OPEN-FILE REPORT 03-19

Geologic Map of the Manitou Springs 7.5-Minute Quadrangle, El Paso and Teller Counties, Colorado

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FOREWORD

The purpose of Colorado Geological Survey Open File Report 03-19, Geologic Map of the Manitou Springs Quadrangle, El Paso and and Teller Counties, Colorado is to describe the geologic setting, mineral resource potential, and geologic hazards of this 7.5-minute quadrangle located directly west of Colorado Springs. The principal geologists for the mapping project were John Keller, CGS staff geologist, Christine Siddoway, Associate Professor of Geology at Colorado College, and Matt Morgan, CGS staff geologist.

This mapping project was funded jointly by the U.S. Geological Survey through the STATEMAP component of the National Cooperative Geologic Mapping Program which is authorized by the National Geologic Mapping Act of 1997, Agreement No. 02HQAG0050, and the Colorado Geological Survey using the Colorado Department of Natural Resources Severance Tax Operational Funds. The CGS matching funds come from the Severance Tax paid on the production of natural gas, oil, coal, and metals.

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We are indebted to several people for providing us access to areas that are normally closed to public use in the Manitou Springs quadrangle. Jeff Hovermale at the U.S. Forest Service Pikes Peak Ranger District office in Colorado Springs provided access and gate keys to areas in the Pike National Forest that were closed during much of the summer because of the extreme fire danger. The watershed management staff of Colorado Springs Utilities, specifically Mike Herrin and Bill Bunt, allowed the mapping team to enter areas with restricted access in the watershed. Kirk Greasby of the City of Manitou Springs water department provided access for mapping in the vicinity of Manitou Reservoir and other areas near the City of Manitou Springs. Art Nielsen, manager of the Crystal Park homeowner's association, provided permission to conduct mapping activities on the large area of private land around Crystal Park.

John Himmelreich, co-author of the concurrently mapped Cascade quadrangle and an expert on geologic hazards in the Colorado Springs area, provided unpublished maps, reports, and insights regarding landslides and other geologic hazards in the populated northeastern part of the Manitou Springs quadrangle. Pete Rowley provided helpful insights regarding mapping techniques and geologic interpretations during the field season. Technical reviews by C.A. Wallace and John Himmelreich improved the quality of the map and text. Vince Matthews, CGS Senior Science Advisor, provided helpful advice and geological insights throughout the project, and performed a final technical review of the map and text prior to publication. Jason Wilson (CGS) provided GIS support for the compilation of the map and cross sections, drafted the final cartographic map, and completed the layout of the text booklet. Larry Scott (CGS) drafted illustrations for the text booklet. Suzie Noble (consultant) set the digital photogrammetric stereo models in ERDAS Stereo Analyst software. Jane Ciener edited the text, map, and cross sections.

CONTENTS

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INTRODUCTION

The Manitou Springs 7.5-minute quadrangle is located in western El Paso County and southeastern Teller County in central Colorado (Fig. 1). The westernmost part of the city of Colorado Springs is on the eastern edge of the quadrangle, and the city of Manitou Springs is entirely within the northeastern part of the quadrangle. The southwestern part of the Garden of the Gods Park, a famous and popular geologic site, occupies the northeastern corner of the quadrangle. The summit of Pikes Peak (14,110 ft), one of the most famous mountains in the United States, is 2.5 mi west of the Manitou Springs quadrangle.

There is 6,250 ft of vertical relief in the Manitou Springs quadrangle. The highest point is Almagre Mountain (12,367 ft). The lowest point (approximately 6,117 ft) is along Fountain Creek in the northeastern part of the quadrangle. Fountain Creek is the largest creek in the quadrangle and flows in a southeasterly direction. Several smaller creeks originate in the mountains and are tributary to Fountain Creek, which flows into the Arkansas River in Pueblo. Some of the higher, western areas of the quadrangle are protected watershed. Lake Moraine, Manitou Reservoir, and Big Tooth Reservoir are part of the water supply system for Colorado Springs and Manitou Springs and are not accessible to the general public. Much of the mountainous part of the quadrangle is in the Pike National Forest and is generally open to public access. Numerous trails provide recreational opportunities for hiking, mountain biking, mineral collecting, off-road motorcycles, and ATVs.

Most of the quadrangle is in the rugged and forested terrain of the southern Front Range. The mountainous area is underlain predominantly by Proterozoic granitic rocks of the Pikes Peak batholith. In the northeastern part of the quadrangle, the Ute Pass fault zone places the Precambrian granitic rocks into contact with Paleozoic and Mesozoic sedimentary rocks that underlie the Colorado Piedmont. Representative exposures of Lower Paleozoic sedimentary rocks in the eastern Front Range are present in the Manitou Springs embayment, a structural and topographic feature that formed in the transfer zone between the northwest-striking Ute Pass fault to the south and the north-striking Rampart Range fault to the north (Kluth, 1997). The southern segment of the Rampart Range fault is exposed in the Garden of the Gods Park and is in large part responsible for the spectacular vertical “fins” of colorful sandstone that make the park an attraction for geologists and tourists alike. The “Great Unconformity” (nonconformity) is well-exposed in the canyon formed by Fountain Creek in the north-central part of the quadrangle, where the Cambrian Sawatch Sandstone lies directly upon the Precambrian crystalline basement rocks. Quaternary deposits are widespread and varied. Glacial deposits from at least two glacial episodes, and landslides, debris fans, pediment gravels, and stream alluvium of several ages are present in the quadrangle. The steep topography and large amount of vertical relief has resulted in rapid erosion of the bedrock. Steep-walled canyons such as Williams Canyon, North Cheyenne Canyon, and South Cheyenne Canyon are scenic testaments to the rapid erosion that is still occurring in the region. Landslides, rockfall, and debris flows are geologic hazards that are related to this rapid erosion in the area.

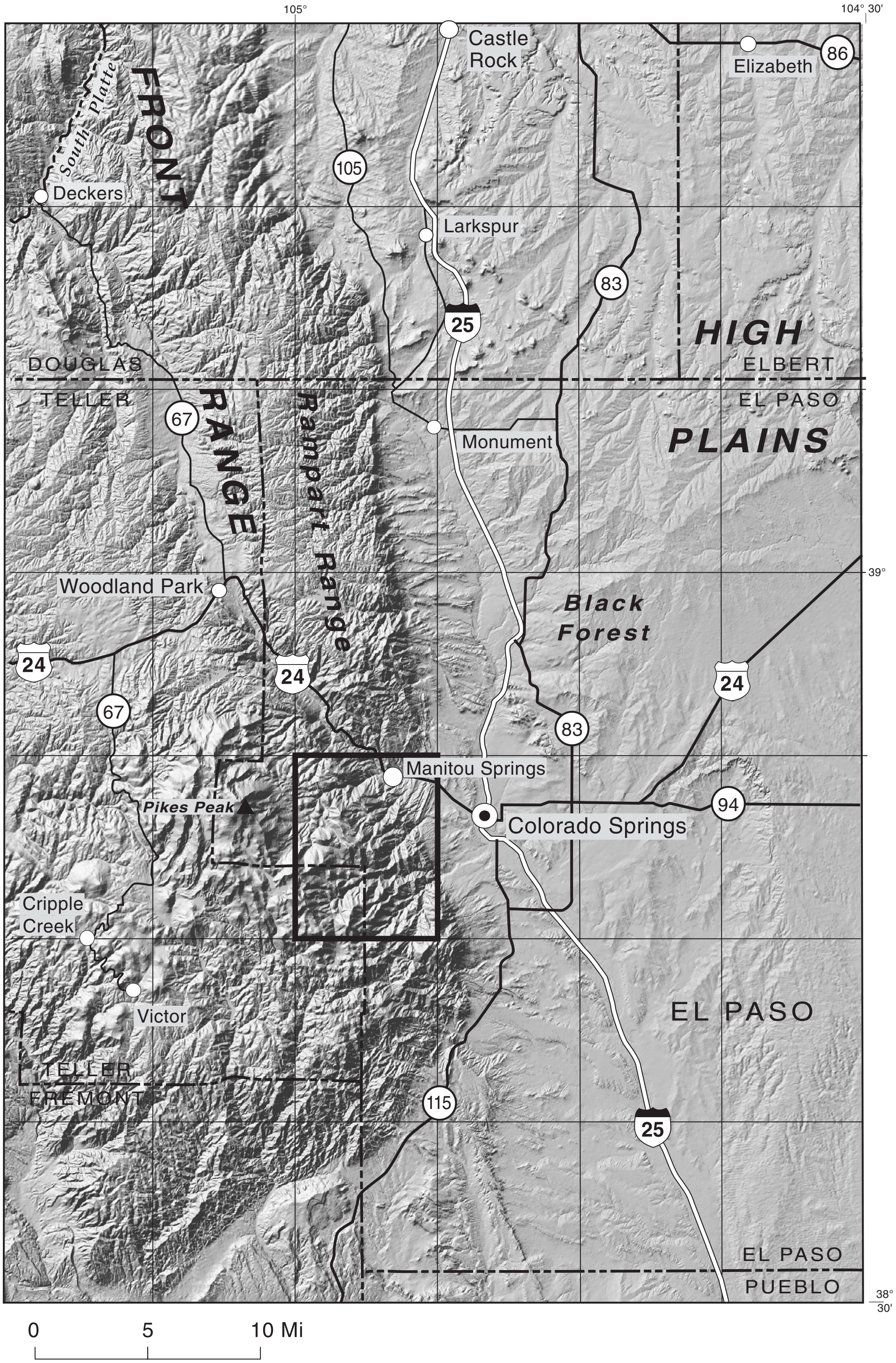
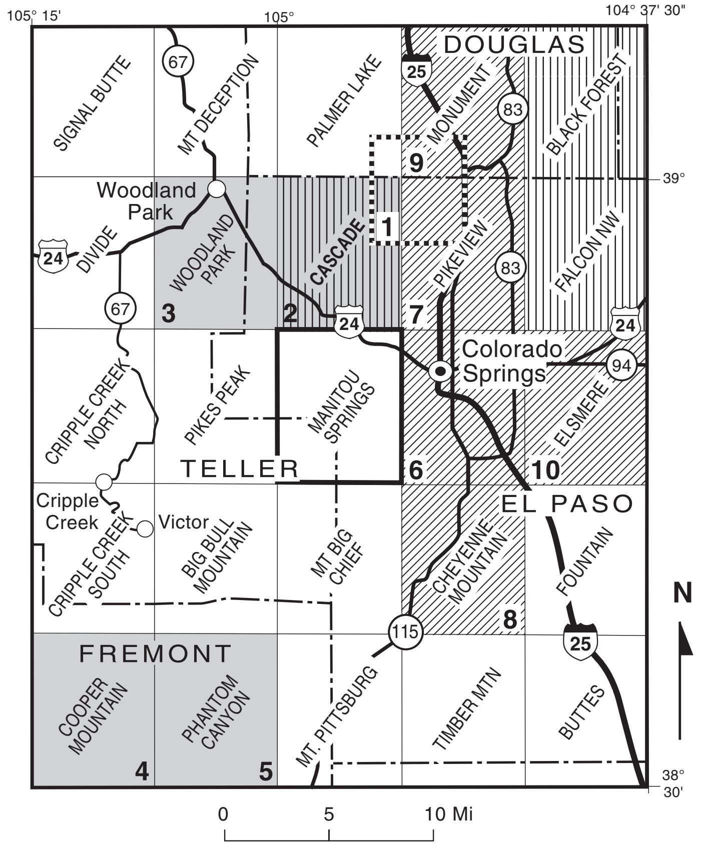


Figure 1. Shaded relief map of the southern Front Range and Colorado Springs region showing the location of the Manitou Springs 7.5-min. quadrangle.

PREVIOUS GEOLOGIC MAPPING

The region that includes the Manitou Springs quadrangle was mapped at a scale of 1:48,000 for the Colorado Springs Folio of the Geologic Atlas of the United States (Finley, 1916). This folio also includes descriptions of the geology of the region, chemical analyses of some of the Proterozoic igneous rocks, and structural interpretations. The geology of the Colorado Springs area, which includes the Manitou Springs quadrangle, was mapped in reconnaissance fashion at a scale of 1:62,500 by Scott and Wobus (1973), and served as a guide for much of our mapping. Trimble and Machette (1979) compiled a 1:100,000 scale map of the area as part of a series of geologic maps of the Front Range Urban Corridor. They based much of their work in Manitou Springs and other quadrangles on the previous work by Scott and Wobus (1973). The Pueblo 1° x 2° sheet (1:250,000 scale) was mapped by Scott and others (1978) and included the Manitou Springs quadrangle.

Recent detailed geologic mapping in the Colorado Springs area at 1:24,000 scale has been conducted by the Colorado Geological Survey (Fig. 2). The Cascade quadrangle borders the Manitou Springs quadrangle to the north and was mapped concurrently with Manitou Springs by Morgan and others (2003). The Colorado Springs quadrangle is east of the Manitou Springs quadrangle and was mapped by Carroll and Crawford (2000). The Pikeview quadrangle to the northeast was mapped by Thorson and others (2001). The Cheyenne Mountain quadrangle (Rowley and others, 2003) lies to the southeast of the Manitou Springs quadrangle. The Woodland Park quadrangle northwest of the Manitou Springs quadrangle was mapped by the U.S. Geological Survey (Wobus and Scott, 1977).



Explanation

- ☐ This report
- ▥ Mapped concurrently with this report
- ▨ Completed CGS 1:24,000-scale geologic maps
- ■ Completed USGS 1:24,000-scale reconaissance geologic maps
- ⬚ Completed USGS 1:12,000-scale geologic map of the U.S. Air Force Academy

Completed 1:24,000-Scale and Larger Geologic Maps

Index Map No.	Publication No.	Date	Scale
1	USGS PP 551 Varnes and Scott	1967	1:12,000
2	USGS OF 77-138 Wobus and Scott	1977	1:24,000
3	USGS MF-842 Wobus and Scott	1977	1:24,000
4	USGS MF-1762 Wobus, Chase, Scott, and Taylor	1985	1:24,000
5	USGS MF-1764 Wobus, Chase, Scott, and Taylor	1985	1:24,000
6	CGS OF 00-3 Carroll and Crawford	2000	1:24,000
7	CGS OF 01-3 Thorsen, Carroll, and Morgan	2001	1:24,000
8	CGS OF 02-5 Rowley, Himmelreich Jr., Kupfer, and Siddoway	2002	1:24,000
9	CGS OF 02-4 Thorsen and Madole	2002	1:24,000
10	CGS OF 02-2 Madole and Thorsen	2002	1:24,000

Figure 2. Location of the Manitou Springs quadrangle and index of previously completed 1:24,000-scale geologic mapping in the area.

PRESENT STUDY

The present study focuses on geologic mapping in the Manitou Springs quadrangle at a scale of 1:24,000. Geologic mapping was completed during July to October, 2002. John Keller and Erik Route mapped and described the bedrock geology in the mountainous western and southern part of the map area. Christine Siddoway, with assistance from Adair Stevenson, mapped the bedrock in the northeastern part of the map area. Siddoway and Keller described and interpreted the structural geology of the quadrangle. The structural geology section includes an expanded description of the faulting in the Garden of the Gods Park, where Siddoway spent a considerable amount of time and effort doing detailed structural mapping prior to this project. Matt Morgan, Matt Grizzell, and Raffaello Sacerdoti mapped the Quaternary surficial deposits throughout the quadrangle. Morgan completed the geologic hazards analysis. John Keller compiled and assembled the map and text from information provided by the co-authors, and completed the description of mineral resources in the quadrangle.

Field data were plotted on color aerial photographs taken by the U.S. Forest Service in 1997 at a nominal scale of 1:24,000. The annotated photos were scanned and imported into ERDAS Imagine Stereo Analyst where they were photogrammetrically corrected and rendered in 3-D. Line work and point data was digitized directly from ERDAS Imagine Stereo Analyst and exported as ESRI shapefiles. In a few areas, geology was mapped directly onto a USGS 1:24,000-scale topographic map and subsequently digitized in ESRI ArcView. Geological editing was done using ESRI ArcView GIS software, and final map production was completed using Adobe Illustrator and Avenza MaPublisher.

