unit (Peters, 2008). Wilson and Bryant (2006) reported a K-Ar age of 37.8 ± 1.3 Ma for a dacite flow near the base of the unit. These ages are similar to the ages of the volcanic rocks at Buffalo Peaks (McIntosh and Chapin, 2004; Peters, 2008), but the flows in the Lone Hills apparently are more variable in composition than those at Buffalo Peaks (Campbell, 1994; Widmann and others, 2007).

A thin boulder conglomerate (unit Ttc) crops out at the north end of the Lone Hills. It is interpreted as overlying the andesitic and dacitic rocks of unit Tad. We tentatively correlate the boulder conglomerate in the Garo quadrangle with the Tallahassee Creek Conglomerate. It is also possible that the very poorly exposed conglomerate unit may be intercalated with or perhaps even locally underlie unit Tad, in which case the conglomerate unit in Garo quadrangle is older than the Tallahassee Creek Conglomerate.

The ash-flow tuff that overlies unit Tad was named the Agate Creek Tuff by De Voto (1964, 1971) and Lozano (1965). Later it was correlated with the Wall Mountain Tuff (Bryant and others, 1981b). The Wall Mountain Tuff is a regionally extensive ignimbrite erupted from the Mount Princeton caldera (Lipman and McIntosh, 2006). In addition to existing in South Park, remnants of the Wall Mountain Tuff have been found in the upper Arkansas valley, the Thirtynine Mile volcanic area, and as far east as Castle Rock, which is east of the Front Range (McIntosh and Chapin, 2004).

The chemistry and phenocryst assemblage of the ash-flow tuff that crops out in the Lone Hills is similar to that of the Wall Mountain Tuff, although they are not unique to it (Shannon and others, 1987; McIntosh and Chapin, 2004). The tuff of Stirrup Ridge has similar petrography. The ash-flow tuff in the quadrangle locally is fairly thick (≥100 ft). Where thick, the tuff forms prominent outcrops. These characteristics reportedly are more typical of the Wall Mountain Tuff than the tuff of Stirrup Ranch (McIntosh and Chapin, 2004). Also, the ash-flow tuff in the quadrangle lies slightly north of the known extent of the tuff of Stirrup Ranch. The Wall Mountain Tuff usually rests on pre-volcanic rocks, yet in the quadrangle the tuff overlies a thick pile of andesitic and dacitic flows, flow breccias, and lahars, a feature that is more typical of the tuff of Stirrup Ridge. However, the Wall Mountain Tuff does locally overlie intermediate composition volcanic rocks (J.R. Shannon, 2007, personal communication).

An $^{40}Ar/^{39}Ar$ age of 36.93 ± 0.11 Ma was obtained on a sample of Wall Mountain Tuff from the Garo quadrangle (sample G153; Appendix B). Samples of Wall Mountain Tuff from other areas yielded an average $^{40}Ar/^{39}Ar$ age of 36.69 ± 0.09 Ma (McIntosh and Chapin, 2004). The date obtained for the ash-flow tuff in the Garo quadrangle lies within the age range of the known Wall Mountain Tuff samples dated by McIntosh and Chapin (2004). The dated sample from the quadrangle is older than the 36.50 ± 0.16 Ma tuff of Stirrup Ridge, which is the only other tuff known to have similar chemistry and phenocrysts (McIntosh and Chapin, 2004).

Two members of the Antero Formation are recognized in the quadrangle: a relatively thin limestone member that is locally present at the base of the formation (unit Tal) and an overlying much thicker tuffaceous member (unit Ta). The limestone member includes rocks thought to be deposited in lakes and also tufa deposited by springs that perhaps were located on the margin of a lake. It is possible that the rocks included in the limestone member of the Antero Formation may be younger than the Antero Formation, and rather than being interbedded with the Antero sediments, they may have been deposited unconformably over them. The tuffaceous member is very poorly exposed. The scant observations made from this unit in the quadrangle suggest it consists of tuffaceous lake sediments, but no exposures were observed of most of the strata within the formation. $^{40}Ar/^{39}Ar$ ages on tuff beds and tuffaceous sediment in the Antero Formation elsewhere in the region are typically about 33.8 Ma (McIntosh and Chapin, 2004). No absolute age dates are available for the Antero Formation within the Garo quadrangle.

The moderately indurated sedimentary rocks of unit Ts crop out in two small areas along U.S. Highway 285. Clasts in these pebbly deposits are subangular to subround fragments of sandstone, shale, conglomeratic sandstone, and limestone derived from Pennsylvanian rocks. In both outcrops the unit appears to unconformably overlie the Minturn Formation. The deposits probably are locally derived. Their stratigraphic relationship to other Tertiary rocks is as yet undetermined. They probably are middle Tertiary in age, perhaps Oligocene, but definitive age control is not available.

We correlate the poorly lithified sedimentary rocks in the axial part of the High Creek syncline with the Miocene Wagontongue Formation. To the south in the Antero syncline similar rocks are somewhat better exposed and much better studied. There they have been subdivided into two formations on the basis of grain size by several researchers (Johnson, 1937a; Stark and others, 1949; De Voto, 1964, 1971). The conglomeratic rocks were included in the Trump

Formation and the finer-grained rocks were called the Wagontongue Formation. However, Scott and others (1978) concluded that the Trump was a coarse-grained facies of the Wagontongue, and therefore was an unnecessary name and should be abandoned. Bryant and others (1981b) applied the name Wagontongue Formation to the poorly lithified sedimentary rocks that overlie the Antero Formation in the High Creek syncline within the quadrangle, an approach that we follow, although it is recognized that in the absence of paleontological data or radiometric age dates, the correlation is tentative. De Voto (1971) described paleontological evidence from the possibly correlative rocks in the Antero syncline that suggested they were late Miocene. Bryant and others (1981b) reported a Miocene age for the Wagontongue Formation in the Garo quadrangle.

Remnants of older gravel deposits (unit QTg) are preserved at four locations within the quadrangle. Stratigraphic relationships between these non-lithified sedimentary deposits and the Wagontongue Formation are uncertain. Deposits of unit QTg may in part be age-equivalent to the Wagontongue Formation in the High Creek syncline, but some may be much younger. Deposits of unit QTg in the southwestern part of the quadrangle were deposited at different positions in the landscape at different times. They probably were deposited in eastward-draining paleovalleys that flowed off the Mosquito Range, but they now cap ridges, forming an inversion of topography. Deposits of unit QTg were mapped west of Highway 285 in the west-central and northern parts of the quadrangle. These deposits appear to be tilted to the east, northeast, or southeast, perhaps in response to subsurface dissolution of evaporite and subsidence of overlying strata. A single deposit of QTg on Bare Hill may be an outlying remnant of Wagontongue Formation, or it could have been deposited more recently by the South Fork or High Creek.

During the Quaternary, outwash from melting glaciers in the Mosquito Range was episodically deposited across much of the quadrangle (units Qa4o, Qa4y, Qa3, Qa2, Qa2o, and Qa2y). Between the episodes of outwash deposition, stream erosion cut slowly into the outwash or into bedrock adjacent to the outwash plains and fans. Remnants of glacial outwash cover over half of the quadrangle. The preserved remnants of outwash within the quadrangle were deposited during at least three and perhaps as many as six glacial ice ages.

Outwash from the oldest glaciation (alluvial unit four) is divided into two subunits, Qa4o and Qa4y, on the basis of relative position in the landscape. Deposits of Qa4o are higher in the landscape and inferred to be somewhat older than those of Qa4y. However, the differences in heights above modern streams also may be a result of subsidence due to dissolution of underlying evaporite rocks. A large remnant of Qa4o caps the interfluve between the Middle Fork and Fourmile Creek in the north-central part of the quadrangle. This deposit and contiguous and equivalent deposits in the Fairplay East quadrangle that were mapped by Kirkham and others (2006) as unit Qa4 are remnants of a very large outwash fan deposited by the Middle Fork during the middle Pleistocene.

Deposits of alluvial unit three (Qa3) are preserved in the valleys of the South Fork, High Creek, and Fourmile Creek. This outwash was probably deposited during the late middle Pleistocene Bull Lake glaciation (oxygen isotope stage 6), although it could be as young as oxygen isotope stage 4. At the time when alluvial unit three was deposited, the South Fork flowed in a paleovalley whose course in part deviated from its modern valley (fig. 5).

A veneer of light-gray, white, or light-brown calcareous silty clay that is as much as 6 feet thick locally overlies alluvial unit three (fig. 7). It is especially prevalent in the paleovalley of the South Fork and in the valley of High Creek north of Bare Hill. The material is composed mostly of gypsum, with minor amounts of calcite and traces of quartz on the basis of x-ray diffraction analysis by R.F. Wendlandt (2007, written communication). Soil scientists have coined the term reverse calcic soil for these deposits (L. Craven, 2006, personal communication). We interpret the deposits as precipitates formed in response to local discharge and evaporation of ground water with high concentrations of dissolved calcium and sulfate.

Alluvial unit two (Qa2) is locally subdivided into older (Qa2o) and younger (Qa2y) subunits. All are interpreted as outwash from the Pinedale glaciation, which occurred during the late Pleistocene during oxygen isotope stage 2. The older and younger subunits may be associated with the early and late phases of the Pinedale glaciation; however, in view of the fact that no absolute age dates are available for these deposits, the older Qa2o deposits potentially could have been deposited during oxygen isotope stage 4.