DESCRIPTION OF MAP UNITS

SURFICIAL DEPOSITS

Surficial deposits shown on the map are generally more than 5 ft thick but may be thinner locally. Residuum, slope wash, colluvium, and artificial fills less than 25 sq ft in extent were not mapped. Contacts between surficial units may be gradational, and mapped surficial units locally include several types of deposits. Siderial age values given for the early, middle, and late Pleistocene Epoch are 1,806–778 ka (kilo-annum, 103 yr), 778–127 ka, and 127–11.7 ka, respectively (Fig. 3). The 1,806 ka age for the Pliocene-Pleistocene boundary is the astronomically tuned value calculated by Lourens and others (1996) based upon the earlier work of Hilgen (1991). The early-middle Pleistocene boundary corresponds to the Matuyama-Brunhes magnetic reversal at about 778 ka, where the magnetic polarity of the earth shifted from reverse to normal. ^{40}Ar/^{39}Ar dates obtained from sanidine grains corroborated with the cyclostratigraphic estimates (Johnson, 1982; Shackleton and others, 1990) given for this division (Izett and Obradovich, 1991; Baksi and others, 1992; Spell and McDougall, 1992; Tauxe and others, 1992; Hall and Farrell, 1993). The boundary between oxygen-isotope (^{18}O/^{16}O) stage 6 and substage 5e is the current accepted age for the middle and late Pleistocene, corresponding to the transition from the Illinoian Glacial to Sangamon Interglacial. Imbrie and others (1984) determined that the division between oxygen isotope stage 6 and substage 5e occurred at 128 ka. This value was subsequently recalculated by Bassinot and others (1994) to 127 ka. The late Pleistocene-Holocene boundary age of 11.7 ka is the value obtained by recalibrating the 10 ka radiocarbon age that was proposed by the International Union for Quaternary Research (INQUA) Commission for the Study of the Holocene (Farrand, 1990). Age divisions for the Holocene used in the Manitou Springs quadrangle are based chiefly on paleontological data compiled for the southwestern United States. Relative age assignments for surficial deposits are based primarily on the degree of erosional modification of original surface morphology, height above modern stream levels, degree of dissection and slope degradation, and soil

Formal Time Divisions		Informal Time Divisions	Age (sidereal years)
	Holocene Epoch		
Quaternary Period	Pleistocene Epoch	late Pleistocene	~11.7 ka
		middle Pleistocene	~127 ka
		early Pleistocene	~778 ka
Tertiary Period (part)	Pliocene Epoch		~1,806 ka

Figure 3. Time chart for the Quaternary from Madole and Thorson (2002).

Varnes and Scott (1967)	Scott and Wobus (1973); Trimble and Machette, (1979)	Carroll and Crawford (2000)	Thorson and others (2001)	This map	Possible Age
Flood-plain alluvium	Post-Piney Creek and Piney Creek Alluvium	Terrace alluvium one	Alluvial and colluvial deposits	Alluvial and colluvial deposits (Qac, Qa); alluvium one and two (Qa_1, Qa_2)	late Holocene
Husted Alluvium			Terrace alluvium one	Alluvium two (Qa_2)	early Holocene
Monument Creek Alluvium	Broadway Alluvium	Terrace alluvium two	Terrace alluvium two	None	late Pleistocene
Kettle Creek Alluvium	Louviers Alluvium	Terrace alluvium three	Terrace alluvum three	None	late Pleistocen
Pine Valley Gravel	Slocum Alluvium	Pediment gravel one	Pediment gravel one	Pediment gravel one (Qg_1)	Pleistocene
Douglass Mesa Gravel	Verdos Alluvium	Pediment gravel two	Pediment gravel two	Pediment gravel two (Qg_2)	Pleistocene
Lehman Ridge Gravel	Rocky Flats Alluvium	Pediment gravel three	Pediment gravel three	Pediment gravel three (Qg_3)	Pleistocene
None	Nussbaum Alluvium	None	None	Pediment gravel four (Qg_4)	late Pliocene—early Pleistocene

Figure 4. Correlation chart of Quaternary stratigraphic names and ages for alluvial units used in the Colorado Springs area.

development. Clast size is based on the modified Wentworth scale. The Front Range piedmont stratigraphic nomenclature of Quaternary alluvial deposits was established by Scott (1960; 1963a). Varnes and Scott (1967), Scott and Wobus (1973), and Trimble and Machette (1979) applied this nomenclature to Quaternary deposits in the Manitou Springs quadrangle (Fig. 4).

Because of correlation uncertainties between the deposits in the Manitou Springs quadrangle and those in areas where this nomenclature was developed, the formal names for alluvial deposits are not used in this report.

HUMAN-MADE DEPOSITS

af

Artificial fill (latest Holocene)—Rip rap, engineered fill, and refuse placed during construction of roads, railroads, buildings, dams, and landfills. Generally consists of unsorted silt, sand, clay, and rock fragments. This unit may also include areas of construction and/or quarrying operations where original deposits have been removed, replaced, or reworked. The average thickness of the unit is less than 30 ft. Artificial fill may be subject to settlement and erosion if not adequately compacted.

mw

Mine waste (latest Holocene)—Waste rock excavated from mines and prospecting pits. Mine waste typically consists of pebble- to cobble-size angular fragments of Proterozoic granite, gneiss, and limestone, Cretaceous sedimentary rocks, and/or Quaternary gravels. The deposits may be as thick as 100 ft. Mine waste may be subject to settlement and erosion if not properly compacted.

ALLUVIAL DEPOSITS—Silt, sand, and gravel deposited in stream channels, on flood plains, on pediments, and as sheetwash along Fountain and Monument Creek and associated tributary drainages. Terrace alluvium and related pediments along these mainstem creeks were deposited mostly during late-glacial and early-interglacial stages. The approximate terrace heights reported for each unit are the elevation differences measured between the creek bed and the top of the original or remnant alluvial surface (tread) near the creek edge of the terraces. Thickness is measured on the riser or maximum exposed thickness of the unit.

Qa

Stream-channel, flood-plain, and terrace alluvium, undivided (Holocene and late Pleistocene)—Clast-supported, pebble, cobble, and rare boulder gravel in a sandy silt matrix. Terrace alluvium rests a maximum of 10 ft above modern stream level. May be locally interbedded with and commonly overlain by sandy silt and silty sand. Clasts are subangular to well rounded and of varied lithology, reflecting the diverse types of bedrock within their provenance. Unit may include locally organic-rich sediments. Deposits may be interbedded with fan deposits (Qf, Qfy, Qfo), colluvium-sheetwash (Qcs) and alluvium-colluvium (Qac). Maximum thickness of this unit may exceed 20 ft. Areas mapped as Qa may be prone to flooding, erosion, and sediment deposition. The unit is a source of commercial sand and gravel.

Qa$_1$

Alluvium one (late Holocene)—Yellow to medium-dark-brown, poorly to moderately sorted, non-consolidated clay, silt, sand, gravel, and rare boulders deposited as clast- or matrix-supported alluvium in modern creek beds. Clasts are subangular to well rounded and of varied lithology. Maximum thickness of this unit may exceed 10 ft. Deposits may include localized organic- and sand-rich layers and may include terraces up to 5 ft above the modern creek bed. Remnants of historical town sites and Native American campsites found on alluvium one suggest that the upper 1-ft of the deposit dates to less than 250 years B. P. (M. Van Ness, oral commun., 2002). Areas mapped as Qa$_1$ may be prone to flooding, erosion, and sediment deposition. The unit is a source of commercial sand and gravel.

Qa$_2$

Alluvium two (early to late Holocene)—Dark-yellow to dark-brown, poorly to moderately sorted, poorly consolidated clay, silt, sand, gravel, and rare boulders deposited as terrace-forming alluvium above the currently active flood plain or as non-terrace forming alluvium in valley headwaters. Clasts are subangular to well rounded and have varied lithology. Deposit commonly includes organic-rich layers interbedded with sand and gravel lenses. Terrace heights reach as much as 15 ft above current stream level. Maximum thickness of unit locally exceeds 15 ft. The unit is generally correlative, by virtue of height and soil characteristics, with the Husted Alluvium of Varnes and Scott (1967) on the U.S. Air Force Academy, the Piney Creek Alluvium of the Denver area (Scott and Wobus, 1973), and unit Qt$_1$ of Carroll and Crawford (2000) and Thorson and others (2001) in the Colorado Springs and Pikeview quadrangles, respectively. Recent charcoal samples from a fire pit buried 3 ft below the alluvium in Garden of the Gods Park yielded a calibrated Carbon-14 date of 3,280 years B. P. (M. Van Ness, personal commun., 2002). The unit is a source of commercial sand and gravel.

Pediment gravels (middle Pleistocene to late Pliocene) — Partially dissected remnants of four levels of older gravel deposits are preserved along Fountain and

Monument Creek and the piedmont. Finlay (1916) recognized two of these "mesa gravels" on the basis of their distinctive topographic form and suggested a fluvial origin. Varnes and Scott (1967) identified a third partially dissected gravel deposit at lower elevation, and from youngest to oldest, formally named them the Pine Valley Gravel, Lehman Ridge Gravel, and Douglass Mesa Gravel (Fig. 4). They classed them as "pediment gravels." Scott and Wobus (1973) referred to all three deposits as "alluvial terrace or pediment gravel" and correlated them with similar deposits in the Denver area that were formally named the Slocum Alluvium, Verdos Alluvium, and Rocky Flats Alluvium by Scott (1960, 1963a). Additionally, a higher and fourth level of gravel, the "Nussbaum Formation", near Pueblo was reinterpreted by Scott (1963b, 1982) and renamed by Scott (1982) the "Nussbaum Alluvium" of possible late Pliocene to early Pleistocene age. This is the highest and oldest deposit in the sequence of alluviums described by Scott (1960, 1963a, 1963b), located 450 ft above modern streams in the Denver area. By definition the deposits on this map with designation Qg or QTg meet the definition of "pediment" as provided by the AGI's Glossary of Geology (Bates and Jackson, 1997):

> A broad gently sloping rock-floored erosion surface or plain of low relief, typically developed by subaerial agents (including running water) in an arid or semiarid region at the base of an abrupt and receding mountain front or plateau escarpment, and underlain by bedrock (occasionally by older alluvial deposits) that may be bare but are more often partly mantled with a thin discontinuous veneer of alluvium derived from the upland masses and in transit across the surface.

Additionally, Worcester (1948) described pediments in the Front Range of Colorado as "pediment-topped, fan-topped pediments". These deposits are considered pediment gravels. The map designations (Qg_1, Qg_2, Qg_3) are similar to those used by Carroll and Crawford (2000) and Thorson and others (2001) in the Colorado Springs and Pikeview quadrangles, respectively. Pediment gravel four (QTg_4) corresponds to the highest (oldest) gravel deposit in this sequence.

Qg_1 **Pediment gravel one (middle Pleistocene)—** Light-red to brown, poorly sorted, moderately to poorly stratified pebble and cobble gravel primarily derived from granitic bedrock, as well as layers of clay, silt, sand, and clay clasts derived from shaly bedrock. Clasts are subrounded to rounded, moderately to highly weathered, and are coated by a thin, discontinuous (less than 0.02-inch) rind of calcium carbonate. Matrix typically consists of feldspar and quartz sand derived from weathered clasts. Commonly becomes richer in boulders and less stratified toward the mountain front. Top of pediment or alluvial gravel is 25 ft to 75 ft above adjacent modern streams. The unit locally exceeds 20 ft in thickness. Unit correlates with Qg_1 of Thorson and others (2001), the Pine Valley Gravel at the U.S. Air Force Academy (Varnes and Scott, 1967), and with the Slocum Alluvium (Scott and Wobus, 1973). Pediment gravel one is considered to be middle Pleistocene in age on the basis of local stratigraphic and physiographic position and soil development. Scott (1960) considered the Slocum Alluvium to be Illinoian or Sangomon in age on the basis of stratigraphic position, mollusks, and pre-Wisconsin age soil profile (Varnes and Scott, 1967). The deposit forms a stable building surface, but excavations may be prone to slumping. The unit is a source of sand and gravel.

Qg_2 **Pediment gravel two (middle Pleistocene)—** Medium-red to brown, poorly sorted, moderately to poorly stratified pebble, cobble, and boulder gravel primarily derived from granitic bedrock. Basal portion of unit contains layers of clay and silt interbedded with coarse-grained sand, cobble, and rare boulder gravels. Clasts are highly weathered and are coated by a thin, discontinuous (0.05-inch) rind of calcium carbonate. Matrix typically consists of feldspar and quartz sand derived from weathered clasts. Becomes richer in boulders and less stratified toward mountain front. Top of pediment gravel is 90 ft to 130 ft above adjacent modern streams. The unit locally exceeds 70 ft in thickness. Unit correlates with Qg_1 of Thorson and others (2001), with the Douglass Mesa Gravel at the U.S. Air Force Academy (Varnes and Scott, 1967), and the Verdos Alluvium of the Denver area (Scott and Wobus, 1973). The unit is considered to be middle Pleistocene on the basis of local stratigraphic and physiographic position and soil development. In the Denver area, the upper part of the Verdos Alluvium contains Lava Creek B ash (Scott, 1960), which was recently dated at 640,000 years B. P. (Lanphere and others, 2002). This unit forms a stable building surface, however, excavations may be prone to slumping. The unit is a source of sand and gravel.

Qg_3 **Pediment gravel three (middle? to early Pleistocene)—**Red to brown, poorly sorted, moderately to poorly stratified pebble, cobble, and boulder gravel primarily derived from granitic bedrock. Clasts are intensely weathered and are coated by a thin, discontinuous (0.03-inch) rind of calcium carbonate. Matrix typically consists of feldspar and quartz pebbles derived from weathered clasts. Boulders are larger and more abundant and the deposit becomes less stratified toward the mountain front. Top of pediment or alluvial gravel is 200 ft to 300 ft above modern streams. Unit locally exceeds 50 ft in thickness. Unit correlates with Qg_1 of Thorson and others (2001), the Lehman Ridge Gravel of the U.S. Air Force Academy (Varnes and Scott, 1967), and with the Rocky Flats Alluvium of the Denver area (Scott and Wobus, 1973). The unit is considered to be middle (?) to early Pleistocene in age based on local stratigraphic and physiographic position and soil development. Forms a stable building surface, but excavations may be prone to slumping. The unit is a source of sand and gravel.

QTg_4

Pediment gravel four (early Pleistocene to late Pliocene)—Dark-red to brown, well-sorted, moderately to well-stratified, sand, pebble, and cobble gravel derived from Proterozoic granite and gneiss and lower Paleozoic sandstone and limestone. Clasts are extremely weathered and commonly coated by a discontinuous rind of calcium carbonate more than 0.05-inch thick. A discontinuous calcareous soil horizon is present in the top 3 ft of some deposits. Matrix typically consists of feldspar, quartz, and limestone pebbles derived from weathered clasts; clay is also abundant. Boulders become more frequent and deposit becomes less stratified toward the mountain front. Top of pediment or alluvial gravel is 375 ft to 500 ft above modern streams. The unit locally exceeds 100 ft in thickness. This unit was correlated with the Nussbaum Alluvium of the Denver area by Scott and Wobus (1973). The deposit is considered to be late Pliocene to early Pleistocene in age on the basis of local stratigraphic and physiographic position and presence of mollusks. Vertebrate fossils of late Pliocene age (3.0 m.y.) were identified in the lower part of the Nussbaum Alluvium near Baculite Mesa, about 50 mi to the southeast of Colorado Springs (Scott, 1982). However, Luiszer (1999) dated the QTg_4 deposits north of Manitou Springs using amino acids taken from mollusks and determined the maximum age of the deposit to be 1.9 + 0.4/-0.2 Ma; this unit may not be correlative with the Nussbaum Alluvium described by Scott (1982) near Baculite Mesa. Forms a stable building surface, but excavations may be prone to slumping. The unit is a source of sand and gravel.

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

Qac

Alluvium and colluvium, undivided (Holocene and late Pleistocene)—Stream channel, terrace, and flood-plain deposits along valley floors of ephemeral, intermittent, and small perennial streams and colluvium deposits along valley sides. Interfingers with stream alluvium (Qa), fan deposits (Qf), and colluvium (Qc) along valley margins. Alluvium is typically composed of poorly to well-sorted, stratified, interbedded, pebbly sand, sandy silt, and sandy gravel. Colluvium may range from unsorted, clast-supported, pebble to boulder gravel in a sandy silt matrix to matrix-supported, gravelly, clayey, sandy silt. Clasts have a wide range of lithologies dependent upon the local bedrock or surficial unit sources. Maximum thickness of the unit is approximately 20 ft.

Qcs

Colluvium and sheetwash deposits, undivided (Holocene and late Pleistocene)— Weathered bedrock fragments transported downslope primarily by gravity and precipitation. Colluvium ranges from unsorted, clast-supported pebble to boulder gravel in a sandy silt matrix to matrix-supported gravelly, clayey, sandy silt. It is generally unsorted to poorly sorted, contains angular to subangular clasts, and is weakly stratified. Colluvial deposits derived from alluvial deposits contain rounded to subrounded clasts. Colluvium of large cobble- and boulder-sized rock fragments may include rockfall debris. The units may contain small landslides of limited extent. Sheetwash is common on slopes with less than a 10 percent grade below hills of granitic bedrock. Clast lithology is variable. Colluvium and sheetwash deposits grade into and interfinger with alluvium, alluvial-fan, and landslide deposits. Maximum thickness of this unit is about 20 ft. Areas mapped as colluvium and sheetwash are susceptible to future colluvial and sheetwash deposition and locally are subject to debris flows and rockfall. Colluvium and sheetwash deposits may be sources of aggregate, especially grüs derived from the weathering of Pikes Peak Granite.

Qf

Fan deposits (Holocene and late Pleistocene)— Poorly sorted to moderately sorted, matrix-supported, gravelly, sandy silt to clast-supported pebble and cobble gravel in a sandy silt or silty sand matrix. Clasts are mostly angular to subrounded and typically composed of granitic bedrock. Sediments are deposited primarily by streams with minor input from sheetwash, debris flows, and hyperconcentrated flows. Locally the deposit is dissected and has a thin, weakly to moderately developed pedogenic soil. The maximum estimated thickness for fans in sections 5, 6, 8, T. 14 S., R. 67 W. exceeds 30 ft. These fans form on slopes with greater than 10 percent grade and lack fan-shaped morphology. Large precipitation events may trigger future deposition in areas underlain by alluvial-fan deposits. Deposits may be prone to collapse, hydrocompaction, or slope failure when wetted or loaded.

Qfy

Young fan deposits (Holocene)—Poorly sorted to moderately sorted, matrix-supported, gravelly, sandy silt to clast-supported, pebble, cobble, and boulder gravel in a sandy silt or silty sand matrix. Clasts are mostly angular to subrounded with varied lithologies. Sediments are deposited primarily by streams with lesser input from sheetwash, debris flows, and hyperconcentrated flows. The deposit exceeds 15 ft in thickness. Fan-shaped deposits form where tributary drainages with steep gradients join lower gradient streams. Soil development is extremely weak to absent. Young fan deposits are subject to flooding and future debris-flow, hyperconcentrated flow, and sheetwash deposits.

Qfo

Old fan deposits (late to middle? Pleistocene)—Poorly sorted to moderately sorted, matrix-supported, gravelly, sandy silt to clast-supported, pebble, cobble, and boulder gravel in a sandy silt or silty sand matrix. Clasts are mostly angular to subrounded and typically composed of granitic bedrock. An extensive old fan complex is present south of Bear Creek in sections 22 and 27, T. 14 S., R. 67 W. is deeply dissected and contains younger debris flow deposits in channels. It overlies pediment gravel two (Qg_2) in the mapped area. The deposit exceeds 150 ft in thickness. Remnants of debris flow deposits in sec. 31, T. 13 S., R. 67 W. are composed of large boulders of Windy Point Granite and Pike Peak Granite, some reaching 5 ft in exposed diameter. The deposits are probably middle Pleistocene in age on the basis of height above adjacent streams (75 ft to 100 ft) and moderate weathering of granitic clasts.

MASS-WASTING DEPOSITS—Earth materials that were transported downslope primarily by gravity and not within or under another medium, such as air, water, or ice. Some of these deposits have moved by creep, which is a slow, gradual, progressive downslope movement of earth materials.

Qta

Talus deposits (Holocene and late Pleistocene)—Angular, cobbly and bouldery rubble derived from bedrock that was transported downslope by gravity principally as rockfalls, rock avalanches, rock topples, and rockslides. Downslope movement may be locally aided by water and freeze-thaw action. This unit typically lacks matrix material near the surface, but dissected talus reveal significant matrix at depth. Talus deposition is active and widespread over the southwestern portion of the mapped area, especially where the lithology is the granite of Almagre Mountain (Yam, this report). Large talus deposits are located on the north face of Almagre Mountain. Thickness of the deposits locally exceed 20 ft. Talus areas are subject to rockfall and rockslide hazards.

Qls

Landslide deposits (Holocene and late Pleistocene)—Heterogeneous deposits consisting of unsorted and unstratified clay, silt, sand, and angular, boulder-size rock fragments. Unit includes rotational slides, translational slides, and complex slide-flow mass movement. At most places, landslides show obvious geomorphic expression that disrupts the profile of slopes. Generally, head scarps (near vertical detachment slope exposed at the top of or occasionally perimeter of the landslide) are readily recognizable. Other common diagnostic features include hummocky topography, closed depressions, and pressure ridges at the toe of the mobilized mass. See the "Geologic Hazards" section of this publication for hazard assessment of landslides in the mapped area.

Landslide areas are subject to future movement during episodes of excessive rain or snowfall or may be reactivated by human-made disturbances such as cutting of slopes for roads, housing developments, irrigation systems, and septic systems. Landslide deposits may be prone to settlement when loaded or wetted. Deposits may contain expansive soils where derived from shale formations. Maximum thickness of landslide deposits in the quadrangle locally exceeds 80 ft.

PALUSTRINE DEPOSITS—Peat, clay, silt, and sand deposited by water in shallow basinal areas.

Qp

Paludal sediments (Holocene to late Pleistocene)—Organic-rich, fine-grained sediments formed in swampy, closed depressions where the local water table is near or slightly above the ground surface. The reducing conditions in these stagnant environments slow the rate of decay of the organic matter, which favors accumulation of organic material. Paludal sediments are susceptible to compaction. Basins in which these sediments are deposited have elevated water tables and may be prone to flooding.

PERIGLACIAL DEPOSITS—Deposits formed in cold environments by freeze-thaw action, solifluction, and nivation.

Qb

Block-slope deposits (Holocene and late Plesitocene)—Poorly sorted, clast supported, subangular to subrounded boulder and cobble gravel surrounded by a silty-sand matrix. The deposit occurs on a north-facing slope in SE¼, sec. 27, T. 14 S., R. 68 W as an area of patterned ground consisting of boulders of Pikes Peak Granite, some reaching 5 ft in exposed diameter. Lack of vegetation on the surface and thick talus, sheetwash, and fan deposits derived from this deposit suggest the area is actively eroding by nivation. Thickness of the deposit exceeds 10 ft.

GLACIAL DEPOSITS—Heterogeneous, mixtures of gravel, sand, silt, and clay deposited by or adjacent to glacial ice and associated melt water in the Lake Moraine area.

Qo

Outwash (late Pleistocene)—Moderately to poorly sorted, clast-supported, cobble, pebble, and boulder gravel in a silty, sandy matrix. The deposit is planar bedded to cross-stratified and generally normal graded. Clasts are predominantly Pikes Peak Granite and Windy Point Granite, some reaching 20 ft in exposed diameter. Unit forms two dissected ridges that breach the Qm_3 terminal moraine. Soils are weakly to moderately developed and granitic clasts have weathering rinds less than 0.06-in thick. Deposit locally exceeds 40 ft in thickness. This unit is considered late Pleistocene in age on the basis of degree of soil development, clast weathering, and crosscutting relationship with Qm_3.

Qm_1

Morainal deposit one (late Pleistocene)—Boulders, cobbles, and gravel set in a silty sand matrix deposited by and adjacent to glacial ice. The deposit contains localized lenses of stratified and crossbedded sand and gravel. Clasts are predominantly Pikes Peak Granite and Windy Point Granite. Unit forms low lateral moraines and a poorly developed terminal moraine, compared to Qm_2, which has been breached and eroded. Terminal moraine of Qm_1 is 0.5 mi up-valley from the outer edge of the Qm_2 terminal moraine. A soil profile examined on the Qm_1 lateral moraine consists of an 8-in A horizon and a 6-in Cox horizon overlying glacial till (Fig. 5; see geologic map for location). Munsell colors (wet; Geological Society of America, 2000) range from 7.5 YR 4/6 for the Cox horizon to 7.5 YR 4/4 for the A horizon. Cumulative soil thickness is 13.8 inch. The exteriors of the granitic clasts are pockmarked but exhibit very little evidence of internal weathering or decomposition. Numerous clasts are visible on the surface of the moraine. Maximum thickness of unit is approximately 40 ft. This unit is considered to be late Pleistocene in age and correlative with the Pinedale glaciation on the basis of degree of soil development, freshness of clasts, moraine morphology, and position relative to Qm_2 (Madole and others, 1998).

Qm_2

Morainal deposit two (late Pleistocene)—Deposit is lithologically and structurally similar to unit Qm_1. Unit forms a topographically distinct and well-formed lateral and terminal moraine 0.6 mi up-valley from the outer edge

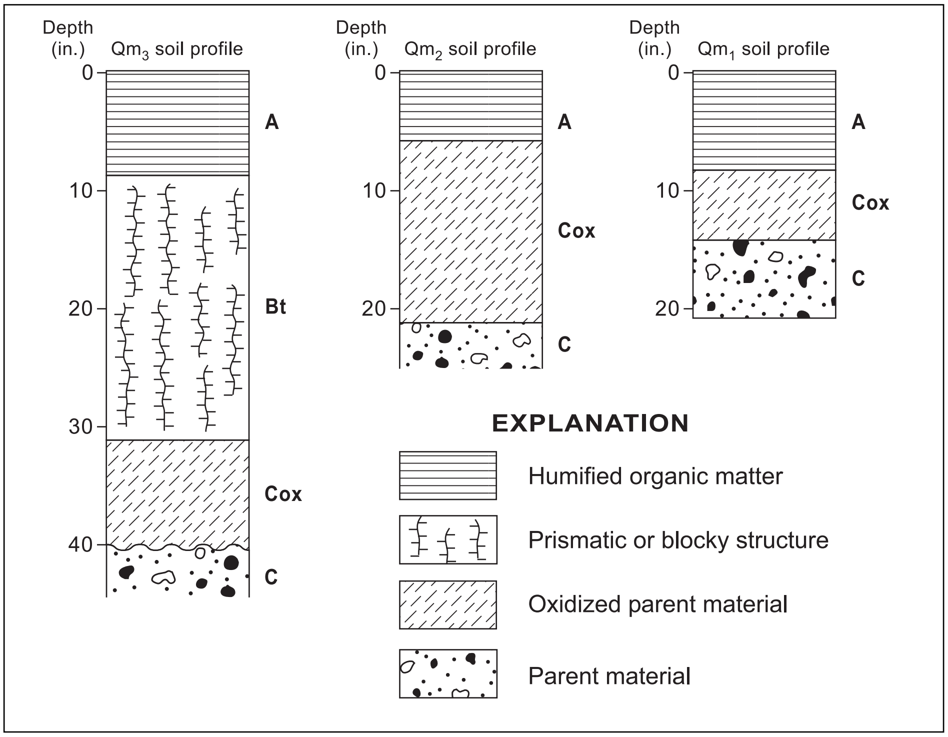


Figure 5. Soil profiles on morainal deposits near Lake Moraine. Relative ages of the deposits were partly determined by their degree of soil development. Unit Qm$_3$ is the oldest deposit, exhibiting a deep red Bt horizon and a 3-foot thick soil, characteristic of Bull Lake age deposits (late middle Pleistocene). Units Qm$_2$ and Qm1 are young, Pinedale-age soils and are pedogenically less developed with respect to unit Qm$_3$.

of unit Qm$_3$ terminal moraine; moraine crests rise approximately 85 ft above Lake Moraine. Closed depressions with organic-rich sediments are common. A soil profile examined on the crest of the Qm$_2$ terminal moraine (Fig. 5; see geologic map for location) consists of a 6-in thick A horizon and a 15-in thick Cox horizon overlying glacial till. Munsell colors (wet; Geological Society of America, 2000) range from 7.5 YR 5/4 for the Cox horizon to 7.5 YR 6/2 for the A horizon. Cumulative soil thickness is 22.8 in. Thickness of weathering rinds on granitic clasts range from 0.06 in- to 0.1 in and less than 10 percent of granitic clasts show signs of decomposition. Numerous clasts are visible on the surface of the moraine. Maximum thickness of unit locally exceeds 60 ft. This unit is considered to be late Pleistocene in age and correlative with the Pinedale glaciation on the basis of moraine morphology, degree of soil development, weathering of clasts, and position relative to Qm$_3$ (Madole and others, 1998).

Qm$_3$

Morainal deposit three (late middle Pleistocene)—Deposit is lithologically and structurally similar to unit Qm$_1$. However, this unit contains soft sediment deformation features and melt-induced faults that offset lenses of stratified gravel with displacement of less than 6 in. Unit forms a broad, topographically subdued lateral and terminal moraine, compared to Qm$_2$, which represent the maximum extent of glacial ice in the mapped area. The Qm$_3$ terminal moraine, 0.5 mi northeast of Lake Moraine, is discontinuous and was breached by glacial outwash probably during the late Pleistocene. A soil profile examined on the Qm$_3$ lateral moraine (Fig. 5; see geologic map for location) consists of a 8.7-in thick A horizon, a 22-in thick Bt horizon, and a 9.5-in thick Cox horizon overlying glacial till. Munsell colors (wet;

Geological Society of America, 2000) range from 5 YR 4/6 for the Bt horizon, to 5YR 7/2 for the A horizon. Cumulative soil thickness is 3.28 ft. Approximately 20 percent of contained clasts are weathered to grüs and fewer clasts are visible on the surface compared to till of Pinedale age. Maximum thickness of unit is approximately 50 ft. This unit is considered to be late middle Pleistocene in age and correlative with the Bull Lake glaciation on the basis of moraine morphology, degree of soil development, and weathering of clasts (Madole and others, 1998).

BEDROCK

MESOZOIC ROCKS

Kp

Pierre Shale (Upper Cretaceous)—Medium-gray to black shale with thin interbeds of tan siltstone and fine-grained sandstone. Commonly weathers to form soft chips and flakes of olive-green to gray-green color. The formation contains thin, discontinuous layers of bentonite, typically a few in. thick or less. Scott and Cobban (1986) determined the age as early Campanian to early Maastrichtian, on the basis of fossil assemblages including ammonites, clams, and oysters that define seven stratigraphic subunits (see also Larson and others, 1997; Cobban and others, 1994). The thickness of the Pierre Shale in Colorado Springs exceeds 5,000 ft (Grose, 1961); however the full thickness of the unit does not fall within the Manitou Springs quadrangle. The basal contact is not exposed but is reported to be gradational and conformable elsewhere. The upper contact lies outside the quadrangle boundary. The Pierre Shale is considered to be of marine origin deposited in a shallow epieric seaway. The formation correlates with Mancos Shale of western Colorado and Utah. The bentonite clay layers have a high shrink-swell potential and can cause heaving bedrock near the surface (Himmelreich and Noe, 1999), slope instability, and landslides on slopes that exceed 10°. Thus the formation can be unstable as a foundation for structures, roads, and developments.

Kn

Niobrara Formation (Upper Cretaceous)— Consists of resistant-weathering, medium-bedded Fort Hayes Limestone Member at the base and nonresistant-weathering Smoky Hills Shale Member above, both of marine origin. The Fort Hayes Member consists of light- to medium-gray, well-bedded, fine-grained limestone approximately 100 ft thick. Thin interbeds of light-gray shale form prominent partings. Inoceramus sp. fossils are common in the limestone. The Smoky Hills Member consists of light- to dark-gray, yellowish-orange, and brown, thin-bedded and laminated, limey shale and local thin beds of slightly resistant-weathering, gray and white chalk and limestone, about 400 ft thick. Fish scales may be present in the chalk. Weathering characteristics between the two members of the Niobrara Formation are distinct with the Fort Hayes Member commonly forming a low hogback and the Smoky Hills Member underlying valleys marked by soils that contain light-gray and buff shale chips. Berman and others (1980) noted that in Colorado the contact of the Niobrara Formation with the overlying Pierre Shale is generally conformable and transitional from shaly chalk of the Smoky Hills member to slightly calcareous silty shale of the Pierre Shale.

Kcgg

Graneros Shale, Greenhorn Limestone, and Carlile Shale, undivided (Upper Cretaceous)— Nonresistant-weathering, poorly exposed marine units comprising the Carlile Shale, Greenhorn Limestone, and Graneros Shale were formerly called the Benton Group (Grose, 1961) and more recently have been referred to as the Colorado Group (Carroll and Crawford, 2000). The Graneros Shale is a nonresistant, dark-gray to black shale that contains several bentonite layers, thin tan and brown silt beds, and commonly weathers to small platy chips. Total thickness of the Graneros Shale is approximately 250 ft. The Greenhorn Limestone consists of thinly interbedded, dark-gray shale and medium-gray, fossiliferous limestone. The unit forms light-gray to light-tan soils and frequently contains outcrops of dense, white-weathering limestone beds approximately 2 ft thick. Total thickness of the Greenhorn Limestone is approximately 50 ft. The Carlile Shale is a black, thin-bedded shale overlain by the distinctive yellow-brown calcareous Codell Sandstone, reaching a combined thickness of approximately 220 ft. Locally, the Codell sandstone forms a subdued hogback. The sandstone is commonly bioturbated, weathers to light tan, and may contain stringers of limonite.

Kd

Dakota Sandstone (Lower Cretaceous)— Interbedded tan, yellow, and gray quartz sandstone and gray shale, approximately 160 ft thick (Grose, 1961). Two medium- to massive-bedded resistant-weathering sandstones in the lower part of the unit grade in to thin-bedded sandstone and shales in the upper one-third of the unit. Upper shales are organic-rich and lignitic. Thin beds that contain clay pellets, phosphatic nodules, and chert granule also occur. The unit is interpreted as a shoreline regressive sequence (Weimer, 1970). In the mapped area, the sandstone beds are steeply dipping and support a prominent, continuous hogback or dual hogback. The hogback-forming sandstones weather to a distinctive golden-green color. Resistant-weathering, parallel vein arrays and deformation bands (Davis, 1999) pervade the Dakota sandstones, with parallel geometries and consistent spacing defining a fracture fabric that is apparent from some distance.