During the late stages of deposition of alluvial unit two, the Middle Fork abandoned a paleovalley along the west side of the Dakota hogback and began flowing through a water gap eroded through the hogback (fig. 5). A relatively small outwash fan with well preserved channel geomorphology was deposited on the east side of the hogback, which suggests the Middle Fork abandoned the paleovalley during the waning stages of the Pinedale glaciation. The abandonment of the paleovalley probably resulted from aggradation of sediment in the paleovalley, not from stream capture. Sediment aggraded in the paleovalley until it reached the elevation of a topographic low in the hogback ridge, at which time the Middle Fork spilled over the hogback ridge and into the Pierre Shale strike valley. The additional surface water flowing in the Pierre Shale strike valley increased incision rates during the Holocene and triggered headward erosion in the Pierre Shale strike valley that migrated northward from the water gap. The headward erosion in the Pierre Shale strike valley eventually resulted in the capture of Trout Creek and abandonment of its late Pleistocene paleovalley located in the Como quadrangle (Widmann and others, 2005).

STRUCTURE

South Park basin is a compressional Laramide-age structural depression that was modified by post-middle Tertiary extensional tectonism. The western side of the South Park basin coincides in part with the eastern margin of the large Sawatch uplift (Tweto, 1980), and the west-vergent Elkhorn thrust forms the eastern margin of the basin. Precambrian rocks are thrust over lower Tertiary and older rocks by the Elkhorn thrust. The Michigan-San Isabel syncline formed in rocks beneath and adjacent to the thrust and structurally is the deepest part of South Park basin (Sawatsky, 1967; Bryant and others, 1981b). Major north-northwest-trending reverse and/or thrust faults with down-to-west displacement locally disrupt the generally east-dipping bedrock on the west side of South Park basin. Two of these major faults, the Bare fault and the Arrowhead Ranch fault, are recognized in the quadrangle.

The structural geology of the Garo quadrangle is very complex. Surficial deposits conceal the bedrock in over half the quadrangle, and even in some areas where exposed, the bedrock forms poor outcrops that yield few clues about structure or stratigraphy. A thick (>10,000 feet) sequence of Pennsylvanian strata underlies the vast majority of the quadrangle. The Pennsylvanian rocks contain relatively few obvious stratigraphic horizons that clearly pinpoint stratigraphic positions. These factors have greatly complicated past efforts to unravel the complex structural geology of the quadrangle. Ongoing detailed stratigraphic studies of the

Pennsylvanian rocks by the Colorado Geological Survey have led to better understanding of known structures and to the discovery of major previously unrecognized structures.

The Bare fault is a major northwest-trending, down-to-west, Laramide fault on the west and south sides of Bare Hill in the center of the quadrangle. The fault was recognized and mapped by many prior workers (for example, De Voto, 1964, 1971; Lozano, 1965; Bryant and others, 1981b). The fault trace is clearly visible where red strata of the Maroon Formation are downdropped against light-gray strata of the evaporite facies of the Minturn Formation (fig. 23). De Voto suggested the Bare fault was a southern extension of the London fault. Our mapping, in conjunction with that of Widmann and others (2006, 2007), suggests the southern end of the London fault and the northern end of the Bare fault terminate against the newly recognized Arrowhead Ranch fault. The London and Bare faults have similar trends and similar down-to west movement; however, they are nearly eight miles apart.

Figure 23. Bare Fault, a major northwest-trending down-to-west fault on the west side of Bare Hill. The fault downdrops red strata of the Maroon Formation (red-brown material exposed in road in middle distance) against the evaporite facies of the Minturn Formation (light-gray material in the road and roadcut in foreground). The fault, which has over 4,000 feet of stratigraphic displacement, crosses the road at the sharp color change. Photograph taken on west side of Bare Hill at about UTM coordinates 418240 m E, 4324440 m N looking west.

The dip of the Bare fault is poorly constrained. No outcrops were discovered that exposed the fault in a vertical section. The fault trace is sinuous, but it crosses essentially flat-lying topography, which precludes geomorphic analysis of the fault trace as it traverses ridges and valleys. No drill hole data were found that could help determine the dip of the fault plane. We speculate that the Bare fault dips east at 40 to 50 degrees and is either a high-angle thrust or low-angle reverse fault.

On the basis of the stratigraphic separation across the fault near Bare Hill, we estimate the dip slip on the Bare fault is at least 4,000 feet. The trace of the Bare fault is mappable for nearly 2 miles. To the north the fault is concealed by Quaternary deposits; we assume it is cut off by the east-west oriented Arrowhead Ranch fault. To the south the Bare fault is concealed by Upper Eocene volcanic rocks, suggesting the last movement of the fault happened prior to the Late

Eocene. We tentatively extend the Bare fault southward as a queried fault following the unpublished map of R.H. De Voto (2005, written communication, provided by K. Lee). Our primary rationale for this assumption relates to the existence of the High Creek syncline, which we interpret as a subsidence feature. The southward extension of the Bare fault allows for the evaporite facies of the Minturn Formation to be uplifted to near the ground surface east of the fault. Dissolution of the evaporite in the hanging wall side of the fault probably created the High Creek syncline, an interpretation supported by the presence of the Minturn evaporite facies east of the syncline.

Another major Laramide structure, the Arrowhead Ranch fault, underlies the valley floor of the South Fork at the west edge of the quadrangle. There is over 4,000 feet of stratigraphic separation across the Arrowhead Ranch fault between the basal strata of the Maroon Formation that crops out on the ridge west of the headquarters of the Arrowhead Ranch (labeled as the Johnson Ranch on the base map used for the geologic map) and the evaporite facies of the Minturn Formation on the north side of the South Fork. The stratigraphic separation can be explained by a fault with either major down-to-south movement or right-lateral slip. Dip of the Arrowhead Ranch fault is poorly constrained.

An alternate explanation involves foundering of the Maroon strata into underlying evaporite. This style of deformation would be similar to that at Hardscrabble Mountain in west-central Colorado (Lidke and others, 2002; Perry and others, 2002). We currently prefer a fault interpretation.

The Arrowhead Ranch fault system can be traced westward as a complex zone of faults, mostly tear faults, that connects with the London fault (Widmann and others, 2007), but the eastward extent of the Arrowhead Ranch fault is uncertain. We suspect the fault trends eastward, because our stratigraphic studies demonstrate that thick sections of strata are absent along the eastward project of the Arrowhead Ranch fault. For example, a major fault with at least a few thousand feet of down-to-south or strike-slip movement is required to explain the juxtaposition of Maroon strata on the west side of the Bare fault in the NE ¼ of section 25, T. 11 S., R. 77 W. and the Minturn strata to the north in section 24. A fault with about 1,000 feet of stratigraphic offset is also needed between the Minturn rocks in the NW ¼ of section 26 and the SE ¼ of section 22. An eastward extension of the Arrowhead Ranch fault would account for these stratigraphic separations.

The Bare fault, Bare syncline, and High Creek syncline cannot be traced north of the inferred eastward extension of the Arrowhead Ranch fault. These structures may terminate against the Arrowhead fault. The sweeping bends in the Dakota hogback, a strike ridge held up by the Dakota Sandstone, and in Reinecker Ridge, a strike ridge formed by the South Park Formation, also could be explained by an eastward extension of the Arrowhead Ranch fault. These sweeping bends are vividly imaged in figure 24.

A down-to-west, north-south-trending fault is required to account for the nearly 2,000 feet of stratigraphic separation of Minturn strata in the SW ¼ of section 35, T. 11 S., R. 77 W., as well as the approximately 1,600 feet of missing strata in the SW ¼ of section 2, T. 12 S., R. 77 W. We name this structure the 285 fault due to its proximity to Highway 285. This fault is subparallel to and has the same sense of displacement as the Bare and London faults.

Many other faults cut the bedrock in the quadrangle. Offsets across these faults range from tens to hundreds of feet. Abrupt offsets of limestone beds clearly delineate some of these faults, and volcanic formations are juxtaposed across other faults (fig. 25).