Kpu

Purgatoire Formation (Lower Cretaceous)— Consists of the basal Lytle Sandstone Member and overlying Glencairn Shale Member (Grose, 1961). The Lytle Sandstone is a moderately resistant-weathering, white to light-gray, weakly cemented and locally friable, massive, coarse-grained sandstone, approximately 80 ft thick. Conglomeratic sandstone containing black chert pebbles is diagnostic for the member. The Glencairn Shale Member consists of dark-gray shale and siltstone with thin brown sandstone beds and tan siltstone near the top. The Lytle Sandstone Member represents fluvial channel and overbank deposits, with a transition to marine deposits in the Glencairn Shale Member (Weimer, 1970).

Jmr

Morrison Formation and Ralston Creek Formation, undivided (Upper Jurassic)— Nonresistant-weathering, variegated claystone and mudstone, interbedded thin-bedded marl, limestone, sandstone, and minor conglomerate. Cumulative thickness is approximately 300 ft. Claystones and mudstones are pale green, red, purple, white, tan, or light gray in color. The lower Ralston Creek Formation consists of thin-bedded gray and red sandstone, siltstone, and shale, and massive gypsum approximately 100 ft thick.

TRPl

Lykins Formation (Lower Triassic? and Upper Permian)—Nonresistant- to moderately resistant-weathering, thin-bedded, reddish-brown and light-tan sandy siltstone and shale that contain two prominent beds of light-gray to tan stromatolitic dolostone (Broin, 1957; Grose, 1961). Thickness is approximately 120 ft. The carbonate beds exhibit a close-laminated texture indicative of algal mats in a shallow marine environment.

PALEOZOIC ROCKS

Pl

Lyons Sandstone (Permian)—Consists of upper, middle, and lower units. The lower and upper ridge-forming units of well-sorted, fine-grained sandstone form massive throughgoing ridges in the "Red Rocks Canyon" area on private land south of Highway 24, north of the closed Colorado Springs landfill. The non-resistant-weathering middle unit (Plm) forms an intervening strike valley. The unit is of dune and stream origin (Noblett and others, 1987) and has a maximum thickness of 700 ft in the Colorado Springs area (Grose, 1961).

Plu

upper unit—White to red, moderately cemented, prominently crossbedded sandstone, approximately 150 ft thick in the mapped area.

Plm

middle unit—Crimson to white arkosic conglomerate and micaceous silty sandstone; 100 ft or less in thickness.

Pll

lower unit—Massive red eolian sandstone with poorly to moderately well-defined large-scale crossbeds, approximately 150 ft thick in the mapped area.

PIPf

Fountain Formation (Lower Permian and Pennsylvanian)—Red and white, coarse-grained, arkosic sandstone and pebble to boulder conglomerate (Suttner and others, 1984; Maples and Suttner, 1990). Maroon micaceous siltstone alternates with the medium- and thickly bedded conglomeratic sandstone. The thick-bedded arkosic sandstone and thin-bedded silty sandstone weather to form comparatively low, slabby to knobby hogbacks and, less commonly, thin strike ridges and spires. Subangular to sub-rounded conglomerate clasts include quartz granules, microcline, vein quartz, and polycrystalline granite. Suttner (1989) interprets the Fountain Formation as a marine delta and subaerial alluvial fan system deposited eastward off of the Frontrangia uplift of the "Ancestral Rockies," which was bounded by the ancestral Ute Pass fault zone (Kluth, 1997; Hoy and Ridgeway, 2002). The formation is 4,050 ft thick (Suttner, 1989) at its type locality (Cross, 1894) along Fountain Creek in the Manitou Springs quadrangle.

PIPfg

Glen Eyrie Member of the Fountain Formation (Early Pennsylvanian)—Black to blue-gray shale and lesser amounts of varicolored blue-green to purple shale and orange-tan sandstone beds. Echinoderm fossil fragments indicate an Early Pennsylvanian or possibly Mississippian age (*crinoids and archaeocidaris dininnii*; Chronic and Williams, 1978). The Glen Eyrie shale forms a substrate of low strength, prone to slope instability and landslides. The shales and derived clay soils are also prone to expansion and can be problematic as a foundation for structures, roads, and developments. The maximum thickness of the unit is 362 ft (Grose, 1961).

MDlh

Hardscrabble Limestone Member of the Leadville Limestone (Mississippian) and Williams Canyon Formation (Devonian), undifferentiated—The Williams Canyon Formation consists of buff-gray to red and lavender thin-bedded sandy limestone and dolomite, with minor beds of shale, sandstone, and siltstone; reaching a thickness of approximately 30 ft. The Williams Canyon Formation is distinguished by thin bedding and bright red color, and is known only in its type locality in Williams Canyon (Brainerd and others, 1933) in the southern Rampart Range. It may be Devonian in age. The Hardscrabble Limestone is tan to gray, sandy dolomitic limestone that disconformably overlies the Williams Canyon Formation (Grose, 1961). Massive-bedded carbonates form the lower portion, and may be sandy, cherty, or oolitic. The upper part of the formation consists of well-indurated karst breccia. Thickness of the Hardscrabble Limestone varies due to karst dissolution but does not exceed 100 ft. The Hardscrabble Limestone correlates with the Mississippian Madison Limestone and Leadville Group (Maher, 1950).

Om

Manitou Limestone (Lower Ordovician)—The Manitou Limestone consists of fine-grained dolostone and limestone. The unit is resistant-weathering, pinkish-gray to tan, and thin- to medium-bedded, with approximately 145 ft of thin wavy-bedded to medium-bedded carbonates giving way to upper, cliff-forming, medium-bedded dolostone, approximately 40 ft thick. Resistant-weathering chert layers are interbedded with limestones in the lower sequence in western Manitou Springs township, and silicic nodules are found throughout. The unit rests in angular unconformity on the Sawatch Sandstone (Myrow and others, 1999). Manitou Springs is the type locality for the Manitou Limestone (Brainerd and others, 1933), in the northwestern Manitou Springs quadrangle.

Ꞓs

Sawatch Sandstone (Upper Cambrian)—Arkosic to glauconite-rich dolomitic sandstone, exposed in Fountain Creek canyon and Williams Canyon. The lower part of the Sawatch Sandstone is resistant-weathering, white- to light-gray-green, medium- to coarse-grained, conglomeratic arkosic sandstone; approximately 14 ft thick. The basal contact is nonconformable upon crystalline basement rocks of Mesoproterozoic age. The arkosic sandstone passes upward into finer-grained, glauconitic, dolomitic sandstones of deep purple and green color, locally crossbedded and bioturbated. Glauconitic sandstones reach 43 ft in thickness. Recent work (Myrow and others, 1999) identifies the glauconitic member as the middle Sawatch Sandstone, by correlation with a unit of the Sawatch Range that contains upper Cambrian trilobite fossils. Long wavelength, low amplitude dunes reflect deposition of the middle Sawatch by tidal currents (Myrow, 1998).

Tectonically disrupted sandstones tentatively identified as Sawatch Sandstone exist within fault-bounded panels along the Ute Pass fault (see also Trimble and Machette, 1979). The arkosic sandstones in that setting lack primary structures such as sorting and grading and have a mottled maroon and white coloration. Petrologically similar sandstone is also present as clastic dikes within Pikes Peak Granite (Ypp) near the Ute Pass fault. Angular fragments of granite and microcline derived from granite are present in small quantities in the dike material that consists predominantly of equigranular, rounded to sub-angular quartz grains, cemented by silica and hematite. The dikes are mostly vertical to sub-vertical and range from a few in. to 20 ft or more in width on the Manitou Springs quadrangle. Similar dikes are known from widely scattered locations in the southeastern Front Range, and the timing of emplacement is poorly known (Harms,1965).

PROTEROZOIC ROCKS—In the Manitou Springs quadrangle, Proterozoic rocks are exposed west of the Ute Pass fault. Granitic rocks of the Middle Proterozoic Pike's Peak batholith are the predominant rock type exposed within the quadrangle. Early Proterozoic gneiss and granitic rocks that predate the batholith are exposed at a few places near the Ute Pass fault in the northeastern part of the quadrangle.

Pikes Peak batholith—The Pikes Peak batholith is exposed over an area of 1,200 sq mi in the southern Front Range (Tweto, 1987). Numerous studies have been conducted on the Pikes Peak batholith, which was emplaced 1.09 to 1.02 Ga (Aldrich and others, 1957; Bickford and others, 1989; Unruh and others, 1995; Smith and others, 1999a). Cross first mapped the geology of the Pikes Peak region and in 1894 applied the formal name Pikes Peak Granite (Ypp) to the most common rock type in the batholith. Hutchinson (1972, 1976) studied the granite tectonics and modes of intrusion of the batholith and showed that the batholith is composite in nature. Barker and others (1975) produced a comprehensive petrologic and geochemical description of the rocks that comprise the batholith and noted that the batholith is composed of granites that have two distinct chemical trends, or series: the dominant potassic series, and a sodic series. They also determined the relative ages of the various granites in the Mt. Rosa area. The potassic series is represented by the Pikes Peak Granite (Ypp) and late-stage phases such as the Windy Point granite (Ywp), granite of Almagre Mountain (Yam), and granite of Nelson's Camp (Ync). The sodic granites occur in smaller, late-stage intrusive centers such as the Mount Rosa center (Gross and Heinrich, 1965), which is mostly located within the Manitou Springs quadrangle. Smith and others (1999b) studied the petrology and geochemistry of late-stage intrusions of the batholith and showed that both fractionation of mantle-derived magmas and melting of preexisting crustal rocks (anatexis) were involved in the petrogenesis of the batholith. The sodic series intrusives are thought to be the result of fractionation of basaltic magmas, and the potassic series (including the Pikes Peak Granite, Ypp) is interpreted to be derived from crustal anatexis. Smith and others (1999a) provide a review of the chemistry and genesis of the Pikes Peak batholith and note that the batholith is a type-example of A-type granitic magmatism. Pegmatites and veins in the Pikes Peak batholith have produced an abundance of specimen-quality mineral samples. Pearl (1972) describes the minerals and collecting localities in the St. Peters Dome and Crystal Park areas in detail. Muntyan and Muntyan (1985) also describe the mineralogy of the pegmatites in the Pikes Peak batholith.

Ym

Mafic dikes (Middle Proterozoic)—Medium-gray to very dark-gray, fine- to locally medium-grained dikes that intrude granitic rocks of the Pikes Peak batholith. Dikes most commonly are linear and have planar contacts but may also form irregular, discontinuous masses and pods in a web-like pattern. Dikes are generally 3 to 15 ft in width, and most have steep dips. Mafic dikes are most numerous in the south-central part of the Manitou Springs quadrangle where the Mt. Rosa granite and fayalite granite are exposed. Gross and Heinrich (1966b) identified the dikes in the Mt. Rosa area as lamprophyres. Small xenoliths of Middle Proterozoic pegmatite, and feldspar xenocrysts derived from Pikes Peak Granite, are present in some of the dikes. Detailed geochemical studies by Smith and others (1999b) show that the dikes vary in composition and include actual lamprophyre, diabase, and quartz diorite.

Yp

Pegmatite (Middle Proterozoic)—Very coarse-grained, white to pink veins, lenses, and pods consisting chiefly of feldspar and quartz. The larger and more continuous pegmatites in the southern part of the map area are genetically related to the sodic Mt. Rosa granite (Gross and Heinrich, 1966a) and are shown on the map. The pegmatites related to Pikes Peak Granite are too small to show at map scale. Pegmatites often contain varying percentages of a large number of accessory minerals, some of which are valuable as specimens or gems. Pegmatites in the Mt. Rosa area have been mined for thorium and uranium on the quadrangle, and some contain rare-earth minerals. A large, sill-like pegmatite containing black riebeckite crystals up to 14 in. long, as well as an abundance of other rare minerals including zircon, cryolite, and bladed, bronze-colored astrophyllite up to 6 in. long, is exposed along Gold Camp Road in sec. 17, T. 15 S., R. 67 W. See the "Mineral Resources" section below for more information on the mineralogy of the pegmatites.

Ymr

Mount Rosa granite (Middle Proterozoic)—Light- to medium-gray and grayish-pink, fine- to medium-grained (rarely coarse-grained) riebeckite-bearing granite in the south-central part of the quadrangle. Weathers moderate orange-pink to gray, and is more resistant to weathering than the coarser grained granites that it intrudes. Part of the sodic series of late-stage granites of the Pikes Peak batholith (Wobus, 1976; Smith and others, 1999b). Occurs as sheet-like masses or dikes that dip moderately (20°-45°) to the east or southeast. Thickness of the sheets varies from approximately 10 to 150 ft (Gross and Heinrich, 1965). The east face of Mt. Rosa is largely a dip slope on a thick sheet of the granite. The granite of Nelson Camp directly underlies the largest mass of Mount Rosa granite. Joints in the Mount Rosa granite commonly are parallel to the dip of the sheet itself. Alignment of riebeckite and/or astrophyllite gives the rock a subdued lineation in places. The texture and mineralogy of the granite is variable. The thinner sheets and dikes are finer grained than the thicker masses. The main constituents, in order of decreasing abundance, are perthitic microcline, quartz, riebeckite (a sodic amphibole), and plagioclase. Astrophyllite is locally common. Biotite may be present as a significant percentage or completely absent. Zircon has been noted as a common accessory mineral, and Gross and Heinrich (1965) identified a large number of other accessory minerals in their detailed petrologic study of the Mt. Rosa area. Some of the accessory minerals contain rare-earth elements. Major and trace element analyses of the Mount Rosa granite are provided by Smith and others (1999b). Age is approximately correlative with Windy Point granite (Trimble and Machette, 1979).

Ywp

Windy Point granite (Middle Proterozoic)—Gray to pinkish-gray, fine- to medium-grained, porphyritic granite and quartz monzonite. Weathers to reddish-tan or buff. Blocky weathering compared to the rounded weathering of the coarse-grained Pikes Peak Granite. Microcline phenocrysts commonly stand out in relief giving some weathered surfaces a "knobby" appearance. Quartz phenocrysts may be present as well but are not as large as microcline phenocrysts. Typically, Windy Point granite is more resistant to weathering than the enclosing coarse-grained granites and forms the rocky caps of linear ridges. However, at some places it is less resistant and occupies topographically lower areas adjacent to ridge tops of Pikes Peak Granite. Forms lens-shaped and arcuate dikes and sheet-like masses that intrude the Pikes Peak Granite, granite of Almagre Mountain, and fayalite granite. Windy Point granite is geochemically similar to Pikes Peak Granite and is thought to be a late-stage, rapidly-cooled variant of Pikes Peak Granite (Wobus, 1976). Windy Point granite is of the potassic series of late-stage granites of the Pikes Peak batholith (Wobus, 1976; Smith and others, 1999b). The principle minerals composing the Windy Point granite, in order of decreasing abundance, are microcline, quartz, biotite, and plagioclase (oligoclase). The microcline is partly perthitic. Biotite commonly occurs in rounded clusters. Quartz is usually as individual grains rather than as clusters of grains. Dikes of Windy Point granite are present in two diffuse northwest-trending zones, both about 1.5 mi wide, that roughly parallel the Ute Pass fault. The individual dikes are aligned parallel to the overall trend. The contacts between the Windy Point granite and Pikes Peak Granite is often diffuse or gradational, and the exact mapped contact between them is somewhat arbitrary based on the overall grain-size. The interior areas of masses of Windy Point granite are fine grained and commonly contain fewer phenocrysts than areas near contacts. Finley (1916) mapped Windy Point granite as "Cripple Creek granite", and Gross and Heinrich (1965) referred to the Windy Point granite as "porphyritic granite" and reserved the name Windy Point granite for specific outcrops on and near Pikes Peak. Major and trace element analyses of Windy Point-type granites were reported by Smith and others (1999b). Age is approximately correlative with Mt. Rosa granite (Trimble and Machette, 1979).

Ync

Granite of Nelson Camp (Middle Proterozoic)—Tan to greenish-brown to dark-green, medium- to coarse-grained granite. Informally named by Scott and Wobus (1976). Finer grained than Pikes Peak Granite, but coarser grained than most Mount Rosa granite. Characterized by biotite clusters up to 0.5 in. in diameter. The main mineral constituents, in order of decreasing abundance, are perthitic microcline, quartz, and biotite. Plagioclase is either completely absent or present in low amounts. Traces of fayalite were observed in thin sections of fresh rock, which was not noted by previous workers. Biotite is deep brownish-red, similar to biotite in the Mount Rosa granite. Astrophyllite and riebeckite are present in trace amounts (Barker and others, 1975). The granite of Nelson Camp weathers more rapidly than other granites, commonly forming light-tan grüs deposits that are barren of vegetation on north-facing slopes. This grüs looks similar to that developed in areas underlain by fayalite granite. Called “tan granite” by Barker and others (1975), who concluded that it is slightly younger than the granite of Almagre Mountain but older than the Mt. Rosa granite. Contact relations between these granitic units are not well understood because contacts are poorly exposed. The granite of Nelson Camp appears to be part of the sodic series of granites of the Pikes Peak batholith (Wobus, 1976; Smith and others, 1999b).

Yam

Granite of Almagre Mountain (Middle Proterozoic)—Pink to red, medium- to coarse-grained, equigranular granite. Informally named by Barker and others (1975). Compared to the Pikes Peak Granite, the granite of Almagre Mountain is more red in color and is slightly finer grained. Weathers more blocky than the Pikes Peak Granite, especially around Almagre Mountain where jointing is prominent. Interlocking pink microcline crystals and rounded quartz aggregates are characteristic and noticeable on smooth joint planes. The principle minerals composing the granite of Almagre Mountain, in order of decreasing abundance, are microcline (perthitic), quartz, and biotite. No plagioclase was noted in thin section, which also distinguishes the granite of Almagre Mountain from Pikes Peak Granite. One of the youngest plutons of the predominant fayalite-free (potassic type) granite of the Pikes Peak batholith (Barker and others, 1975).

Ypp

Pikes Peak Granite (Middle Proterozoic)—Pink, light reddish-brown, light-gray, coarse-grained, equigranular to locally porphyritic granite. Resistant outcrops are typically rounded and bouldery. Weathering often produces deposits of grüs (loose, disaggregated mass of constituent minerals). Grüs is best developed on north-facing slopes and can accumulate to thicknesses as much as 150 ft (Blair, 1976). Grüs develops first along joints in the granite. More resistant rock between joints may remain intact as rounded “corestones” which may be seen in many roadcuts in the area. Gross and Heinrich (1965) described the petrology of the Pikes Peak Granite in detail. The constituent minerals of Pikes Peak Granite, in order of decreasing abundance, are perthitic microcline, quartz, plagioclase (oligoclase), and biotite. Accessory minerals include hornblende, zircon, apatite, magnetite, and fluorite, plus rare allanite and bastnaesite. Aplite dikes, typically 0.5 to 2.0 ft in width, are widely scattered in the Pikes Peak Granite but have not been mapped separately. Irregularly-shaped pegmatite dikes and quartz veins are typically small and also were not mapped separately. Pegmatites and miarolitic cavities in the granite are notable for spectacular mineral specimens in places (see “Mineral Resources” section of this booklet). Pikes Peak Granite is the most abundant of the intrusive rock types on the Manitou Springs quadrangle. This granite is the main constituent of the potassic series of intrusives that constitute more than 90 percent of the batholith as a whole (Wobus, 1976; Smith and others, 1999b). Major and trace element analyses of the Pikes Peak Granite were reported by Smith and others (1999b).

Yfg

Fayalite granite (Middle Proterozoic)—Dark-olive-green to greenish-gray, coarse-grained, equigranular granite that contains small amounts of fayalite (iron-rich olivine). Texturally similar to the Pikes Peak Granite. Weathered surfaces and grüs are a very light-brown or tan color, which distinguishes it from Pikes Peak Granite, which weathers to a darker reddish-brown or pink color. Forms smooth, rounded, resistant outcrops, such as those at Helen Hunt Falls in North Cheyenne Canyon Park. Gross and Heinrich (1965) described the petrology of fayalite granite in detail. The constituent minerals, in order of decreasing abundance, are perthitic microcline, quartz, plagioclase (sodic oligoclase), biotite, and fayalite. Fayalite is usually in various stages of alteration to serpentine, chlorite, biotite, calcite, and magnetite. Plagioclase is present as individual grains and as exsolution lamellae in the perthite, and in antiperthite. Accessory minerals include allanite, zircon, apatite, pyroxene, amphibole, and fluorite. Our mapping shows that fayalite granite is exposed over a larger, more cohesive area along Gold Camp road than previous mapping has shown. Contacts with Pikes Peak Granite are gradational (Gross and Heinrich, 1965). Barker and others (1975) concluded that the fayalite granite crystallized slightly before the intrusion of the Pikes Peak Granite. Fayalite granite is part of the sodic series of granites of the Pikes Peak batholith (Wobus, 1976; Smith and others, 1999b). Major and trace element analyses of fayalite granite were reported by Smith and others (1999b).

YXg

Granite (Early or Middle(?) Proterozoic)— Pink, medium-grained, equigranular, massive to poorly foliated granite or quartz monzonite present only as dikes and irregular masses along the Ute Pass fault between Iron Mountain and Section 16 Open Space Park north of Bear Creek. Associated with granodiorite and migmatitic gneiss. In order of decreasing abundance, consists of microcline, quartz, plagioclase, biotite, and hornblende. Possibly correlative with Middle Proterozoic quartz monzonite in the Cheyenne Mountain quadrangle (Rowley and others, 2003).

Xgd

Granodiorite (Early Proterozoic)—Medium- to dark-gray, pink-mottled, medium- to coarse-grained, porphyritic granodiorite and quartz diorite. Present only in small masses along the Ute Pass fault in the Iron Mountain area, where it is associated with migmatitic gneiss and light-colored granitic rock. Phenocrysts of pink microcline up to 1 in across constitute about 30 percent of the rock. Other minerals, in order of decreasing abundance, are plagioclase, quartz, biotite, and minor hornblende. Biotite appears to be more abundant than quartz in some samples. The granodiorite is poorly to moderately foliated. Unit is similar in appearance to granodiorite in the Cheyenne Mountain quadrangle (Rowley and others, 2002) southeast of Manitou Springs. The unit is similar to the Boulder Creek Granodiorite of the northern Front Range, which has an age of about 1.67 Ga (Hedge and others, 1967; Reed and others, 1987).

Xgn

Migmatitic gneiss (Early Proterozoic)— Potassium feldspar-biotite migmatite, quartzose gneiss, biotite schist, and amphibolite gneiss. Sillimanite and garnet are locally present in the biotite gneiss. Gneiss forms a limited outcrop in and west of Williams Canyon in the southern Rampart Range, intruded by Pikes Peak Granite along low angle contacts. Xenolith blocks and fault-bounded masses of migmatitic gneiss are exposed adjacent to the Ute Pass fault between Englemann Canyon and Bear Creek. The migmatitic gneiss is part of a large belt of metamorphosed sedimentary and volcanic rocks that underwent deformation as they were added to the southern edge of the Archean Wyoming craton along a convergent margin between 1.66 and 1.79 Ga (Reed and others, 1987). The original volcanic and sedimentary protoliths are interpreted to be products of arc magmatism and contemporaneous sedimentation (Reed and others, 1987). The gneiss has been previously identified as Idaho Springs Formation (Grose, 1961); however, recent work on amphibolite gneiss in the southern Front Range (Folley and Wobus, 1997) suggests that gneiss in the vicinity of Pikes Peak is tectonically distinct from gneiss in the Idaho Springs locality, further north. Aeromagnetic anomalies (Oshetski and Kucks, 2000) over the bedrock offer a general means of distinguishing gneiss from granitoids in areas of dense vegetation or in the subsurface.

STRUCTURAL GEOLOGY

The Ute Pass fault forms a major fault zone in the northeastern part of the Manitou Springs quadrangle. The fault generally coincides with a break in slope between steep, rugged mountain topography upon Proterozoic crystalline rocks, and the more subdued topography at lower elevations underlain by Phanerozoic strata and Quaternary deposits. Secondary high-angle faults and fracture arrays are abundant within the Proterozoic crystalline rocks that form the hanging-wall block of the Ute Pass fault. The predominant orientation of the faults and fractures is north-northwest (azimuth 350º). In the footwall, alternating resistant- and soft-weathering sedimentary units form northeast- to north-northeast-trending hogbacks and strike valleys in the northeastern corner of the Manitou Springs quadrangle. Bedding attitudes in Fountain Formation define a north-northeast-trending monocline. Bedding dips in Permian and younger units are typically subvertical to overturned. The bedrock units are mantled with unconsolidated Tertiary and Quaternary deposits that conceal many fundamental structural contacts, except where they have been incised by the modern Fountain and Bear Creek drainages and their tributaries.

UTE PASS FAULT ZONE

The west-dipping to vertical Ute Pass fault juxtaposes Precambrian rocks on the west against downthrown steeply dipping to overturned Paleozoic and Mesozoic rocks on the east. From Manitou Springs to the south, the Ute Pass fault corresponds with a broad zone of north-northwest-striking, high-angle reverse faults that forms the range-bounding structure for the southern Front Range (Kupfer and others, 1968; Carroll and Crawford, 2000; Rowley and others, 2003). In the eastern part of the Manitou Springs quadrangle, the trace of the Ute Pass fault curves gently toward the northwest, then assumes a very linear trend oriented 315° to 320º (azimuth). The linear trace across varied elevation indicates that the fault is steeply dipping to vertical. Along the curved segment and at the transition from curved to straight trace, a zone of deformation and shear reaching several hundred feet in width exists along the Ute Pass fault. The zone affects Early Proterozoic gneiss and intrusive rocks in the vicinity of Iron Mountain and the lower Crystal Park road. Rocks within the zone are incompetent and clay-rich due to chemical alteration and are penetrated with shear surfaces.

The Ute Pass fault zone is interpreted as a Late Cretaceous–Tertiary Laramide fault system that reactivated an Ancestral Rockies structure (Pennsylvanian) (Kluth, 1997; Hoy and Ridgeway, 2002). The origin of the structure may be earlier yet , according to ^{40}Ar/^{39}Ar cooling data across the Ute Pass fault (Heizler, 2002). An important record of the Pennsylvanian Ancestral Rockies orogeny comes from the Fountain Formation in the Manitou Springs quadrangle. The Fountain Formation represents a great thickness of orogenic sediments deposited in an asymmetric depositional center. In its type locality along Fountain Creek in the Manitou Springs quadrangle (Cross, 1894), the Fountain Formation is 4,050 ft thick and consists largely of coarse clastic materials derived from granitic rocks of the Pikes Peak batholith (Suttner, 1989) shed to the northeast off of the reverse-fault-bounded Frontrangia uplift. It formed in a marine delta and nonmarine, subaerial alluvial fan system (Suttner, 1989), bounded by the ancestral Ute Pass fault zone (Kluth, 1997; Hoy and Ridgeway, 2002). The coarse-grained facies of the Fountain Formation thins northward, to an estimated 650 ft (~200 m) at Glen Eyrie (Maples and Suttner, 1990).

At one locality in the Manitou Springs quadrangle, boulder-sized clasts of biotite gneiss (Xgn) occur, with an apparent proximal source from a fault-bounded panel at Iron Mountain, suggesting that segments of the Pennsylvanian Ute Pass fault zone are preserved at that site. The boulders exceed 10 in. in diameter and are identified as mass flow deposits that cannot have undergone large sedimentary transport at the time of deposition (Suttner and others, 1984). The gneisses of Iron Mountain appear to be the only proximal source for the boulder clasts within the upthrown basement blocks that consists primarily of Pikes Peak Granite. To preserve this close spatial relationship, the easternmost fault strands at Iron Mountain must not have accommodated significant Laramide slip; thus they are interpreted to be abandoned segments of the Ancestral Rockies fault. The fault strands are arcuate, with their trace following a topographic contour, suggesting that the faults have a shallow or only moderate dip to the west and southwest. On the west, the strands are cut by the subvertical, “straight” segment of the Ute Pass fault, according to mapped fault relationships. To the east, the faults juxtapose the Paleoproterozoic units (Xgn, Xgd, and YXg) forming Iron Mountain from the coarse conglomerate facies of the Fountain Formation. Since post-Pennsylvanian faulting has not separated the Fountain Formation from its proximal source rock, and the arcuate faults are cut by the subvertical, “straight” segment of the Ute Pass fault, the straight segment is younger and is interpreted as a Laramide feature. If this reasoning is sound, the curved fault segments on the east and north side of Iron Mountain are vestiges of the Ancestral Rockies fault system, and Iron Mountain is one of the few locations in Colorado where abandoned segments of Ancestral Rockies faults are preserved.

The Laramide Ute Pass fault zone juxtaposes Proterozoic crystalline rocks (predominantly Pikes Peak Granite) with strata as young as Cretaceous. Subparallel fault strands exist wholly within the basement rock, and these are deeply weathered and oxidized, offering little direct information about fault slip. Subhorizontal to steeply plunging fault slickenside striae within the Ute Pass fault zone typically trend northwest.

There is evidence that movement on the Ute Pass fault zone continued into the Neogene and possibly into Quaternary time. Based on offset of the Eocene erosion surface and late Tertiary sedimentary deposits, Epis and Chapin (1975) and Taylor (1975) estimated at least 1,000 ft of Neogene vertical displacement across the fault zone west of Woodland Park. Kirkham and Rogers (1981) described several features that suggest the possibility of Quaternary movement on the Ute Pass fault near the eastern base of Cheyenne Mountain, south of the Manitou Springs quadrangle. Aerial photos reveal a linear, scarp-like feature that transects older Quaternary fan alluvium (Qfo) in sec. 27, T. 14 S., R. 67 W. in the Manitou Springs quadrangle. This feature is directly on strike with, and adjacent to, a bedrock exposure of the Ute Pass fault and may be further evidence of Quaternary fault movement. The "Geologic Hazards" section, below, describes evidence that the Ute Pass fault zone and the Rampart Range fault zone may have generated earthquakes in the recent past.

KINEMATICS

The fundamental juxtaposition of Precambrian plutonic rocks and migmatite gneisses against vertical to overturned Mesozoic strata suggests predominant west-side up, reverse movement. However, low-raking slickenside striae on steep northwest-striking faults and shears cutting Precambrian rocks within the Ute Pass fault zone record a component of lateral translation (see section on “High angle faults and fractures” below), and the exceptionally linear trace of the fault in the northern Manitou Springs quadrangle indicates a very steep fault geometry that could be consistent with a strike-slip or transfer fault (Kupfer and others, 1968; Epis and others, 1980). A potential piercing point across the Ute Pass fault is provided by the fault-bounded panel of Early Proterozoic gneiss and granitoids at Iron Mountain. Biotite-sillimanite gneisses in the footwall of the Ute Pass fault at Iron Mountain may correlate with an exposure of similar rocks in the Ute Pass fault hanging wall, on the north flank of Bear Creek Canyon. If so, apparent left-lateral separation across the Ute Pass fault is 4,000 ft or more, and map relationships within the Manitou Springs quadrangle suggest sinistral reverse oblique displacement across the Ute Pass fault in Laramide time. However, the kinematic history of the Ute Pass fault in adjoining areas suggests a complex Laramide history. For example, northwest of the Manitou Springs quadrangle at the town of Woodland Park, the Ute Pass fault forms the western boundary of the Manitou Springs graben and accommodated normal-sense offset (Scott and others, 1978; Epis and others, 1980; Dickson and others, 1986). In the Cheyenne Mountain quadrangle to the south, map relationships show thrust to reverse-sense slip (Rowley and others, 2003).

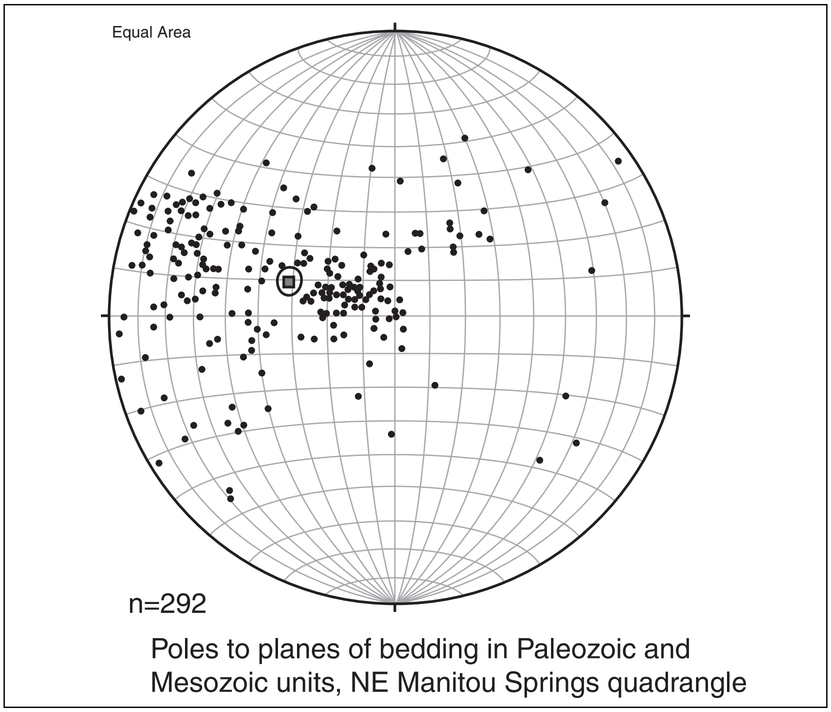


Figure 6. Stereonet diagram of bedding planes in Paleozoic and Mesozoic rock units, Manitou Springs quadrdangle.

STRUCTURAL GEOLOGY OF FOOTWALL STRATA

Rocks in the footwall of the Ute Pass fault consist of gently to steeply dipping Paleozoic and Mesozoic sedimentary strata that form the upper and middle limb of an asymmetrical, southeast-facing monocline in the northeast corner of the Manitou Springs quadrangle. Dips of bedding steepen from northwest to southeast in the footwall rocks, as is evident from the stereographic plot of poles to bedding for all Phanerozoic strata in the quadrangle (Fig. 6).