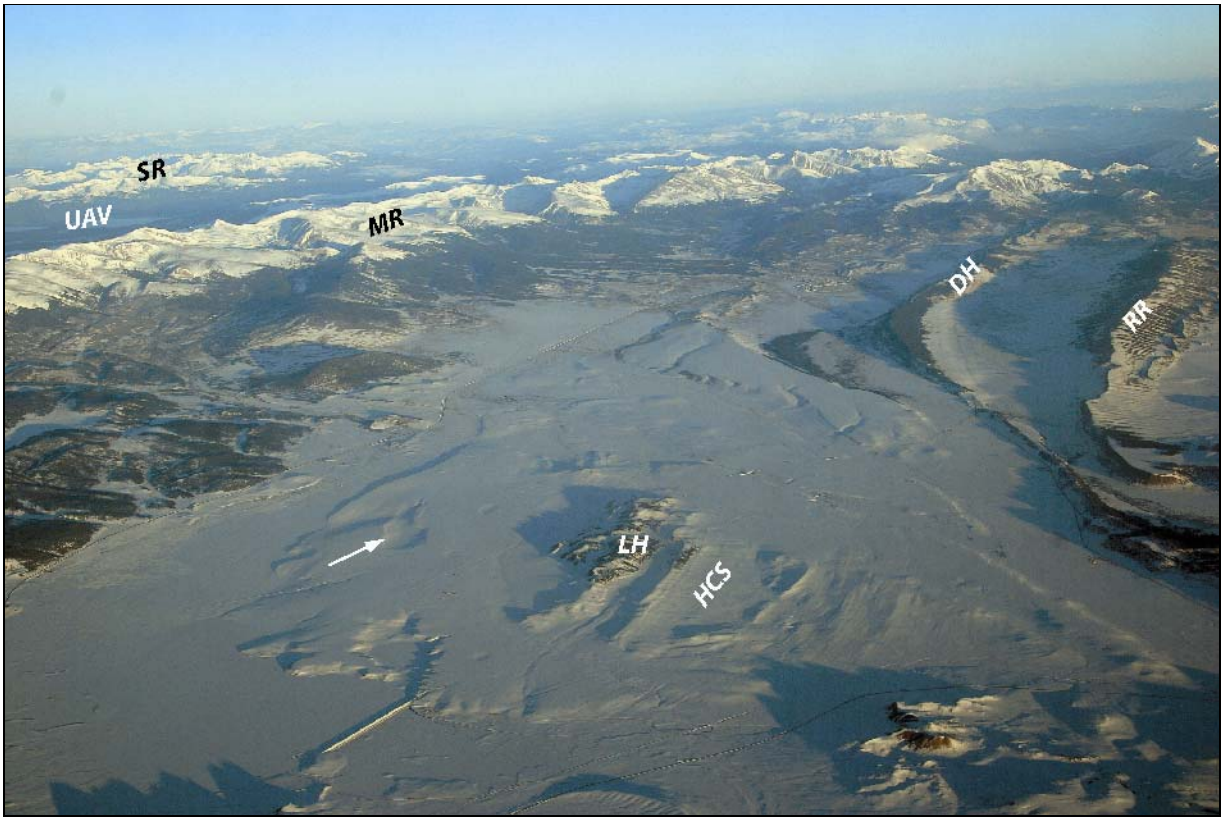

Figure 24. Aerial photograph looking northwest across the Garo quadrangle. Mosquito Range (MR), Upper Arkansas Valley (UAV), and Sawatch Range (SR) are visible in the upper left. U-shaped ridges east of the Lone Hills (LH) are held up by conglomerate beds in the basal part of the Wagontongue Formation that crop out in the east, west, and south flanks of the north-plunging High Creek syncline (HCS). Arrow points to large subsidence depression formed in surface capped by alluvial unit four west of the Lone Hills. Other smaller subsidence depressions also are visible on the surface capped by alluvial unit four. Note the prominent change in strike of the Dakota hogback ridge (DH) and Reinecker Ridge (RR). These sweeping bends may be caused by deformation related to the hypothesized eastward extension of the Arrowhead Ranch fault, which also may truncate the northern ends of the Bare fault, Bare syncline, and High Creek syncline. Photograph by V. Matthews.

Several synclines exist in the quadrangle. No anticlines were documented at the ground surface by mapping, but a concealed one may exist east of the Bare syncline (see cross section A-A'; plate 2). Some of the synclines are interpreted as Laramide-age structures that formed sometime between the Late Cretaceous and Early Eocene. Small synclines in the southwest part of the quadrangle probably are Laramide structures. The Bare syncline formed on the upthrown side of the Bare fault; therefore it is not a drag fold associated with the fault. But it could, however, be a Laramide fold in the deformed overthrust or overhanging block of the Bare fault, which is thought to be a thrust or reverse fault. The Bare syncline also overlies the evaporite facies of the Minturn Formation and potentially could be a subsidence feature related to evaporite dissolution.

The axis of the Bare syncline appears to be offset to the west relative to the axis of the High Creek syncline, which as described in the following paragraphs probably is an evaporite-related subsidence structure. If an unrecognized fault lies between the Bare and High Creek synclines, then both structures could be subsidence features over the same interval of evaporite.

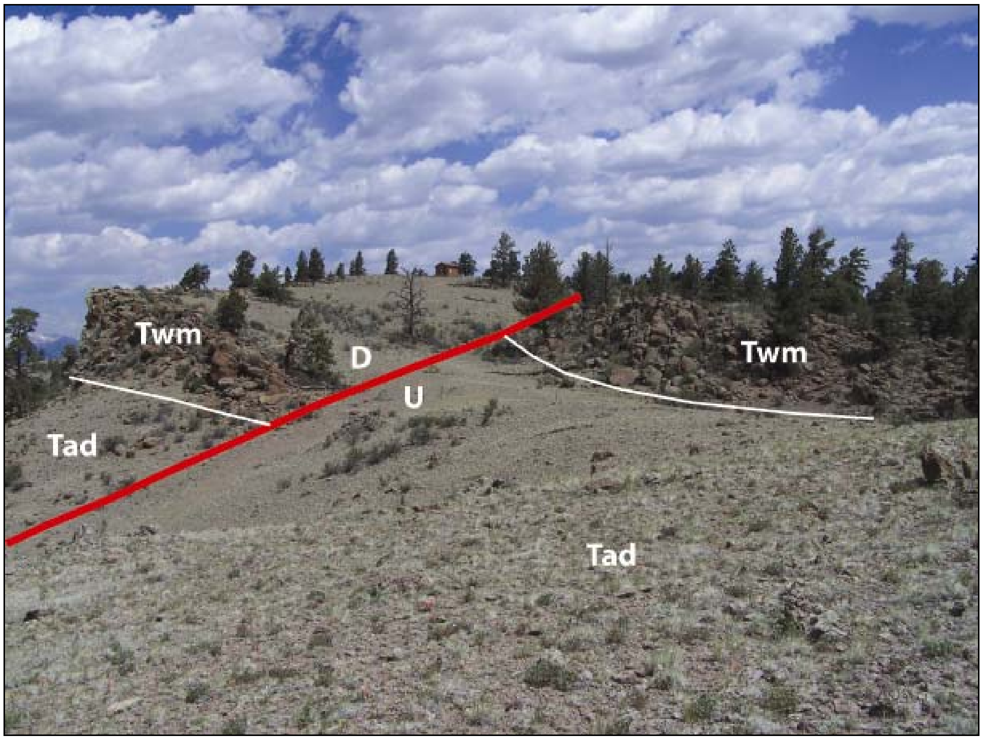

Figure 25. High-angle fault (red line) with down-to-west movement cuts the Wall Mountain Tuff (Twm) and underlying andesitic and dacitic volcanic rocks (Tad) in the Lone Hills. View looking northwest from about UTM coordinates 422200 m E, 4320090 m N. Apparent dip of the fault plane in this view is less than the actual dip. Vertical displacement is several tens of feet.

The small syncline in the SW ¼ NW ¼ of section 30 west of Bare Hill is interpreted as a localized drag fold on the downthrown side of the Bare fault. The axis of a syncline to the west in section 25 is concealed by surficial deposits. This structure is inferred on the basis of dip changes in the bedrock that crops out on the flanks of the gravel-capped surface. Dip changes in the windows of upper Paleozoic rocks exposed adjacent to the arms of Antero Reservoir along the south edge of the quadrangle (sections 16 and 17) suggest a broad, relatively short syncline probably exists between the two windows of bedrock. Lozano (1965) connected what we show as two short disconnected synclines as the large Mount Hall syncline. A few bedding attitudes were measured in the rocks in the west limb of Lozano's Mount Hall syncline in sections 1 and 6 between the two short synclines that we found. These beds dip east, as if they were in the west limb of a syncline. A single outcrop with bedding was found in what would be the eastern limb of the Lozano's Mount Hall syncline (in NW ¼ of section 5), but the beds there also dipped east. The limited bedding plane measurements, although few in number, raise doubts about the existence of the Mount Hall syncline.

De Voto (1971) suggested that the Antero syncline and its northern extension, the High Creek syncline, formed over a graben bounded by deep basement-controlled faults, each downthrown towards the axis of the syncline. We hypothesize that the High Creek syncline is a result of a different mechanism. Rocks ranging in age from Eocene to Miocene are folded by the High Creek syncline. Therefore the deformation, or at least the final stages of deformation, must post-date the folded Miocene rocks, which precludes a Laramide age for the High Creek syncline. Late Tertiary compressional stresses, which potentially could have formed the

Neogene syncline, have never been documented in the region. Also, no late Tertiary anticlines are paired with the syncline, as would be expected if compressional tectonism was the causative mechanism.

An alternative explanation for the High Creek syncline involves subsidence caused by dissolution of a large volume of evaporite in the Minturn Formation. Numerous sinkholes exist in and near the quadrangle. They probably are a result of subsidence related to evaporite dissolution (Shawe and others, 1995; Widmann and others, 2007). The discharge of saline ground water from springs in the region, such as the spring at the Salt Works ranch and the Salt spring (George and others, 1920; Simmons, 2002), indicates ongoing dissolution of evaporite in the subsurface. Synclines with characteristics similar to the High Creek syncline are well exposed in Spain and are attributed to suffosion or to sagging plus suffosion of unconsolidated cover material over underlying karst features formed in evaporite bedrock (F. Gutierrez, 2007, written communication).

Float consisting of angular pieces of tan, gray, and red-brown sandstone and siltstone was observed in the northeast part of the syncline. This material could be weathering out of strata within the Wagontongue Formation that is rich in angular clasts of sandstone and siltstone. Alternatively, the material also could reflect the presence of a window of Pennsylvanian age Minturn Formation on the wall and floor of the syncline.

These data lead us to surmise that the High Creek syncline probably formed in response to evaporite dissolution. Because the Eocene and Oligocene rocks are thick in the west limb of the syncline and thin or absent from the east limb, it is likely that the fold underwent movement as those formations were deposited. Significant folding also is required after deposition of the Miocene Wagontongue Formation, because that formation also is folded.

The southern end of the Bare syncline is concealed by Tertiary volcanic rocks. If the syncline continues southeast beneath the Tertiary volcanic cover, then a concealed anticline is required in the Pennsylvanian and older rocks beneath the axis of the High Creek syncline to account for the steeply east dipping Minturn rocks that crop out east of the Wagontongue rocks. If the anticline exists, then the High Creek syncline, which affects only middle Tertiary and younger rocks, is the surface expression of a collapsed salt anticline.

Several large depressions in the quadrangle also are attributed to subsidence due to evaporite dissolution. The High Creek fen lies in a nearly closed topographic depression that has subsided to the point where the land surface is at, below, or barely above the water table. Ground water supports the vegetation of the fen. High Creek has cut an outlet in the southeast end of the depression, but the cut is not deep enough to drain the wetland. The abundant sinkholes in the southwest part of the fen support a subsidence origin for the entire depression.

Another prominent subsidence depression formed in the surface capped by deposits of alluvial unit four west of the Lone Hills (figs. 5 and 24). This feature is over one mile long, about one-half mile wide, and is over 60 feet deep. When alluvial unit four was originally deposited, it must have blanketed this entire area, including where the depression is today. The depression was created by subsequent collapse of alluvial unit four into a void formed in the underlying evaporite. Other smaller subsidence depressions also exist in the surface capped by alluvial unit four west of the Lone Hills (fig. 24).

Other evidence of regional subsidence related to evaporite dissolution is provided by the tilted deposits of early Quaternary or late Tertiary gravel (unit QTg). All three deposits are west of Highway 285 in the northwest part of the quadrangle, and all three are tilted generally eastward. When viewed from a distance or on aerial photographs, the northernmost and southernmost tilted deposits of unit QTg (fig. 9) can easily be and have in the past been mistakenly interpreted as a flatiron formed by tilted bedrock. But the gravel deposits rest on an angular unconformity cut into underlying bedrock. These tilted deposits of gravel lie outside the currently recognized and mapped limits of subsidence depressions, which indicates the area affected by regional subsidence is very extensive and as yet not fully understood.

MINERAL RESOURCES

Sand and gravel are the only industrial mineral commodities currently being mined in the Garo quadrangle. The outwash gravels along the Middle Fork and South Fork of the South Platte River, Fourmile Creek, and High Creek contain potentially valuable sand and gravel resources. High-quality aggregate deposits exist in units Qa1, Qa2, Qa2y, Qa2o, and Qa3. Units Qa4y, Qa4o, QTg, Qac, Qf, and Qao also may contain economically significant aggregate resources. The R&R Regester Enterprises Inc. Antero Gravel pit in section 7, T. 12 S., R. 76 W. is the only permitted active sand and gravel operation in the quadrangle. Schwochow (1981) reported three other historically operated sand and gravel mines in the quadrangle.

Uranium, vanadium, radium, and copper were produced from the Garo deposit, also known as the Shirley May mine or DuVall discovery, which is located in section 16, T. 11 S., R. 76 W. and adjacent sections. Fleck (1909) first described the Garo deposit. The most complete description of the property was provided by Wilmarth (1959); this report included results from a drilling program by the U.S. Bureau of Mines. Most ore came from small, lenticular deposits contained in sandstone beds in the Maroon Formation. Most ore deposits were adjacent to small faults that cut the sandstone beds. The deposits include a variety of uranium, vanadium, and copper minerals. Channel samples from the deposits contained as much as 0.48 % uranium and 1.37 % vanadium (Wilmarth, 1959). One "carload" of ore was shipped from the property in 1919, and 180 tons of ore containing 0.16 % U_3O_8, and 0.71 % V_2O_5 were produced in 1952 (Nelson-Moore and others, 1978). No other metal occurrences are reported for the Garo quadrangle (Streufert and Cappa, 1994).

Deposits of peat have been mined in the quadrangle at the High Creek fen, along High Creek near the eastern edge of the quadrangle, and near Antero Reservoir in the south-central part of the quadrangle (mapped as mine waste on the geologic map). Units Qao and Qa1 are potential sources of peat.

The South Park basin, particularly the area between the town of Como and Spinney Mountain Reservoir, has been the target of sporadic oil and gas exploration since the early 1930s. Although no significant commercial production has yet been established in the basin, some encouraging shows have been found. The principal potential reservoir rocks in the basin are the Cretaceous Dakota Sandstone, Fox Hills Sandstone, and sandstone members of the Pierre Shale, such as the Apache Creek member (Clement and Dolton, 1970). The Permian Garo Sandstone also is a potential hydrocarbon reservoir. These rocks are present only in the northeast corner of the Garo quadrangle. The remainder of the quadrangle has very low potential for oil and gas.

Thick deposits of gypsum and perhaps halite exist in the evaporite facies of the Minturn Formation (unit Pme). Although no mining of these deposits is known to have occurred in the past, there is some potential for future development of these resources.

The hot spring at Hartsel is about four miles east of the Garo quadrangle, and the Rhodes warm springs along High Creek are a little over four miles northwest of the quadrangle (Barrett and Pearl, 1978). These occurrences suggest geothermal resources may exist at depth within the Garo quadrangle.

The Dakota Sandstone (unit Kd) has been quarried elsewhere in the state for use as dimension stone, silica sand, and crushed-rock aggregate (Schwochow, 1981). Currently, the Dakota Sandstone is being mined primarily for use as riprap at the Table Mountain quarry southwest of Colorado Springs. Clay is mined from the Dakota at places along the eastern base of the Front Range; however, no significant clay zones are known to exist in the Dakota Sandstone in South Park.

The Pierre Shale (Kp) is a potential source for common clay and lightweight aggregate. Clay from the Pierre Shale is used for manufacturing bricks and tiles, although other formations such as the Laramie and the Dawson are preferred by current manufacturers. Certain horizons in the Pierre Shale are mined and processed for use as lightweight aggregate at a facility near Boulder, well to the northeast of the Garo quadrangle.

Limestone in the Niobrara Formation (Kn) has been quarried in small quantities in the South Park area for lime (Stark and others, 1949). Limestone beds in the Niobrara are commonly quite pure, but these beds are seldom greater than one foot in thickness (Stark and others, 1949). The Niobrara is very poorly exposed, and there are no active or abandoned limestone quarries in the Garo quadrangle.

WATER RESOURCES

The Garo quadrangle is located in the headwaters region of the South Platte River watershed. The Middle Fork and South Fork of the South Platte River are the largest streams in the quadrangle. The Middle Fork of the South Platte originates at the Continental Divide near Hoosier Pass, flows through the town of Fairplay, and crosses the northeast corner of the Garo quadrangle. The headwaters of the South Fork are on Weston Pass. The South Fork flows eastward as it enters the quadrangle, bends southward after passing beneath Highway 285, and flows into Antero Reservoir south of the quadrangle. The Middle Fork and South Fork join downstream of Hartsel to form the mainstem of the South Platte River.

Other perennial streams in the quadrangle include High, Fourmile, and Trout Creeks. Crooked Creek joins the Middle Fork near the center of the quadrangle. High Creek passes through the High Creek fen and is channelized for much of its course downstream of the fen. Fourmile Creek approximately parallels High Creek across the quadrangle and merges with it about two miles east of the quadrangle. Their combined flows enter the South Fork about one mile upstream of Hartsel. Trout Creek crosses the northeastern corner of the quadrangle and flows into the Middle Fork a short distance east of the quadrangle. Surface water in the quadrangle historically was used primarily for irrigation, but during the past few decades the adjudicated rights for much of the surface water flowing across the quadrangle have been transferred to the municipalities in the Front Range Urban Corridor for municipal use.

Real-time flow data are available for perennial streams near the Garo quadrangle at http://www.dwr.state.co.us/SurfaceWater/default.aspx. The only readily available annual summaries of stream discharge in and near the quadrangle are found at http://cdss.state.co.us/DNN/Stations/tabid/74/Default.aspx. This database includes flow data from stream gauges on the Middle Fork of the South Platte above Fairplay, the Middle Fork near Hartsel and above the confluence with the South Fork, and Fourmile Creek about 3 miles west and upstream of the quadrangle, but only for the short time period from May 1978 through September 1980. During this short time period the mean annual discharge of the Middle Fork of the South Platte above Fairplay was 36,641 acre-feet, whereas the mean annual discharge of the Middle Fork above the confluence with the South Fork was 43,883 acre-feet. The mean annual discharge at the gage on Fourmile Creek was 9,841 acre-feet.

Topper and others (2003) describe the general ground water conditions in South Park. According to water well records held by the Colorado Division of Water Resources, most bedrock formations in the quadrangle are capable of yielding sufficient ground water for domestic purposes at depths of 75 to 200 feet, although in the Lone Hills the yield can be slightly greater. One 400-feet-deep dry hole was drilled on the west flank of the High Creek syncline (permit no. 200025). Wells drilled into alluvial units one, two, and three also usually yield adequate ground water for domestic purposes. Wells drilled into alluvial unit four also usually produce ground water except where the unit consists of relatively thin veneers over bedrock on ridges and mesas (for example, the Qa4o deposit on the interfluve between the Middle Fork and Fourmile Creek in the north-central part of the quadrangle).

GEOLOGIC HAZARDS AND CONSTRAINTS

The primary geologic hazards and geotechnical constraints in the Garo quadrangle include flooding, debris flows, sinkholes, and subsidence. Landslides, problematic soils, and earthquakes also pose potential threats. Areas underlain by alluvial unit one (Qa1), alluvium and colluvium (unit Qac), and alluvium and organic-rich sediment (unit Qao) are prone to water flooding. Debris flows, mudflows, and sheet flooding may affect areas mapped as fan deposits (unit Qf), alluvium and colluvium (unit Qac), and colluvium (unit Qc).

Sinkholes and subsidence are hazards in areas underlain by the evaporite facies of the Minturn Formation, perhaps even in areas where those rocks are hundreds of feet below the ground surface. Dozens of sinkholes were mapped in the quadrangle, including several previously documented by Shawe and others (1995), and several large subsidence depressions were identified (figs. 5 and 24). Examples of the sinkholes are shown in figure 26. The subsidence depressions are as much as two miles long, nearly a mile wide, and as much as 60 feet deep. If the High Creek syncline formed in response to subsidence into voids created by dissolution of evaporite, then many hundreds of feet of vertical collapse are possible, although such a large amount of subsidence probably required many tens, hundreds, and perhaps thousands of years of time or longer to fully develop.

A few small landslides were mapped in the quadrangle. Two are on the hillslopes of the Dakota hogback ridge, and the third formed in the Minturn Formation in the west-central part of the quadrangle. The latter feature could be related to subsidence over an evaporite karst area rather than conventional slope instability. Human activities, including excavations and earth fills on slopes and changes to the hydrologic environment from irrigation, septic systems, and water impoundments and diversions, also can contribute to slope failure. Future landsliding may not be restricted to areas mapped as landslide deposits.