Northeast-trending faults cut the steeply dipping Phanerozoic strata in the footwall of the Ute Pass fault, south of Fountain Creek. Kinematics interpreted from map pattern are for down to the north or sinistral separation of bedding across the faults.

A more complex fault pattern exists in Garden of the Gods Park, in the northeastern corner of the Manitou Springs quadrangle, where colorful maroon and white, vertically dipping upper Paleozoic sandstones form dramatic fins and spires. Superb exposures in the Garden of the Gods reveal west-vergent, younger-on-older reverse faults within a broad zone of deformation in the footwall of the Rampart Range fault. The fault complexity and reversal in sense of displacement may reflect structural accommodation within the hinge zone of the footwall syncline or at the change in strike of the Rampart Range fault from northwest-southeast to north-south.

RAMPART RANGE FAULT IN GARDEN OF THE GODS PARK

The south end of the Rampart Range fault system is mapped in the northeast corner of the Manitou Springs quadrangle, in Garden of the Gods Park, Colorado Springs. A fault juxtaposes moderately steeply dipping strata (73–78º dips) of the Fountain Formation in the hanging wall, on the west, up to the east over steeply dipping to overturned beds of Permian through Cretaceous rocks in the footwall. In Garden of the Gods, the Rampart Range fault trend changes from northwest to north, and a complex geometry of secondary faults exists in the footwall of the Rampart Range fault (Grose, 1961; Trimble and Machette, 1979; Morgan and others, 2003). Clearly exposed in the Garden, the moderately dipping secondary faults strike northeast and dip 61–75° southeast and cut vertical to overturned footwall strata. The faults are marked slickenside surfaces with northeast-plunging striae, and bedding provides a piercing point for measurement of offset, showing that the hanging wall blocks are upthrown to the west, with tens of meters of displacement. Other minor structures evident in sandstone units of Garden of the Gods include joints, veins, and shear fractures at centimeter to decimeter spacing. Kinematic analysis of the fault and shear fracture arrays indicates east-west shortening (Siddoway and others, 1999; Siddoway, unpublished data), consistent with Laramide stress trajectories along the Front Range (Erslev, in press).

INTERPRETATION OF THE RELATIONSHIP BETWEEN THEUTE PASS AND RAMPART RANGE FAULTS

At depth, the Ute Pass and Rampart Range faults may sole in to a master or detachment fault (Erslev, 1993), or the Rampart Range fault may be an east-breaking splay off of the Ute Pass fault. A monocline within the Fountain Formation (Grose, 1961; this report) is interpreted to conceal a blind segment of the Rampart Range fault, south of Fountain Creek, that breaks the surface in Garden of the Gods. Mesozoic strata are involved in the steep limb of the monocline, so the monocline must be of Laramide age. The monocline is cut by the Ute Pass fault, indicating that Ute Pass fault movements were contemporaneous with or outlasted activity on the Rampart Range fault. The fault and fold relationships suggest that reverse motion is transferred from the Ute Pass fault, the Front Range-bounding structure south of Fountain Creek, to the Rampart Fault, the range-bounding structure north of Fountain Creek. Support for this interpretation comes from the observation that the Ute Pass fault changes from an approximately north-striking, dominantly reverse fault to a northwest-striking, subvertical transfer (?) fault at this location. Thus, the linear, northwest-striking segment of the Ute Pass fault accommodates differential motion between the Rampart Range block and the Pikes Peak/Cheyenne Mountain block of the southern Front Range.

TIMING OF MOVEMENT ON THE UTE PASS AND RAMPART RANGE FAULT ZONES

The Ute Pass fault dips steeply west and southwest and is downthrown to the east, involving units as young as Late Cretaceous in the footwall. Along its trace from northwest to southeast, the Ute Pass fault cuts up-section from lower Paleozoic through Pennsylvanian to Late Cretaceous strata at Bear Creek canyon. South of Bear Creek canyon, well-exposed overturned bedding in the Fort Hayes Limestone of the Niobrara group dips as much as 35° west along a considerable length of the fault. The relationship provides a maximum age for deformation along the Ute Pass fault as Late Cretaceous, corresponding in time with the Laramide Orogeny. Similar relationships exist along the Rampart Range fault in the Cascade quadrangle to the north (Morgan and others, 2003), suggesting contemporaneity of the two structures. Furthermore, in the Cascade quadrangle, progressive unconformities exist in Maastrictian arkosic conglomerates of the Dawson Formation deposited on the footwall of the Rampart Range fault (Morgan and others, 2003; Raynolds, 2002; Kluth and Nelson, 1988).

The time of initiation of the fault zones and other high-angle faults that cut crystalline basement rocks is open to debate. Structures involving Proterozoic basement may have originated during, and participated in, any of several deformational events during Colorado's protracted tectonic history, following the emplacement of the Pikes Peak batholith at 1.05 Ga. Major events are (1) regional northeast-southwest extension in the foreland or continental interior (intracratonic deformation) during the Grenville orogeny at approximately 1 Ga (Timmons and others, 2001; Marshak and others, 2000); (2) regional east-west extension during supercontinent breakup at approximately 0.80–0.74 Ga (op.cit.); (3) east-northeast—west-southwest convergent tectonics of the Ancestral Rockies event in Pennsylvanian time (Kluth, 1997; Hoy and Ridgway, 2002); (4) east-west shortening during the Laramide Orogeny during Late Cretaceous-early Tertiary time (Erslev and others, in press, and references therein); and (5) Miocene to Recent epeirogeny (Leonard, 2002; McMillan and others, 2002; Leonard and others, 2002; Steven and others, 1997). Regional geological studies elsewhere in the Southwest show that Laramide contraction reactivated Proterozoic faults (Marshak and others, 2000; Timmons and others, 2001; Heizler, 2002).

With superb exposures of extensive Proterozoic outcrops, the Pikes Peak area offers rich ground for investigation of the Precambrian ancestry and subsequent reactivation of the Ute Pass fault zone and associated faults, including possible activity during Neogene time. The Pikes Peak area may hold important information relating to current hypotheses about late Tertiary uplift of the range (Epis and others, 1980; Steven and others, 1997), identified using geomorphic markers such as the broad topographic bench at Crystal Park, on the east side of Pikes Peak. The bench is an extensive segment of the Rocky Mountain erosion surface (Chapin and Kelley, 1997), that according to Steven and others (1997), is cut by faults bounding the Woodland Park graben, northwest of the Manitou Springs quadrangle. Mid-Tertiary gravels resting upon the surface are cut and downdropped approximately 1,100 ft, a sign of Neogene faulting that may continue to the present day (see "Geologic Hazards" section, below).

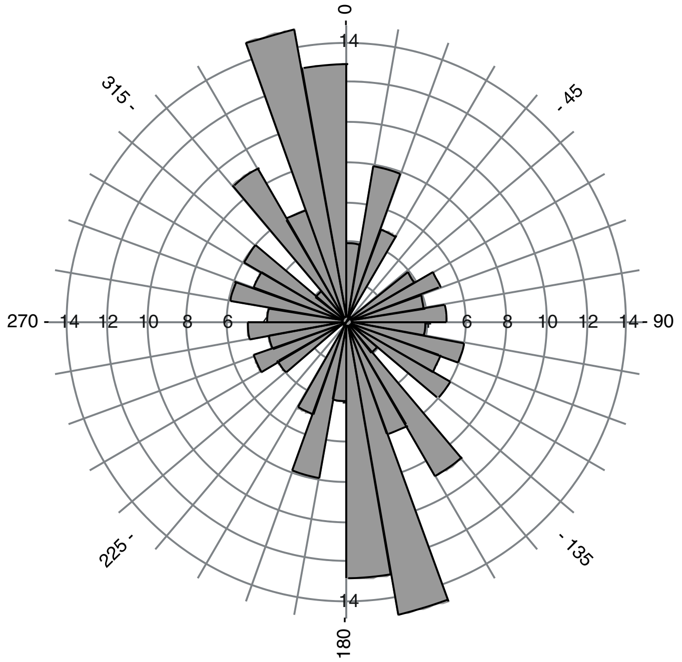
HIGH ANGLE FAULTS AND JOINTS WITHIN PROTEROZOIC ROCKS

Prominent, throughgoing north-south- to north-northwest-trending lineaments transect the Proterozoic crystalline rocks in the western and central parts of the Manitou Springs quadrangle east of Pikes Peak and are evident on topographic map, DEM, and aerial photographs. A north-northwest- to northwest-striking shear fabric, defined by discrete east-dipping high-angle faults, abundant fractures, and locally abundant iron oxide and manganese oxide staining of the granitic rock, is present in the vicinity of and oriented parallel to the Ute Pass fault. This zone of shearing extends about one mi horizontally west of the Ute Pass fault. A few east-northeast- and north-northwest-striking faults were mapped in the Proterozoic rocks, but these are not as common or throughgoing as the dominant north-northwest-, north-south-, and northwest-striking faults. A single throughgoing north-northeast-striking, southeast-dipping fault indicated by a strong valley lineament, brecciated rock, parallel fractures, and localized quartz veining is present in the southeastern part of the quadrangle along Old Stage Road.

At outcrop scale, evidence of fracturing and brittle shear is widespread throughout the Proterozoic crystalline rock of the Manitou Springs quadrangle. Fault zones in the granitic rocks are marked by intense fracturing and sheeting of joints, slickensides, oxidation and deep weathering, or alteration. Fractures and joints have dominant strike orientations of north-northwest, northwest, and north-northeast, with lesser east-northeast to west-northwest trends (Fig. 7). Quartz veins, gouge zones and brecciated rock are rare. At map scale, the correspondence of stream drainages with lineaments and faults reflects the greater erodability of highly fractured and chemically weathered rock along fracture systems. Most individual fractures are open, exposed as fractured, weathered rock rather than annealed or mineralized zones. The "sheeted fracture" fabric, widespread in the Pikes Peak Granite, commonly exhibits a black or dark-brown color due to presence of iron and manganese oxides. These fractured, slickensided outcrops occur widely but in isolated exposures that are difficult to trace laterally. The width of sheared rock along lineaments or in outcrops of sheeted fractures ranges from less than 0.5 ft to over 5 ft. Zones of parallel, sheeted fractures related to "main" fault planes may be 100 ft wide or more. The dominant orientation of sheeted fractures and joints is north-northwest (Fig. 7).

Criteria used to distinguish mappable faults from joints, shear fractures, and minor faults include the following: (1) presence of slickensides or gouge zones, evident in roadcuts, cliff faces, or other "clean" exposures; (2) zones of parallel-fractured and/or propylitically altered rock; (3) mineralization, alteration, veining or brecciation; and (4) correspondence with lineaments expressed on maps, air photos, and DEM. Lineaments were field checked and if these other criteria were present, the lineament was mapped as a fault. In a few cases where time and accessibility limitations did not allow for direct examination of outcrops in the most rugged areas of the quadrangle, lineaments were mapped as dashed faults with queries.

Exposures of steeply dipping faults in the Precambrian area of the Manitou Springs quadran-

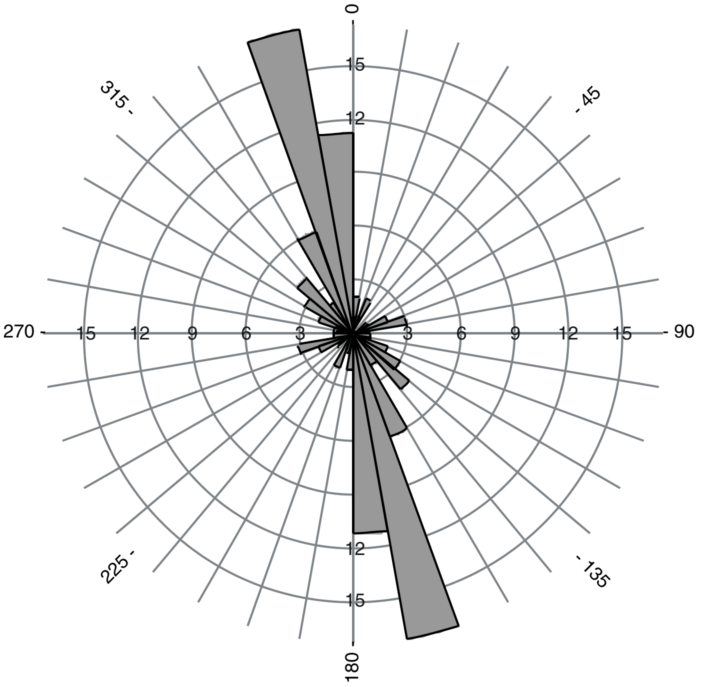


Fractures and Joints —

Manitou–Precambrian area

Calculation Method	Frequency
Class Interval	10 Degrees
Length Filtering	Deactivated
Azimuth Filtering	Deactivated
Data Type	Bidirectional
Population	101
Maximum Percentage	14.9 Percent
Mean Percentage	6.3 Percent
Standard Deviation	3.35 Percent
Vector Mean	295.39 Degrees
Confidence Interval	15.4 Degrees
R-mag	0.6

Figure 7. Rose diagram of strike directions of fractures and joints in Proterozoic rocks west of the Ute Pass fault, Manitou Springs quadrangle.



Fault plane measurements—

Manitou–Precambrian area

Calculation Method	Frequency
Class Interval	10 Degrees
Length Filtering	Deactivated
Azimuth Filtering	Deactivated
Data Type	Bidirectional
Population	59
Maximum Percentage	28.8 Percent
Mean Percentage	6.2 Percent
Standard Deviation	7.3 Percent
Vector Mean	320.45 Degrees
Confidence Interval	15.81 Degrees
R-mag	0.71

Figure 8. Rose diagram of strike directions of fault planes in Proterozoic rocks west of the Ute Pass fault, Manitou Springs quadrangle.

gle are found in roadcuts, in abandoned mine pits and adits, and locally in stream cuts and steep canyons. Measurements of faults in outcrop show that nearly all are high-angle, with dips of 60º or greater. The dominant strike orientation is north-northwest, between 340º and 360º (Fig. 8). Subsidiary fault plane orientations are east-northeast (between 70º and 80º) and northwest (between 300º and 320º). The dominant strike direction generally corresponds with the dominant north-northwest strike of sheeted fractures and joints (Fig. 7). In the eastern and northern part of the Manitou Springs quadrangle, this orientation is subparallel with that of the Ute Pass fault. Orientation of fault striae is quite variable, from low rake to high rake on slickensides. Fracture arrays and faults in coarse-grained granites of the Pikes Peak batholith rarely exhibit slickensides; however, at two sites, slickenside striae on east-northeast-striking fault planes have rakes of 5° or less.

Piercing points and surface kinematic criteria (Petit, 1987; Angelier, 1994) for determining movement sense on high-angle faults are usually lacking in the homogeneous, porphyritic plutonic phases comprising the Precambrian bedrock of the Pikes Peak massif. Phanerozoic sedimentary units have been eroded away. Crosscutting relationships between fault arrays are generally unclear, due to the deep chemical weathering along the fault planes. Advanced chemical weathering of surface outcrops means poor preservation of delicate surface features that provide brittle shear criteria (Angelier, 1994). Thus, within the interior portion of the range block, direct determination of fault slip and relative timing between fault arrays is generally not possible. The timing of brittle structures within the Precambrian crystalline rocks is uncertain because the structures may have initiated or been reactivated during several deformational events during Colorado’s protracted tectonic history, (see “Timing of movement on the Ute Pass and Rampart Range fault zones,” above); or may even have formed during cooling of Mesoproterozoic granitoids following emplacement (Hutchinson, 1976; Blair, 1976).

FOLIATION IN PROTEROZOIC GNEISS

Migmatite gneiss forms part of the Proterozoic bedrock in the southern Rampart Range, primarily in Williams Canyon. Layering in the stromatic migmatite is defined by alternation of biotite-rich (melanosome) and K-feldspar-rich layers (leucosome). Some layers consist of fine-grained quartz-rich gneiss, or amphibolitic gneiss. The melanosome contains rare garnet and sillimanite, indicating that metamorphism occurred in the middle amphibolite facies. Foliation is slightly folded into open, northwest-southeast-trending folds. Contacts of Pikes Peak Granite (Ypp) are discordant to the foliation and discordant dikes of pegmatite, aplite and fine-grained granite also cut the metamorphic foliation at a shallow to high angle. Foliation in large xenoliths of migmatitic gneiss near Bear Creek Canyon differs in orientation with gneiss exposed at Iron Mountain and in Williams Canyon.

MINERAL RESOURCES

There are currently no active mines in the Manitou Springs quadrangle (Guilinger and Keller, in preparation). In the past, mines in the quadrangle have produced sandstone, refractory clay, sand and gravel, limestone, gypsum, fluorite, uranium, thorium, rare earth minerals, and high-quality mineral specimens and gems. It is unlikely that commercial quantities of oil or gas are present in the quadrangle, and there are no coal resources.