Figure 26. Sinkholes in the Garo quadrangle. Broad shallow sinkhole in upper left is encircled by shrubs and partially filled with water. Approximate location: UTM coordinates 414880 m E, 4327880 m N. It is one of several sinkholes on the southwest margin of the High Creek fen, all of which are filled with organic-rich sediment. The sinkhole in the upper right formed in the evaporite facies of the Minturn Formation north of the South Fork about 0.6 miles from the west edge of the quadrangle (approximate location 414420 m E, 4326170 m N). This sinkhole has vegetated slopes that appear to be stabilized, but a recent collapse chimney has formed within the larger sinkhole (lower left). Gypsum is exposed in the wall of the recent collapse chimney (lower right).

Surficial deposits derived from the Pierre Shale may have high shrink-swell potential, which can be detrimental to foundations, roads, and other infrastructure. Heaving bedrock may also be a problem in areas underlain by beds of dipping shale on the east side of the Dakota hogback. Soils in areas underlain by the evaporite facies of the Minturn Formation, as well as areas containing gray gypsum-rich fluffy precipitate, may have properties that are deleterious to concrete and metal. Fine-grained sediments rapidly deposited in fan environments and on colluvial slopes may create conditions favorable for hydrocompaction and piping. Such sediments may be found in units Qf, Qc, and Qac.

Earthquakes due to rupture of nearby faults, like those at Spinney Mountain (Shaffer and Williamson, 1986) or in the upper Arkansas Valley (Ostenaa and others, 1981; Lettis and others, 1996), could cause moderately strong ground motion in the quadrangle. A random or "floating" earthquake along a fault that is deep in the crust and does not rupture the ground surface also could generate moderately strong ground motion. Structures should at least be designed and built to the standards of the current International Building Code or other appropriate building code. Earthquakes can also trigger secondary effects, such as liquefaction, rockfall, and landslides, which potentially can cause great damage. No late Quaternary faults, which pose the hazards of surface rupture and strong ground shaking when they suddenly move, were identified within the quadrangle.

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APPENDIX A. Whole-rock major-element geochemical analyses of samples from Garo quadrangle. All analyses were performed by ALS Chemex using the XRF method. Sample locations (in NAD 83) are listed below the table. Sample locations also are shown on the geologic map.

ID #	Unit[#]	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
		wt %	wt %	wt %	wt %	wt %	wt %	wt %	wt %	wt %	wt %	wt %	wt %	wt %	wt %	wt %
G153	Twm	70.28	14.13	2.16	1.41	0.40	3.54	5.22	<0.01	0.43	0.06	0.08	0.03	0.16	0.96	98.86
G156	Tad	61.60	16.00	5.42	4.80	2.35	2.99	3.01	0.01	0.64	0.09	0.25	0.08	0.16	1.70	99.09
G159	Twm	67.38	15.97	2.38	1.41	0.40	3.72	5.85	<0.01	0.59	0.06	0.11	0.04	0.22	0.57	98.69
G161	Tad	58.11	16.21	7.25	6.03	3.32	2.72	2.70	0.01	0.88	0.11	0.27	0.07	0.17	1.81	99.66
G164	Tad	63.32	16.19	4.13	4.52	0.85	3.16	3.35	0.01	0.64	0.03	0.23	0.07	0.16	1.82	98.49
G170	Tad	60.83	16.16	4.65	4.02	2.11	2.82	2.58	<0.01	0.63	0.07	0.21	0.08	0.15	4.29	98.60
G178	Twm	70.15	14.03	1.98	1.47	0.33	3.29	5.17	<0.01	0.42	0.02	0.08	0.03	0.18	1.68	98.83
G200	soil*	13.93	2.42	0.76	26.73	1.78	0.27	0.60	<0.01	0.07	0.01	0.06	0.37	0.02	20.20	67.21
G314	Tgp	72.80	15.36	0.51	0.69	0.10	3.98	5.08	<0.01	<0.01	0.02	0.02	0.04	0.08	0.49	99.16

[#] Refer to map or to section on Description of Map Units for an explanation of the unit symbols
* gypsiferous soil overlying unit Ｐme
[§] LOI = loss on ignition

Sample Locations
G153: 422015 m E; 4320917 m N
G156: 422188 m E; 4320875 m N
G159: 421956 m E; 4321818 m N
G161: 422127 m E; 4321534 m N
G164: 421017 m E; 4322853 m N
G170: 421458 m E; 4321660 m N
G178: 421198 m E; 4323594 m N
G200: 420288 m E; 4322901 m N
G314: 413922 m E; 4327840 m N

APPENDIX B. $^{40}Ar/^{39}Ar$ report.

$^{40}Ar/^{39}Ar$ Geochronology Results From the Buffalo Peaks Area, Central Colorado

By

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AUGUST 15, 2008

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Introduction

Three samples from the Buffalo Peaks area south of Fairplay in central Colorado were submitted for evaluation by Beth Widmann of the Colorado Geological Survey (G153, G164 and JH210). Sanidine was separated from samples G153 and JH210 while bioitite was separated from sample G164. The ages obtained from these samples are summarized in Table 1.

Table 1. Brief summary of results.

Sample	Phase	Age±2σ (Ma)
G153	Sanidine	36.93±0.11
G164	Biotite	38.59±0.14
JH210	Sanidine	60.95±0.15

$^{40}Ar/^{39}Ar$ Analytical Methods and Results

The sanidine separates were initially prepared by crushing and cleaning with dilute hydrofluoric acid. The sanidine was then separated with standard heavy liquid, magnetic separator and handpicking techniques. The biotite was separated with a similar process except that dilute hydrofluoric acid was not used. The mineral separates were loaded into aluminum discs and irradiated for 7 hours at the Nuclear Science Center in College Station, Texas.

The sanidine separates were analyzed by the single crystal laser fusion method. The biotite was analyzed with the furnace incremental heating age spectrum method. Abbreviated analytical methods for the dated samples are given in Table 2, and details of the overall operation of the New Mexico Geochronology Research Laboratory are provided in the Appendix. The argon isotopic results are summarized in Tables 1 and 2 and listed in Tables 3 and 4.

G153 Weighted Mean Age=36.90±0.11 Ma n/n_{total}=15/15 MSWD=3.86

All of the analyzed crystals were used to calculate a weighted mean age of 36.90±0.11 Ma for sample G153 (Figure 1). The MSWD of 3.86 suggests scatter in the data greater than would be expected due to analytical error alone (MSWD of 1.8 would be considered acceptable for a population of 15). The radiogenic yields are consistently high, with values ranging only from 96.9% to 99.4%. The K/Ca values are also consistent with values that vary from 23.1 to 28.0.

G 164 Weighted Mean Age=38.59±0.14 Ma n/n_{total}=4/9 MSWD=2.23

G 164 biotite yielded a nearly flat age spectrum (Figure 2a). Anomalously old apparent ages are revealed in the initial 2.7% of the ^{39}Ar released. The remaining steps of the age spectra are nearly concordant (MSWD = 2.23); a weighted mean age of 38.59±0.14 Ma is calculated from these steps (F-I). Both the K/Ca values and radiogenic yields increase over the first 20-30% of the ^{39}Ar released. Radiogenic yields increase from 0.3% to 93.5% and the K/Ca values increase from ~0 to 98.5. The data was evaluated with the inverse isochron technique and yielded an atmospheric intercept of 299.0±7.2 and an isochron age, for steps F-I, of 38.53±0.26 (Figure 2b).

JH 210 Weighted Mean Age=60.95±0.15 Ma n/n_{total}=12/15 MSWD=1.83

Twelve of the fifteen analyzed crystals were used to calculate a weighted mean age of 60.95±0.15 Ma for sample JH 210 (Figure 3). As with the previous sample, the MSWD is larger than would be expected due to analytical error. The radiogenic yields vary from 92.5% to 99.5% and the K/Ca values vary from 65.2 to 132.6.

Discussion

Sample G153 yielded a high precision sanidine age that represents an accurate eruption age (36.93±0.11 Ma) for the extrusive rock from which it was sampled. The well-behaved biotite age spectra from sample G164 also provides a precise weighted mean age (38.59±0.14 Ma). When both biotite and sanidine are analyzed from the same rock, the biotite age is occasionally found to be up to ~0. 5 Ma older than the co-existing sanidine. In these cases, the sanidine age is thought to represent the most accurate eruption age. This must be considered when comparing the age assigned to G153 and the age assigned to G164. The sanidine from sample JH210 provides an age (60.95 ± 0.15 Ma) with similar precision to the other two samples in this study. The youngest two crystals that were deleted from the weighted mean age are thought to have undergone Ar loss. The oldest crystal was also eliminated, this crystal displayed the lowest radiogenic yield and a K/Ca value roughly half that of the other crystals. As JH210 is from a high level intrusive rock the age interpretation is less straightforward than that for sample G153. If JH210 was emplaced at a very shallow depth and cooled very rapidly, the assigned age can be considered an emplacement age. Obviously, increased depth and slower cooling would affect the interpretation of the assigned age. In Table 5, we compare some pre-existing data from the Buffalo Peaks area with the results from this study. The age and K/Ca ratio of sanidine from sample G153 are similar to published values from Wall Mountain Tuff (McIntosh and Chapin, 2004). Likewise biotite from G164 is similar in age to hornblende from the Buffalo Peaks Tuff (McIntosh and Chapin, 2004). Sanidine from JH210 is similar in age to K rhyolites north of Buffalo Peaks (McIntosh, unpublished data).

Table 5. Possible correlations with previously dated samples from the Buffalo Peaks area.

Unit	Age (McIntosh and Chapin, 2004)	Age (corrected for FCT san = 28.02 Ma)	Comment
Wall Mountain Tuff	36.69±0.09 Ma		Compares closely with sample G253 sanidine (36.91—0.11 Ma)
Tuff of Buffalo Peaks	38.18±0.32 Ma	38.41±0.32 Ma	Compares closely with sample G164 (38.59—0.14 Ma)
	Age (unpublished data)		
K rhyolite N of Buffalo Peaks	59.88±0.17 Ma	60.24±0.17 Ma	Similar to sample JH210 sanidine (60.97±0.105 Ma)

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Table 2. Summary of $^{40}Ar/^{39}Ar$ results and analytical methods

Sample	Lab #	Irradiation	mineral	age analysis	steps/analyses	Age	±2σ	MSWD
G153	57343	NM -210	sanidine	laser total fusion	15	36.9	0.11	3.86
G164	57342	NM-210	biotite	furnace step-heat	4	38.59	0.14	2.69
JH210	57344	NM-210	sanidine	laser total fusion	13	60.95	0.15	1.83

Sample preparation and irradiation:
Minerals separated with standard heavy liquid, Franz Magnetic and hand-picking techniques.
Samples in NM-210 irradiated in a machined Aluminum tray for 7 hours in D-3 position, Nuclear Science Center, College Station, TX.
Neutron flux monitor Fish Canyon Tuff sanidine (FC-2). Assigned age = 28.02 Ma (Renne et al, 1998).

Instrumentation:
Analyses performed on a Mass Analyzer Products 215-50 mass spectrometer on line with automated all-metal extraction system.
Biotite step-heated, using a Mo double-vacuum resistance furnace.
Sanidine fused by a 50 watt Synrad CO_2 laser.

Analytical parameters:
J-factors determined by CO_2 laser-fusion of 6 single crystals from each of 6 or 10 radial positions around the irradiation tray.
Decay constants and isotopic abundances after Steiger and Jäger (1977).

Table 3. $^{40}Ar/^{39}Ar$ analytical data.

	ID	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$ (x 10^{-3})	$^{39}Ar_K$ (x 10^{-15} mol)	K/Ca	$^{40}Ar^*$ (%)	Age (Ma)	±1σ (Ma)
	G153, Sanidine, J=0.0007758±0.11%, D=1.0044±0.001, NM-210L, Lab#=57343								
	01	27.01	0.0196	2.123	2.421	26.0	97.7	36.55	0.08
	15	27.18	0.0211	2.238	1.389	24.2	97.6	36.74	0.09
	11	27.37	0.0212	2.845	1.951	24.0	96.9	36.76	0.07
	09	27.04	0.0195	1.658	1.511	26.1	98.2	36.79	0.08
	14	27.72	0.0215	3.805	2.127	23.7	96.0	36.85	0.08
	04	27.14	0.0216	1.794	2.064	23.6	98.1	36.86	0.07
	13	27.23	0.0221	2.094	1.275	23.1	97.7	36.87	0.10
	03	27.37	0.0193	2.486	1.678	26.4	97.3	36.91	0.09
	10	27.55	0.0191	2.898	0.889	26.7	96.9	36.98	0.13
	08	27.06	0.0209	1.246	1.532	24.4	98.6	36.99	0.09
	06	27.21	0.0206	1.718	2.203	24.7	98.1	36.99	0.07
	12	27.22	0.0204	1.687	1.549	25.0	98.2	37.02	0.09
	07	26.96	0.0209	0.7993	3.373	24.5	99.1	37.03	0.06
	02	26.95	0.0194	0.5666	1.243	26.3	99.4	37.10	0.10
	05	27.07	0.0182	0.6899	1.224	28.0	99.3	37.21	0.09
	Mean age ± 2σ	n=15		MSWD=3.86		25.1 ±2.8		36.90	0.11
	JH 210, Sanidine, J=0.0007752±0.10%, D=1.0044±0.001, NM-210L, Lab#=57344								
#	01	43.87	0.0047	1.815	1.715	108.7	98.8	59.60	0.13
#	12	44.43	0.0050	2.179	2.631	102.9	98.6	60.22	0.09
	07	45.06	0.0048	2.980	2.549	105.8	98.0	60.75	0.10
	08	46.98	0.0053	9.423	2.108	95.8	94.1	60.78	0.12
	06	47.82	0.0057	12.22	1.865	89.1	92.5	60.79	0.12
	04	45.13	0.0053	3.105	1.826	97.2	98.0	60.80	0.11
	02	44.98	0.0044	2.401	1.707	115.0	98.4	60.87	0.11
	13	44.68	0.0044	1.199	2.466	115.1	99.2	60.95	0.10
	10	44.89	0.0050	1.901	3.174	102.6	98.7	60.95	0.09
	05	44.67	0.0038	1.143	3.247	132.6	99.2	60.95	0.09
	14	44.85	0.0046	1.505	3.350	110.4	99.0	61.06	0.09
	09	45.00	0.0054	1.875	1.920	95.1	98.8	61.12	0.11
	03	44.69	0.0043	0.7851	1.882	119.0	99.5	61.12	0.11
	15	44.87	0.0046	1.373	2.267	109.8	99.1	61.14	0.10
#	11	47.52	0.0078	9.901	2.786	65.2	93.8	61.32	0.12
	Mean age ± 2σ	n=12		MSWD=1.83		107.3 ±24.5		60.95	0.15

Notes:

Isotopic ratios corrected for blank, radioactive decay, and mass discrimination, not corrected for interfering reactions.
Errors quoted for individual analyses include analytical error only, without interfering reaction or J uncertainties.
Mean age is weighted mean age of Taylor (1982). Mean age error is weighted error of the mean (Taylor, 1982), multiplied by the root of the MSWD where MSWD>1, and also incorporates uncertainty in J factors and irradiation correction uncertainties.
Decay constants and isotopic abundances after Steiger and Jäger (1977).
symbol preceding sample ID denotes analyses excluded from mean age calculations.
Ages calculated relative to FC-2 Fish Canyon Tuff sanidine interlaboratory standard at 27.84 Ma
Decay Constant (LambdaK (total)) = 5.543e-10/a
Correction factors:

$(^{39}Ar/^{37}Ar)_{Ca} = 0.00068 \pm 5e-05$

$(^{36}Ar/^{37}Ar)_{Ca} = 0.00028 \pm 2e-05$

$(^{38}Ar/^{39}Ar)_K = 0.01077$

$(^{40}Ar/^{39}Ar)_K = 0 \pm 0.0004$

Table 4. $^{40}Ar/^{39}Ar$ analytical data.

	ID	Temp	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$ ($\times 10^{-3}$)	$^{39}Ar_K$ ($\times 10^{-15}$ mol)	K/Ca	$^{40}Ar^*$ (%)	^{39}Ar (%)	Age (Ma)	$\pm 1\sigma$ (Ma)
	G164, Biotite, 5.62 mg, J=0.0007769±0.09%, D=1.0006±0.001, NM-210L, Lab#=57342-01										
Xi	A	625	4278.8	-0.4114	14433.6	0.026	-	0.3	0.1	19.1	27.0
X	B	700	420.3	0.0577	1334.1	0.037	8.8	6.2	0.3	36.2	4.7
X	C	750	153.7	0.1030	409.0	0.043	5.0	21.3	0.6	45.4	2.3
X	D	800	99.55	0.1554	241.8	0.059	3.3	28.2	0.9	39.0	1.4
X	E	875	67.48	0.0619	130.8	0.344	8.2	42.8	2.7	40.00	0.48
	F	975	39.91	0.0166	40.50	1.85	30.7	70.0	12.5	38.75	0.15
	G	1075	31.21	0.0052	11.90	3.07	98.5	88.7	28.8	38.413	0.086
	H	1250	31.19	0.0283	11.19	8.30	18.0	89.4	73.0	38.671	0.071
	I	1700	29.76	0.0222	6.567	5.09	23.0	93.5	100.0	38.587	0.071
	Integrated age ± 2σ			n=9		18.8	22.8	K2O=1.66%		38.62	0.23
	Plateau ± 2σ		steps F-I	n=4	MSWD=2.23	18.3	34.2	±75.3	97.3	38.59	0.14
	Isochron±2σ		steps B-I	n=8	MSWD=2.69		$^{40}Ar/^{36}Ar$=	299.7±3.1		38.53	0.18

Notes:

Isotopic ratios corrected for blank, radioactive decay, and mass discrimination, not corrected for interfering reactions.
Errors quoted for individual analyses include analytical error only, without interfering reaction or J uncertainties.
Integrated age calculated by summing isotopic measurements of all steps.
Integrated age error calculated by quadratically combining errors of isotopic measurements of all steps.
Plateau age is inverse-variance-weighted mean of selected steps.
Plateau age error is inverse-variance-weighted mean error (Taylor, 1982) times root MSWD where MSWD>1.
Plateau error is weighted error of Taylor (1982).
Decay constants and isotopic abundances after Steiger and Jäger (1977).
symbol preceding sample ID denotes analyses excluded from plateau age calculations.
Weight percent K_2O calculated from ^{39}Ar signal, sample weight, and instrument sensitivity.
Ages calculated relative to FC-2 Fish Canyon Tuff sanidine interlaboratory standard at 27.84 Ma
Decay Constant (LambdaK (total)) = 5.543e-10/a
Correction factors:
$(^{39}Ar/^{37}Ar)_{Ca} = 0.00068 \pm 5e\text{-}05$
$(^{36}Ar/^{37}Ar)_{Ca} = 0.00028 \pm 2e\text{-}05$
$(^{38}Ar/^{39}Ar)_K = 0.01077$
$(^{40}Ar/^{39}Ar)_K = 0 \pm 0.0004$