METAL RESOURCES

The only documented metal production on the Manitou Springs quadrangle is uranium and thorium from mines in the Mt. Rosa area (Fig. 9). Uranium, thorium, and rare earth elements occur locally in pegmatites and veins in or near the Mt. Rosa granite. The St. Peters Dome 1 Mine in sec. 7, T. 15 S., R. 67 W. reportedly produced 500 tons of ore that contained both uranium and thorium (Nelson-Moore and others, 1978). The 1957 Annual Report by the Colorado Bureau of Mines (Scott, 1957) reported that during 1957, Trail Mines, Inc. produced and shipped thorium ore from their mine along the "Corley Mountain Road" (now called Gold Camp Road). Heinicke (1960) states that the thorium is of the ferrothorite type and occurs in both veins and pegmatites in the area and is commonly associated with zircon. The exact location of this mine is not known with certainty, but it is said to be "along a jeep road one mile past the first tunnel". The Bluebird Mine, in sec. 9, T. 15 S., R. 67 W. produced uranium ore from a pegmatite. No production data is available (Nelson-Moore and others, 1978). Several small pits and shallow shafts occur at the location of this mine. Two other prospects in the area are known to contain uranium-bearing minerals. The Dorothy O. Claim and the B.F. Reed Claim are both located in sec. 8, T. 15 S., R. 67 W. near the Gold Camp Road. No metal production has been recorded from these sites, but considerable underground work has been done, presumably in an exploration effort.

The Proterozoic terrane of the quadrangle was systematically prospected for gold in the years following the discovery of the rich gold deposits at Cripple Creek (Finley, 1916). No significant deposits have been found and no gold or base metal production has been recorded in the quadrangle. The MRDS database (Mason and Arndt, 1996) shows that a few widely scattered gold occurrences may be present in the quadrangle, none of which were productive. No base metal or silver prospects are present on the quadrangle. Figure 9. Location of mines and mineral resources in the Manitou Springs quadrangle.

SANDSTONE

The Cambrian Sawatch Sandstone, the Permian Lyons Sandstone, and the Cretaceous Dakota Sandstone have been quarried in the past in the Manitou Springs quadrangle for use as dimension stone. The Sawatch Sandstone was quarried in the SE¼, sec. 31, T. 13 S., R. 67 W., west of U.S. Highway 24 in the northern part of the quadrangle. It was known as "Manitou Green Stone" (Schwochow, 1981). The Lyons Sandstone was quarried prior to 1912 in sec. 10, T. 14 S., R. 67 W. in the northeastern part of the quadrangle, in an area referred to as the Kenmuir quarries near Red Rock Canyon southeast of Manitou Springs (Argall, 1949). The red-orange sandstone from this area was used in the construction of several historic buildings in Denver, including the Masonic Temple, the Boston Building, and the Central Presbyterian Church (Murphy, 1995). The Dakota Sandstone was quarried along the Dakota hogback north of Bear Creek from the 1860s to the 1910s by Anthony Bott (Red Rock Canyon Committee, 2003).

CLAY

Refractory clay was mined from beds in the Dakota Sandstone from several small mines in sec. 15, T.14 S., R. 67 W. in the northeastern part of the Manitou Springs quadrangle. Between 1896 and 1908, nearly 50,000 tons of clay were extracted from these mines and used in local fire brick plants (Lewis and Sundaram, 1975). Additional clay resources are likely to exist within the Dakota Sandstone in this quadrangle.

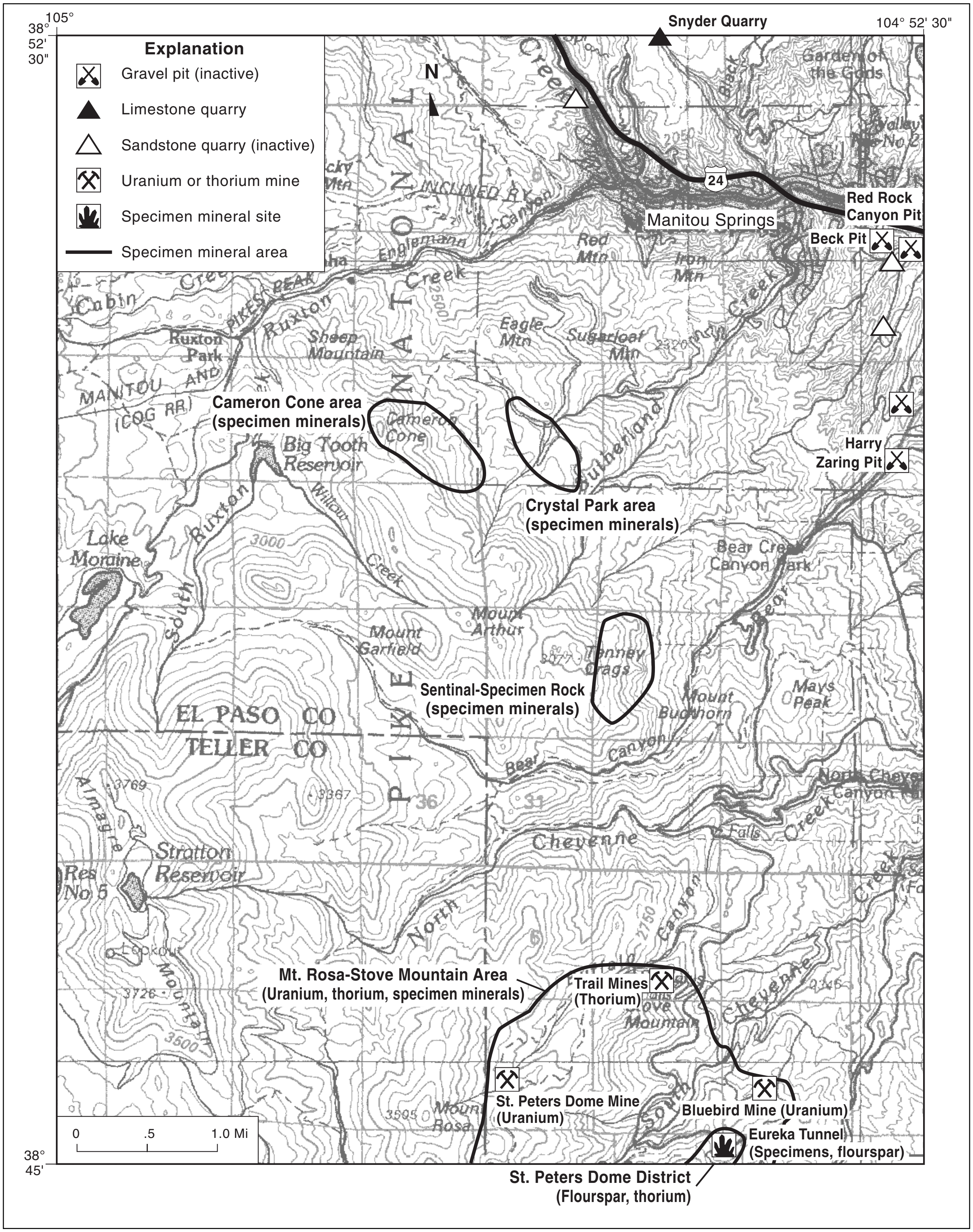


Figure 9. Location of mines and mineral resources in the Manitou Springs quadrangle.

SAND AND GRAVEL

Sand and gravel for use as aggregate has been mined in the past from a few pits in the populated northeastern part of the Manitou Springs quadrangle. The most significant of these appears to be the Red Rock Canyon Pit and the Bock Mine, both located south of U.S. Highway 24 in sec. 10, T. 14 S., R. 67 W (Keller and others, 2002). Quaternary gravel deposits (Qg_2, this report) were mined in the topographically low areas between the more resistant sandstone hogbacks in the Red Rock Canyon area, southeast of Manitou Springs. The Harry Zaring Pit was located in the valley of Bear Creek in what is now the Bear Creek Regional Park but is no longer active and apparently has been reclaimed.

FLUORSPAR

Fluorspar was mined in the St. Peters Dome fluorspar district, the northern extremity of which is in the Manitou Springs quadrangle (Fig. 9). The productive mines in the district are on the Mt. Big Chief quadrangle (Steven, 1949). Through the 1940s, the district produced around 16,000 tons of fluorspar ore (Argall, 1949). Narrow, steeply dipping veins containing fluorspar, quartz, and minor amounts of sphalerite and galena occupy north-trending fault or fracture zones in Pikes Peak Granite (Ypp) and possibly fayalite granite (Yfg). Fluorite is also present in pegmatites associated with the Mt. Rosa granite in this area (Gross and Heinrich, 1965). Originally prospected for gold during the height of the Cripple Creek boom, the veins produced fluorspar between 1910 and 1918, and again in 1944–1945 (Steven, 1949). The Eureka Tunnel is in the northernmost part of the St. Peters Dome fluorspar district along the southern boundary of the Manitou Springs quadrangle (Fig. 9).

LIMESTONE

Finley (1916) reported that the Manitou Limestone (Ordovician) was mined at a site above Williams Canyon and used for making lime and for processing sugar beets. Although the Manitou Limestone is no longer mined for these purposes in this area, it is mined in large quantities for use as crushed rock aggregate at several places in the Cascade quadrangle to the north (Morgan and others, 2003). The Snyder Quarry is an active limestone mining operation that lies along the boundary between the Cascade quadrangle and the Manitou Springs quadrangle in sec. 32, T. 13 S., R. 67 W.

GYPSUM

Gypsum was mined in an area once known as "Gypsum Canyon" during the 1860s (Red Rock Canyon Committee, 2003). This is an area that was used as a landfill in the 1970s and 1980s in sec. 10, T.14 S., R.67 W. southeast of Manitou Springs. The landfill has been reclaimed, and no evidence of the former gypsum mine remains visible. The gypsum is present in the Upper Jurassic Ralston Creek Formation (Jmr).

SPECIMEN MINERALS AND GEMS

Pegmatites in the rocks of the Pikes Peak batholith offer some of the best mineral collecting opportunities in Colorado. Two areas in the Manitou Springs quadrangle are well-known to collectors around the world: the St. Peters Dome area in the southern part of the quadrangle near Gold Camp Road, and Crystal Park southwest of the town of Manitou Springs.

The St. Peters Dome area is one of the outstanding mineral localities in the world, especially known for producing gem-quality zircon crystals (Pearl, 1972). There is an abundance of other minerals also, some that are rare and others that are not rare but are of good quality. Along with purple, green, and white fluorite, unusual fluorine- and rare-earth-element-bearing minerals such as cryolite, weberite, bastnasite, elpasolite (type locality), pachnolite, fluocerite, and gearksutite are present. Additional minerals found in the pegmatites include black to deep blue riebeckite crystals up to 15 in. long, astrophyllite, pyrochlore, xenotime, thorite, columbite, monazite, lanthanite, and several types of sulfides. This was the first known locality for astrophyllite in the U.S. (Pearl, 1972). Bladed bronze crystals of astrophyllite up to 6 in. long have been found, associated with riebeckite and zircon in the pegmatites (Eckel, 1997). The predominant rock-forming minerals of these complex pegmatites are microcline perthite, quartz, and oligoclase. The pegmatites of the St. Peters Dome area are spatially and probably genetically related to the sodic, riebeckite-bearing Mt. Rosa granite (Ymr).

Some amazonite, smoky quartz, and topaz has been found in the St. Peters Dome and Stove Mountain areas as well, but these minerals are present in cavities in pegmatites within the Pikes Peak Granite (Ypp) rather than in the fluorine- and rare-earth-element-bearing pegmatites associated with the Mt. Rosa granite (Ymr).

The Crystal Park area near Manitou Springs is one of Colorado's oldest and best-known mineral collecting areas (Pearl, 1972). The area has produced fine specimens of amazonite, smoky quartz, topaz, and phenakite. These minerals are found in miarolitic cavities in pegmatites within the Pikes Peak Granite (Eckel, 1997). The pegmatites are chiefly composed of quartz, feldspar, and mica. The miarolitic cavities are up to 3 ft wide (Pearl, 1972). Cameron Cone, just west of Crystal Park, has also produced many good specimens of amazonite, smoky quartz, topaz, and phenakite. Sentinal Rock and Specimen Rock (Fig. 9; Tenney Crags area on map sheet) are about 1.7 mi south of Crystal Park and are known collecting localities for smoky quartz, amazonite, fluorite, and bladed hematite crystals (Voynick, 1994).

OIL AND GAS RESOURCE POTENTIAL

No oil and gas exploratory wells have been drilled in the quadrangle, and the nearest hydrocarbon production is located 24 mi to the south in the Florence field of Fremont County. There is a low probability for a hydrocarbon play in El Paso County where the Cretaceous Muddy J and D sandstones of the Dakota Formation merge, and also where fractured calcareous Niobrara Formation shales are located along a narrow zone paralleling the Front Range (Keller and others, 2003). The low probability is due to the limited availability of hydrocarbon source rocks and traps in the area. Wells drilled in the 1930s encountered shows of natural gas in sandstone and fractured shale adjacent to the Front Range southeast of the Manitou Springs quadrangle. The price of gas was low, therefore making it uneconomic to build pipelines. Developing and drilling a prospect adjacent to the Front Range in El Paso County today is problematic because of urbanization and the presence of the Fort Carson Military Reservation and the U.S. Air Force Academy.

GEOLOGIC HAZARDS

Many types of geologic hazards, such as landslides, debris flows, swelling soils and rockfall, are present in the Manitou Springs quadrangle. Landslides and swelling soils are the most common and most costly hazards in the eastern urbanized area, potentially accounting for millions of dollars in property loss and damage (Noe and others, 1997; Himmelreich and Noe, 1999; Himmelreich, 1996; and City of Colorado Springs Office of Emergency Management Homepage, 2003). Not surprisingly, they are also the most-studied geologic hazards in the area, primarily due to their effects on urban development. However, other less well-known hazards such as rockfall, debris flows, erosion and siltation, radon gas, earthquakes, and hydrocompactive soils are also present in much of the quadrangle. Other geologic hazards/constraints that are present such as corrosive soils, settlement, high groundwater, springs, and flooding are not discussed.

Bedrock structure, hydrogeology, topography, surface drainage, and lithology are very important controls on the development of geologically hazardous areas in the mapped area. Along the eastern margin of the quadrangle, these five factors combine to produce a complex geologic environment where geologic hazards are prevalent. Some of the rock types, in particular the Cretaceous bedrock formations and Glen Eyrie Shale, are weak and prone to landslides, swelling soils, and heaving bedrock (Himmelreich and Noe, 1999; White and Wait, 2003).

LANDSLIDES

Several landslides are located on the eastern part of the quadrangle, mostly associated with incompetent sedimentary rocks. Historically, property damage from landslides has occurred along the eastern margin of the Front Range (Hansen, 1973) and in the Colorado Springs area (Johnson and Himmelreich, 1998). Beginning in the mid-1960s, property damage from landslides was documented in various areas in or near Colorado Springs (Himmelreich, 2003). In 1999, after severe storms and heavy spring flooding reactivated old landslides and triggered several new ones, the area received a presidential disaster area designation. During the same year, the City of Colorado Springs estimated 75 million dollars in property damage and mitigation costs due to landslides (City of Colorado Springs Office of Emergency Management Homepage, 2003). The Federal Emergency Management Agency (FEMA) designated funds to buy-out distressed properties damaged by the 1999 landslides. This program has spent nearly 6 million dollars on property loss and damage as of 2002 (White and Wait, 2003).

The most significant landslide deposit occurs in the Cedar Heights neighborhood, west of Garden of the Gods Park (secs. 32 and 33, T. 13 S., R. 67 W) where the Glen Eyrie Shale member of the Fountain Formation is responsible for several old and active landslides. Some of the landslides are very recent, exhibiting clear signs of active movement such as deposition of material on sidewalks and roadways and disruption of curbs, driveways, and foundations. Translational landslides, like those in the Cedar Heights area, form where jointed and fractured, east-dipping Fountain Formation beds are undercut by the downward erosion of Black Canyon and its tributaries (Himmelreich and others, 1980; Myers, 1981; White and Wait, 2003). Some of the recent landslides are cut-slope and fill-slope failures.

Smaller, non-damaging and less active landslides occur in isolated areas of the quadrangle. In sections 15 and 16, T. 14 S., R. 67 W., a landslide caused by failure in Morrison Formation dislodged and transported large blocks of Dakota Sandstone, some larger than 5 ft in diameter. This landslide could potentially be hazardous, since the upper parts of the slopes are hummocky, poorly vegetated, and dissected by an intermittent network of drainages. However, no signs of damage to the road near the toe of the landslide were observed. Two small, inactive landslides occur in section 32, T. 13 S., R. 67 W in the Glen Eyrie Shale Member of the Fountain Formation. In section 3, T. 15 S., R. 68 W., a previously mapped deposit of glacial till was remapped as a landslide on the basis of hummocky topography, large angular boulders, and lack of other glacial deposits or landforms in this area. The landslide occurs in granite of Almagre Mountain (Yam), probably through failure along a system of joints caused by freeze-thaw action or hydrostatic pressure.