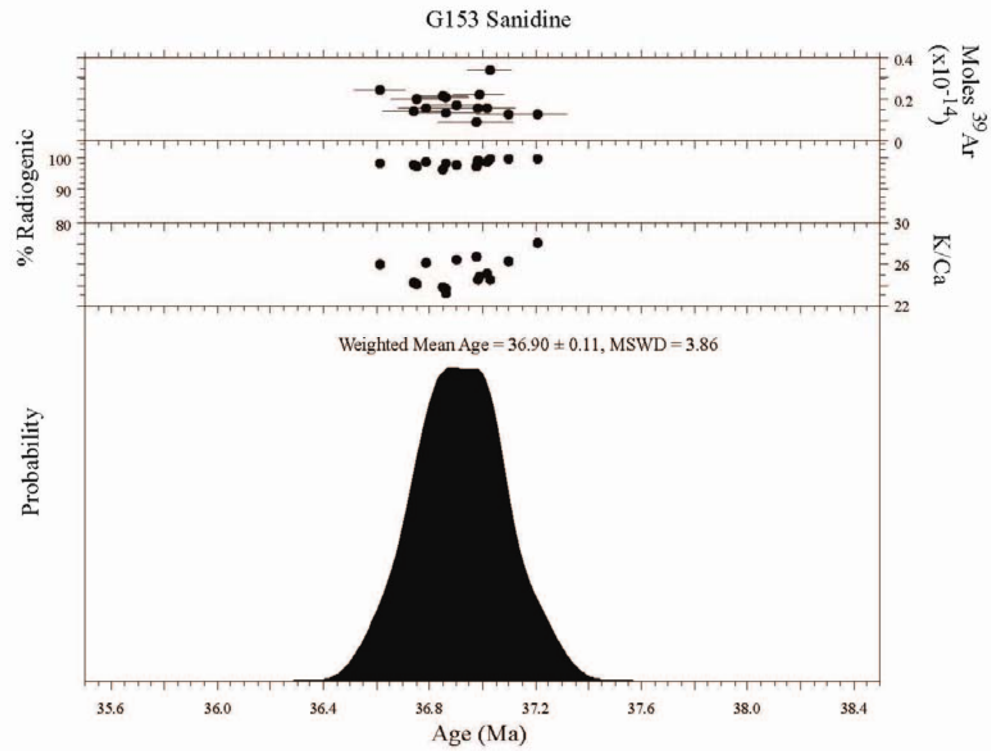

Figure 1. Age probability distribution diagram for G153 single crystal sanidine. All errors quoted at 2 sigma.

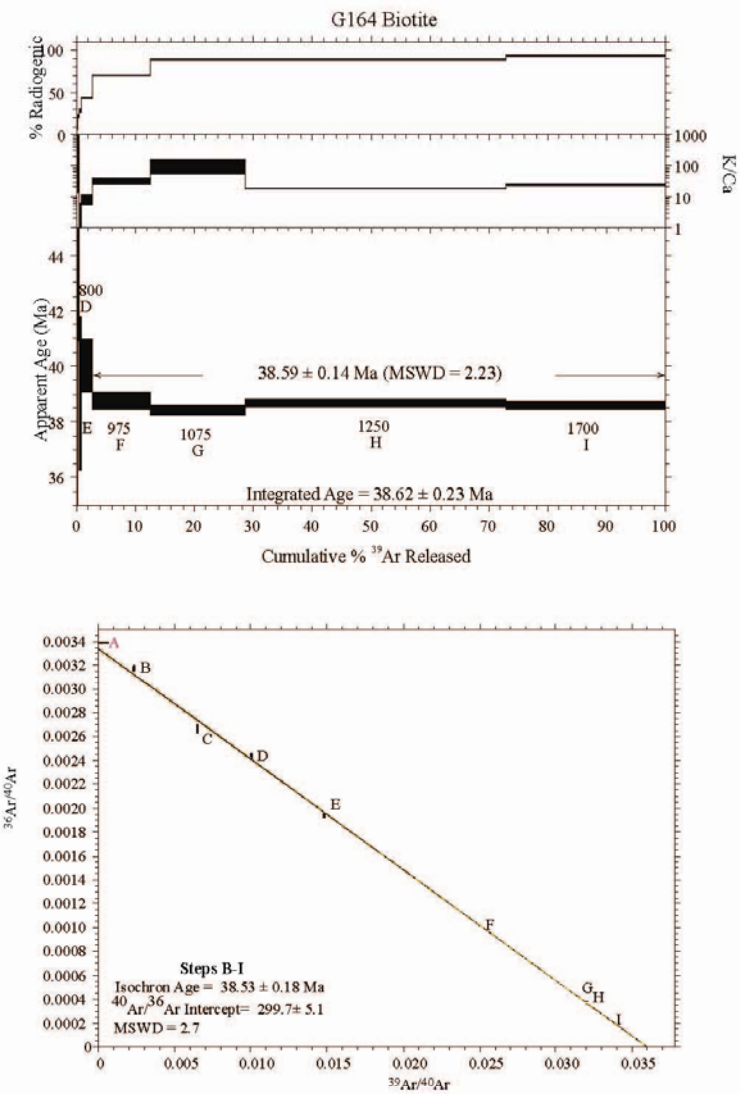

Figure 2. Age spectrum (2a) and isochron (2b) of G164 biotite. All errrors quoted at 2 sigma.

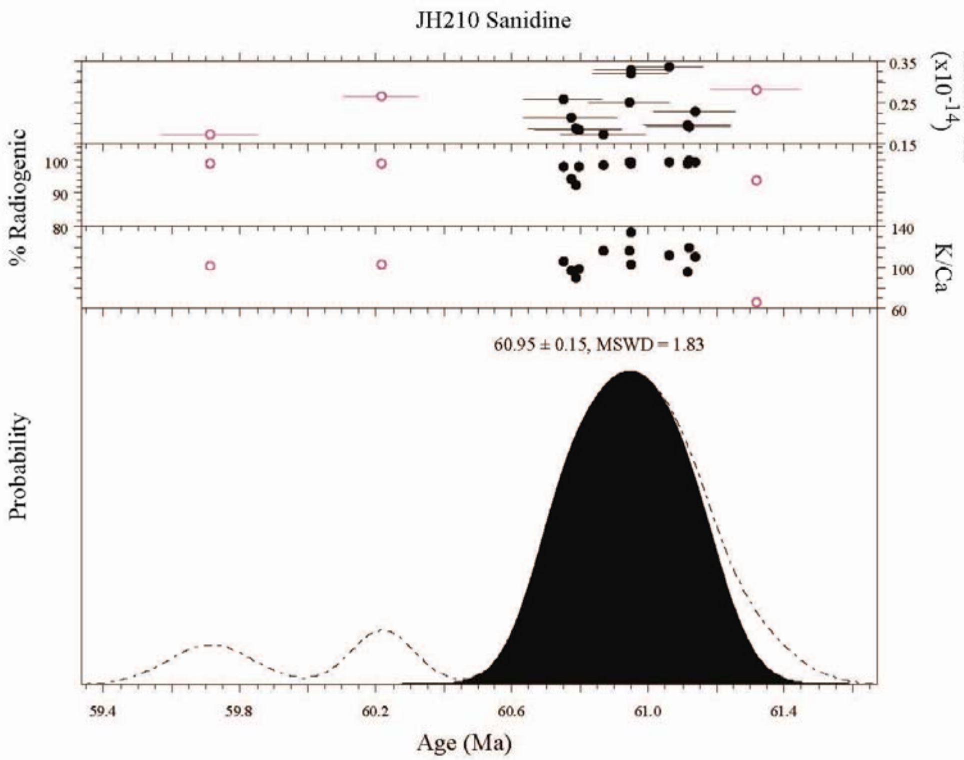

Figure 3. Age probability distribution diagram for J210 single crystal sanidine. All errors quoted at 2 sigma. Points shown in purple eliminated from weighted age.

New Mexico Bureau of Mines and Mineral Resources

Procedures of the New Mexico Geochronology Research Laboratory

For the Period June 1998 – present

Matthew Heizler
William C. McIntosh
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$^{40}Ar/^{39}Ar$ and K-Ar dating

Often, large bulk samples (either minerals or whole rocks) are required for K-Ar dating and even small amounts of xenocrystic, authigenic, or other non-ideal behavior can lead to inaccuracy. The K-Ar technique is susceptible to sample inhomogeneity as separate aliquots are required for the potassium and argon determinations. The need to determine absolute quantities (i.e. moles of $^{40}Ar^*$ and ^{40}K) limits the precision of the K-Ar method to approximately 1% and also, the technique provides limited potential to evaluate underlying assumptions. In the $^{40}Ar/^{39}Ar$ variant of the K-Ar technique, a sample is irradiated with fast neutrons thereby converting ^{39}K to ^{39}Ar through a (n,p) reaction. Following irradiation, the sample is either fused or incrementally heated and the gas analyzed in the same manner as in the conventional K-Ar procedure, with one exception, no argon spike need be added.

Some of the advantages of the $^{40}Ar/^{39}Ar$ method over the conventional K-Ar technique are:

1. A single analysis is conducted on one aliquot of sample thereby reducing the sample size and eliminating sample inhomogeneity.
2. Analytical error incurred in determining absolute abundances is reduced by measuring only isotopic ratios. This also eliminates the need to know the exact weight of the sample.
3. The addition of an argon spike is not necessary.
4. The sample does not need to be completely fused, but rather can be incrementally heated. The $^{40}Ar/^{39}Ar$ ratio (age) can be measured for each fraction of argon released and this allows for the generation of an age spectrum.

The age of a sample as determined with the $^{40}Ar/^{39}Ar$ method requires comparison of the measured $^{40}Ar/^{39}Ar$ ratio with that of a standard of known age. Also, several isotopes of other elements (Ca, K, Cl, Ar) produce argon during the irradiation procedure and must be corrected for. Far more in-depth details of the determination of an apparent age via the $^{40}Ar/^{39}Ar$ method are given in Dalrymple et al. (1981) and McDougall and Harrison (1988).

Analytical techniques

Sample Preparation and irradiation details

Mineral separates are obtained in various fashions depending upon the mineral of interest, rock type and grain size. In almost all cases the sample is crushed in a jaw crusher and ground in a disc grinder and then sized. The size fraction used generally corresponds to the largest size possible which will permit obtaining a pure mineral separate. Following sizing, the sample is washed and dried. For plutonic and metamorphic rocks and lavas, crystals are separated using standard heavy liquid, Franz magnetic and hand-picking techniques. For volcanic sanidine and plagioclase, the sized sample is reacted with 15% HF acid to remove glass and/or matrix and then thoroughly washed prior to heavy liquid and magnetic separation. For groundmass concentrates, rock fragments are selected which do not contain any visible phenocrysts.

The NMGRL uses either the Ford reactor at the University of Michigan or the Nuclear Science Center reactor at Texas A&M University. At the Ford reactor, the L67 position is used (unless otherwise noted) and the D-3 position is always used at the Texas A&M reactor. All of the Michigan irradiations are carried out underwater without any shielding for thermal neutrons, whereas the Texas irradiations are in a dry location which is shielded with B and Cd. Depending upon the reactor used, the mineral separates are loaded into either holes drilled into Al discs or into 6 mm I.D. quartz tubes. Various Al discs are used. For Michigan, either six hole or twelve hole, 1 cm diameter discs are used and all holes are of equal size. Samples are placed in the 0, 120 and 240° locations and standards in the 60, 180 and 300° locations for the six hole disc. For the twelve hole disc, samples are located at 30, 60, 120, 150, 210, 240, 300, and 330° and standards at 0, 90, 180 and 270 degrees. If samples are loaded into the quartz tubes, they are wrapped in Cu foil with standards interleaved at ~0.5 cm intervals. For Texas, 2.4 cm diameter discs contain either sixteen or six sample holes with smaller holes used to hold the standards. For the six hole disc, sample locations are 30, 90, 150, 210, 270 and 330° and standards are at 0, 60, 120, 180, 240 and 300°. Samples are located at 18, 36, 54, 72, 108, 126, 144, 162, 198, 216, 234, 252, 288, 306, 324, 342 degrees and standards at 0, 90, 180 and 270 degrees in the sixteen hole disc. Following sample loading into the discs, the discs are stacked, screwed together and sealed in vacuo in either quartz (Michigan) or Pyrex (Texas) tubes.

Extraction Line and Mass Spectrometer details

The NMGRL argon extraction line has both a double vacuum Mo resistance furnace and a CO_2 laser to heat samples. The Mo furnace crucible is heated with a W heating element and the temperature is monitored with a W-Re thermocouple placed in a hole drilled into the bottom of the crucible. A one inch long Mo liner is placed in the bottom of the crucible to collect the melted samples. The furnace temperature is calibrated by either/or melting Cu foil or with an additional thermocouple inserted in the top of the furnace down to the liner. The CO_2 laser is a Synrad 10W laser equipped with a He-Ne pointing laser. The laser chamber is constructed from a 3 3/8" stainless steel conflat and the window material is ZnS. The extraction line is a two stage design. The first stage is equipped with a SAES GP-50 getter, whereas the second stage houses two SAES GP-50 getters and a tungsten filament. The first stage getter is operated at 450°C as is one of the second stage getters. The other second stage getter is operated at room temperature and the tungsten filament is operated at ~2000°C. Gases evolved from samples heated in the furnace are reacted with the first stage getter during heating. Following heating, the gas is expanded into the second stage for two minutes and then isolated from the first stage. During second stage cleaning, the first stage and furnace are pumped out. After gettering in the second stage, the gas is expanded into the mass spectrometer. Gases evolved from samples heated in the laser are expanded through a cold finger operated at -140°C and directly into the second stage. Following cleanup, the gas in the second stage and laser chamber is expanded into the mass spectrometer for analysis.

The NMGRL employs a MAP-215-50 mass spectrometer which is operated in static mode. The mass spectrometer is operated with a resolution ranging between 450 to 600 at mass 40 and isotopes are detected on a Johnston electron multiplier operated at ~2.1 kV with an overall gain of about 10,000 over the Faraday collector. Final isotopic intensities are determined by linear regression to time zero of the peak height versus time following gas introduction for each mass. Each mass intensity is corrected for mass spectrometer baseline and background and the extraction system blank.

Blanks for the furnace are generally determined at the beginning of a run while the furnace is cold and then between heating steps while the furnace is cooling. Typically, a blank is run every three to six heating steps. Periodic furnace hot blank analysis reveals that the cold blank is equivalent to the hot blank for temperatures less than about 1300°C. Laser system blanks are generally determined between every four analyses. Mass discrimination is measured using atmospheric argon which has been dried using a Ti-sublimation pump. Typically, 10 to 15 replicate air analyses are measured to determine a mean mass discrimination value. Air pipette analyses are generally conducted 2-3 times per month, but more often when samples sensitive to the mass discrimination value are analyzed. Correction factors for interfering nuclear reactions on K and Ca are determined using K-glass and CaF_2, respectively. Typically, 3-5 individual pieces of the salt or glass are fused with the CO_2 laser and the correction factors are calculated from the weighted mean of the individual determinations.

Data acquisition, presentation and age calculation

Samples are either step-heated or fused in a single increment (total fusion). Bulk samples are often step-heated and the data are generally displayed on an age spectrum or isochron diagram. Single crystals are often analyzed by the total fusion method and the results are typically displayed on probability distribution diagrams or isochron diagrams.

The Age Spectrum Diagram

Age spectra plot apparent age of each incrementally heated gas fraction versus the cumulative % $^{39}Ar_K$ released, with steps increasing in temperature from left to right. Each apparent age is calculated assuming that the trapped argon (argon not produced by *in situ* decay of ^{40}K) has the modern day atmospheric $^{40}Ar/^{36}Ar$ value of 295.5. Additional parameters for each heating step are often plotted versus the cumulative %$^{39}Ar_K$ released. These auxiliary parameters can aid age spectra interpretation and may include radiogenic yield (percent of ^{40}Ar which is not atmospheric), K/Ca (determined from measured Ca-derived ^{37}Ar and K-derived ^{39}Ar) and/or K/Cl (determined from measured Cl-derived ^{38}Ar and K-derived ^{39}Ar). Incremental heating analysis is often effective at revealing complex argon systematics related to excess argon, alteration, contamination, ^{39}Ar recoil, argon loss, etc. Often low-temperature heating steps have low radiogenic yields and apparent ages with relatively high errors due mainly to loosely held, non-radiogenic argon residing on grain surfaces or along grain boundaries. An entirely or partially flat spectrum, in which apparent ages are the same within analytical error, may indicate that the sample is homogeneous with respect to K and Ar and has had a simple thermal and geological history. A drawback to the age spectrum technique is encountered when hydrous minerals such as micas and amphiboles are analyzed. These minerals are not stable in the ultra-high vacuum extraction system and thus step-heating can homogenize important details of the true ^{40}Ar distribution. In other words, a flat age spectrum may result even if a hydrous sample has a complex argon distribution.

The Isochron Diagram

Argon data can be plotted on isotope correlation diagrams to help assess the isotopic composition of Ar trapped at the time of argon closure, thereby testing the assumption that trapped argon isotopes have the composition of modern atmosphere which is implicit in age spectra. To construct an "inverse isochron" the $^{36}Ar/^{40}Ar$ ratio is plotted versus the $^{39}Ar/^{40}Ar$ ratio. A best fit line can be calculated for the data array which yields the value for the trapped argon (Y-axis intercept) and the $^{40}Ar^*/^{39}Ar_K$ value (age) from the X-axis intercept. Isochron analysis is most useful for step-heated or total fusion data which have a significant spread in radiogenic yield. For young or low K samples, the calculated apparent age can be very sensitive to the composition of the trapped argon and therefore isochron analysis should be preformed routinely on these samples (cf. Heizler and Harrison, 1988). For very old (>Mesozoic) samples or relatively old sanidines (>mid-Cenozoic) the data are often highly radiogenic and cluster near the X-axis thereby making isochron analysis of little value.

The Probability Distribution Diagram

The probability distribution diagram, which is sometimes referred to as an ideogram, is a plot of apparent age versus the summation of the normal distribution of each individual analysis (Deino and Potts, 1992). This diagram is most effective at displaying single crystal laser fusion data to assess the distribution of the population. The K/Ca, radiogenic yield, and the moles of ^{39}Ar for each analysis are also often displayed for each sample as this allows for visual ease in identifying apparent age correlations between, for instance, plagioclase contamination, signal size and/or radiogenic concentrations. The error (1σ) for each age analysis is generally shown by the horizontal lines in the moles of ^{39}Ar section. Solid symbols represent the analyses used for the weighted mean age calculation and the generation of the solid line on the ideogram, whereas open symbols represent data omitted from the age calculation. If shown, a dashed line represents the probability distribution of all of the displayed data. The diagram is most effective for displaying the form of the age distribution (i.e. gaussian, skewed, etc.) and for identifying xenocrystic or other grains which fall outside of the main population.

Error Calculations

For step-heated samples, a plateau for the age spectrum is defined by the steps indicated. The plateau age is calculated by weighting each step on the plateau by the inverse of the variance and the error is calculated by either the method of Samson and Alexander (1987) or Taylor (1982). A mean sum weighted deviates (MSWD) value is determined by dividing the Chi-squared value by n-1 degrees of freedom for the plateau ages. If the MSWD value is outside the 95% confidence window (cf. Mahon, 1996; Table 1), the plateau or preferred age error is multiplied by the square root of the MSWD.

For single crystal fusion data, a weighted mean is calculated using the inverse of the variance to weight each age determination (Taylor, 1982). Errors are calculated as described for the plateau ages above.

Isochron ages, $^{40}Ar/^{36}Ar_i$ values and MSWD values are calculated from the regression results obtained by the York (1969) method.

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