DEBRIS FLOWS

Debris flows are heterogeneous mixtures of mud, rock fragments, and plant material that commonly occur in the lower parts of tributary streams where they enter a major valley (Rogers and others, 1974). As a debris flow moves down valley, non-consolidated surficial material is incorporated into the flow until the suspended sediment is no longer confined and is released as a fan-shaped deposit at the mouth of the tributary stream. Debris flows are the result of torrential rainfall or very rapid snowmelt runoff where sediment supply is abundant and easily mobilized (Selby, 1993). Such conditions may exist in areas mapped as alluvial fan (Qf), colluvium and sheetwash (Qcs), landslide (Qls), or areas where crystalline bedrock units are weathered to grüs.

ROCKFALL

Rockfall deposits are grouped into the colluvium and sheetwash deposits (Qcs) or talus deposits (Qta). Although rockfall deposits were not very extensive or of great thickness east of the Ute Pass fault zone, they represent a significant hazard in the map area where hogbacks are located near urban development. The Dakota Sandstone is densely jointed at some locations, forming large boulders locally exceeding 8 ft in diameter. Some boulders appear to have spalled sporadically while others have come down as debris avalanches, probably during times of high precipitation and runoff. Sections of U.S. Highway 24, where Fountain Creek passes through Proterozoic and Paleozoic rocks and forms steep-walled cliffs, are in an area of significant rockfall hazard. These slopes are very steep, contain loose rock material, and are adjacent to a major highway. As a result they are highly rated as hazards in the Colorado Department of Transportation Rockfall Rating System (J. White, personal comm.). Very large granite boulders, some exceeding 15 ft in diameter, are found along the highway with smaller boulders, cobbles, and fan deposits. Rockfall hazards can also occur from weathered exposure of granitic rocks that are exposed on the steep slopes around Almagre Mountain.

EARTHQUAKES

Minor seismic activity has been recorded near Colorado Springs, possibly occurring from movement along the Rampart Range or Ute Pass fault zones. In April of 1991, MicroGeophysics Corporation (1991) located an earthquake swarm with magnitudes 2.6 to 2.8 on the south end of the Rampart Range fault zone. A magnitude 3.6 earthquake occurred near Manitou Springs on December 25, 1995 (U.S. Geological Survey, 2002). Epicentral coordinates in the National Earthquake Information Center (NEIC) database suggest a location near the east flank of the Rampart Range about 21 mi north of Manitou Springs. The December 25 earthquake was felt at intensity IV at Victor, Cripple Creek, and Manitou Springs (Kirkham and Rogers, 2000). Additional information on faulting and earthquakes in this area can be found in the Colorado Late Cenozoic Fault and Fold Database and Internet Map Server (Widmann and others, 2002), available on-line at http://geosurvey.state.co.us/pubs/ceno/. Widmann and others (1998) present a database of faults and folds that were potentially active in Quaternary time.

The Rampart Range and Ute Pass fault zones are considered to be potentially active by the Colorado Geological Survey. This area, like most of central Colorado, is subject to a degree of seismic risk. The Colorado Geological Survey considers this area of Colorado to be in Seismic Risk Zone 2 (Kirkham and Rogers, 1981). If a significant and damaging seismic event should occur, it may trigger slope failures. Seismic forces should be considered in the analysis and design of essential facilities and critical slopes (Essigmann and Himmelreich, 1986; Himmelreich and Hoffmann, 1997a and 1997b).

SWELLING SOILS AND HEAVING BEDROCK

Expansive or swelling soils and heaving bedrock are among the most costly geologic hazards along the Front Range Urban Corridor, accounting for tens of millions of dollars in damage and maintenance and repair costs (Noe, 1997). The swelling in surficial materials is caused by the expansion of clay minerals from wetting. The expansive minerals are commonly derived from layers of bentonitic clay found in the Pierre Shale and other Cretaceous bedrock units. Heaving bedrock occurs where in situ claystone layers with much higher expansive clay content within upturned bedrock are found at shallow depth below the ground surface. When wetted, these clay layers may heave at markedly different rates over small lateral distances. Differential ground movements can cause significant and damaging deformation to houses, roads, sidewalks, and other constructions (Noe, 1997).

In the Manitou Springs quadrangle, areas along the mountain front where the Pierre Shale and other Cretaceous formations are upturned, and where soils are derived from these units, are most susceptible to damage caused by expansive clays; these areas are mostly within the city limits of Colorado Springs. Past studies of potentially swelling soils along the Front Range Urban Corridor (Hart, 1974) and heaving bedrock (Himmelreich and Noe, 1999) place a moderate to high potential for expansive clays along the eastern margin of the Manitou Springs quadrangle. Areas particularly susceptible are east of the Ute Pass fault, north of Bear Creek Regional Park where the Pierre Shale is near vertical to overturned. The surficial soils in this area, derived from these claystone formations, may also be susceptible to swelling. Proper engineering practices with a focus on expansive clays should be used for construction in these areas.

HYDROCOMPACTIVE SOILS

Soils that are susceptible to hydrocompaction (settlement or collapse due to the addition of water) may exist in areas mapped as alluvial fan (Qf) and colluvium and sheetwash (Qcs). Particularly susceptible are the soils derived from the Colorado Group (Niobrara, Carlile, and Greenhorn) and the Fountain Formation. Soils derived from the Glen Eyrie Shale Member of the Fountain Formation in the Cedar Heights subdivision showed 3 to 4 percent compaction rate, significant enough to cause minor damage (J. White, personal comm.).

CARBONATE KARST

Solution features and clay alteration in the Paleozoic carbonates (Om, MDlh) range from narrow openings along joints to extensive solution caves. A large feature is the Cave of the Winds, a tourist attraction situated in the Manitou Limestone, which forms the west wall of Williams Canyon. Sites of solution are prone to collapse and block fall. High permeability of bedrock allows penetration of surface waters derived from snow melt or torrential summer rains; these can rapidly mobilize the alteration clays that accumulate in the solution caves, according to anecdotal observations from Cave of the Winds staff. Luiszer (1999) investigated the paleohydrology of the karst systems surrounding Cave of the Winds at the interface between cells of geothermal fluid circulation along fault systems and meteoric waters associated with the paleo-Fountain Creek drainage.

RADIOACTIVITY

Minor occurrences of radioactive minerals have been reported from the Manitou Springs quadrangle in the form of uranium and thorium in rocks of the Pikes Peak batholith (Nelson-Moore, 1978). Radon gas is a hazard from long-term exposure to high levels. This is a potential problem in buildings if they are not well ventilated. The Pikes Peak Granite, and Quaternary deposits derived from it, typically generate ‘above average’ levels of radon gas (Smith and others, 1987). There also appears to be a zone of low-grade uranium occurrence at the base of the Glen Eyrie Shale (Himmelreich and Essigmann, 1996). The potential for radon gas accumulation should be addressed in building design and construction.

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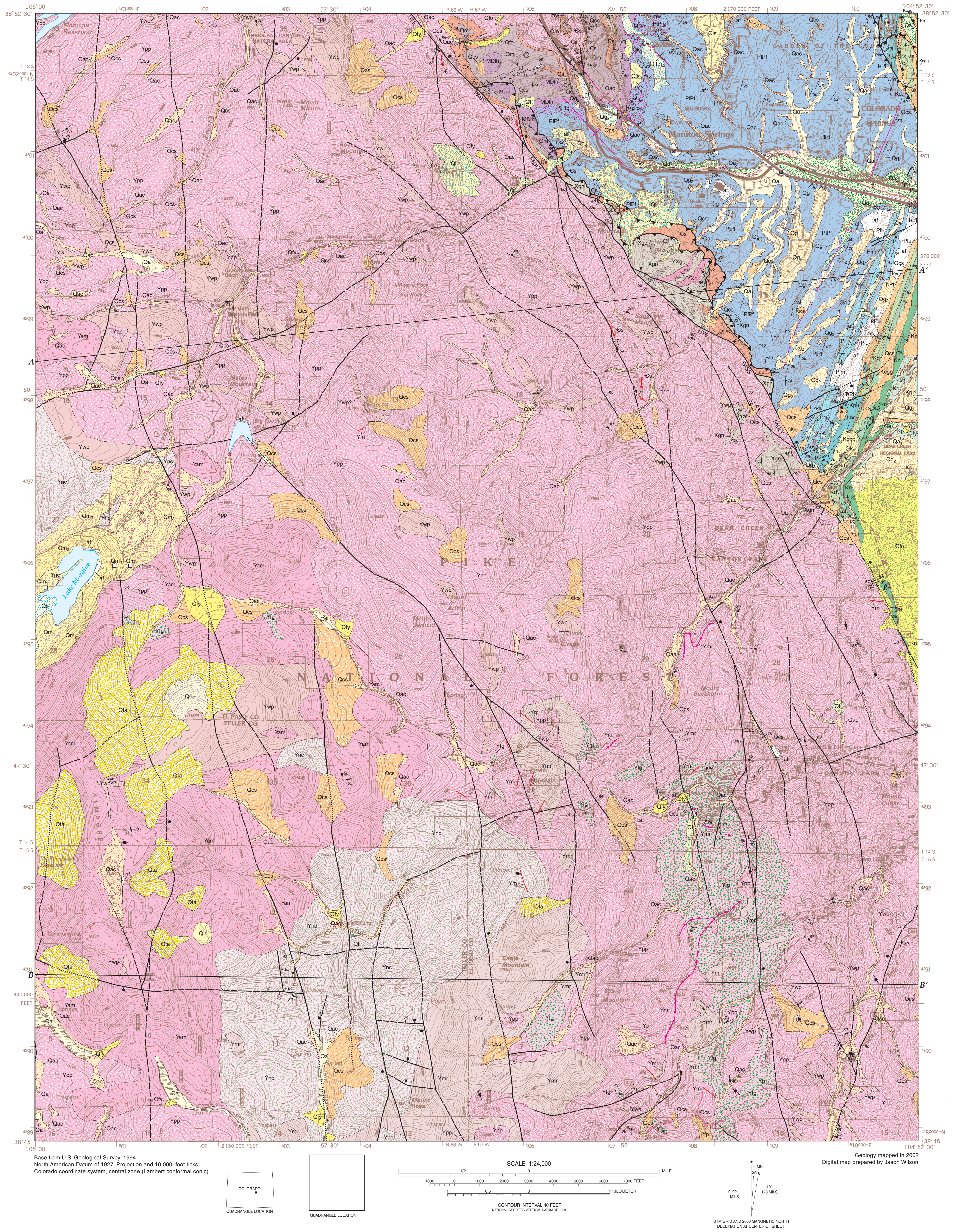
COLORADO GEOLOGICAL SURVEY
DIVISION OF MINERALS AND GEOLOGY
DEPARTMENT OF NATURAL RESOURCES
DENVER, COLORADO

OPEN-FILE MAP 03-19
GEOLOGIC MAP OF THE MANITOU SPRINGS QUADRANGLE,
EL PASO AND TELLER COUNTIES, COLORADO
Booklet accompanies map



Base from U.S. Geological Survey, 1994
North American Datum of 1927. Projection and 10,000–foot ticks:
Colorado coordinate system, central zone (Lambert conformal conic)

Geology mapped in 2002
Digital map prepared by Jason Wilson

MAP UNITS

The complete description of map units and references are in the accompanying booklet.

SURFICIAL DEPOSITS

HUMAN–MADE DEPOSITS

af	**Artificial fill (latest Holocene)**
mw	**Mine waste (latest Holocene)**

ALLUVIAL DEPOSITS

Qa	**Stream-channel, flood-plain, and terrace alluvium, undivided (Holocene to late Pleistocene)**
Qa_1	**Alluvium one (late Holocene)**
Qa_2	**Alluvium two (late to early Holocene)**
Qg_1	**Pediment gravel one (middle Pleistocene)**
Qg_2	**Pediment gravel two (middle Pleistocene)**
Qg_3	**Pediment gravel three (middle? to early Pleistocene)**
QTg_4	**Pediment gravel four (early Pleistocene to late Pliocene)**

ALLUVIAL AND COLLUVIAL DEPOSITS

Qac	**Alluvium and colluvium, undivided (Holocene to late Pleistocene)**
Qcs	**Colluvium and sheetwash deposits, undivided (Holocene to late Pleistocene)**
Qf	**Fan deposits (Holocene to late Pleistocene)**
Qfy	**Young fan deposits (Holocene)**
Qfo	**Old fan deposits (late to middle? Pleistocene)**

MASS–WASTING DEPOSITS

Qta	**Talus deposits (Holocene to late Pleistocene)**
Qls	**Landslide deposits (Holocene to late Pleistocene)**

PALUSTRINE DEPOSITS

Qp	**Paludal sediments (Holocene to late Pleistocene)**

PERIGLACIAL DEPOSITS

Qb	**Block-slope deposits (Holocene to late Plesitocene)**

GLACIAL DEPOSITS

Qo	**Outwash (late Pleistocene)**
Qm_1	**Morainal deposit one (late Pleistocene)**
Qm_2	**Morainal deposit two (late Pleistocene)**
Qm_3	**Morainal deposit three (late middle Pleistocene)**

BEDROCK

MESOZOIC ROCKS

Kp	**Pierre Shale (Upper Cretaceous)**
Kn	**Niobrara Formation, (Upper Cretaceous)**
Kcgg	**Graneros Shale, Greenhorn Limestone, and Carlile Shale, undivided (Upper Cretaceous)**
Kd	**Dakota Sandstone (Lower Cretaceous)**
Kpu	**Purgatoire Formation (Lower Cretaceous)**
Jmr	**Morrison Formation and Ralston Creek Formation, undivided (Upper Jurassic)**
TRPl	**Lykins Formation (Lower Triassic? and Upper Permian)**

PALEOZOIC ROCKS

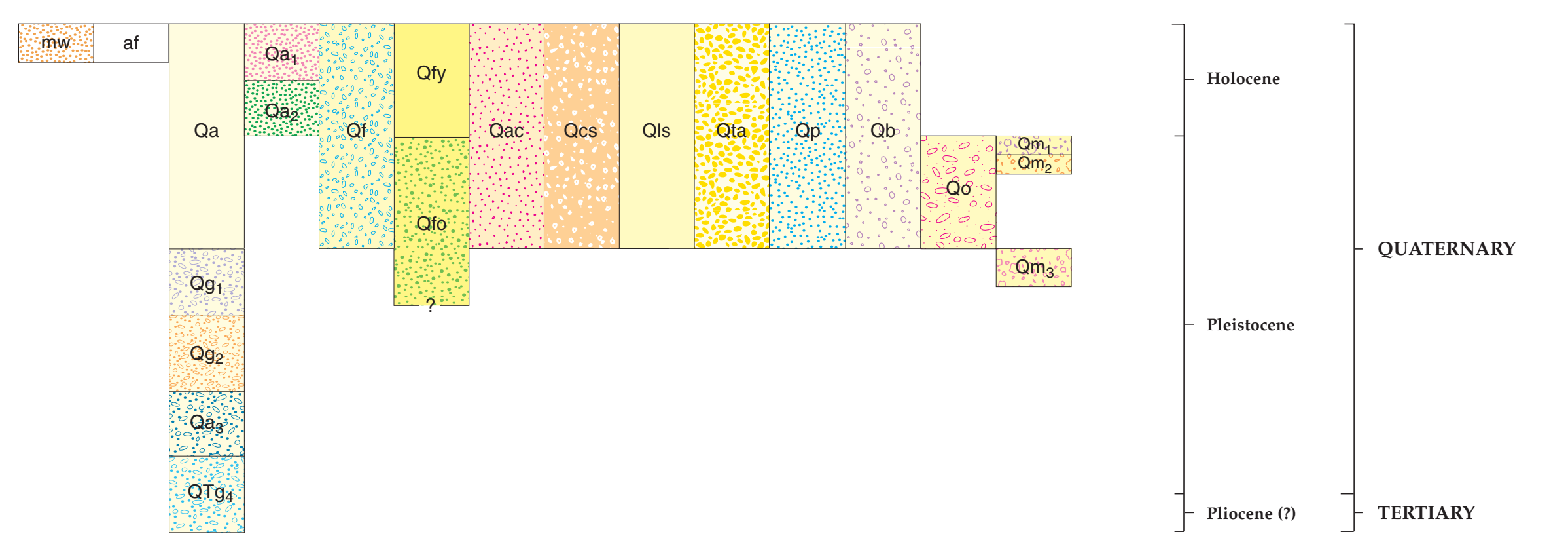
	Lyons Sandstone (Permian)
Plu	**upper unit**
Plm	**middle unit**
Pll	**lower unit**
PℙPf	**Fountain Formation (Lower Permian and Pennsylvanian)**
PℙPfg	**Glen Eyrie Member of the Fountain Formation (Lower Pennsylvanian)**
MDlh	**Hardscrabble Limestone Member of the Leadville Limestone (Mississippian) and Williams Canyon Formation (Devonian), undifferentiated**
Om	**Manitou Limestone (Lower Ordovician)**
Ꞓs	**Sawatch Sandstone (Upper Cambrian)**

PROTEROZOIC ROCKS

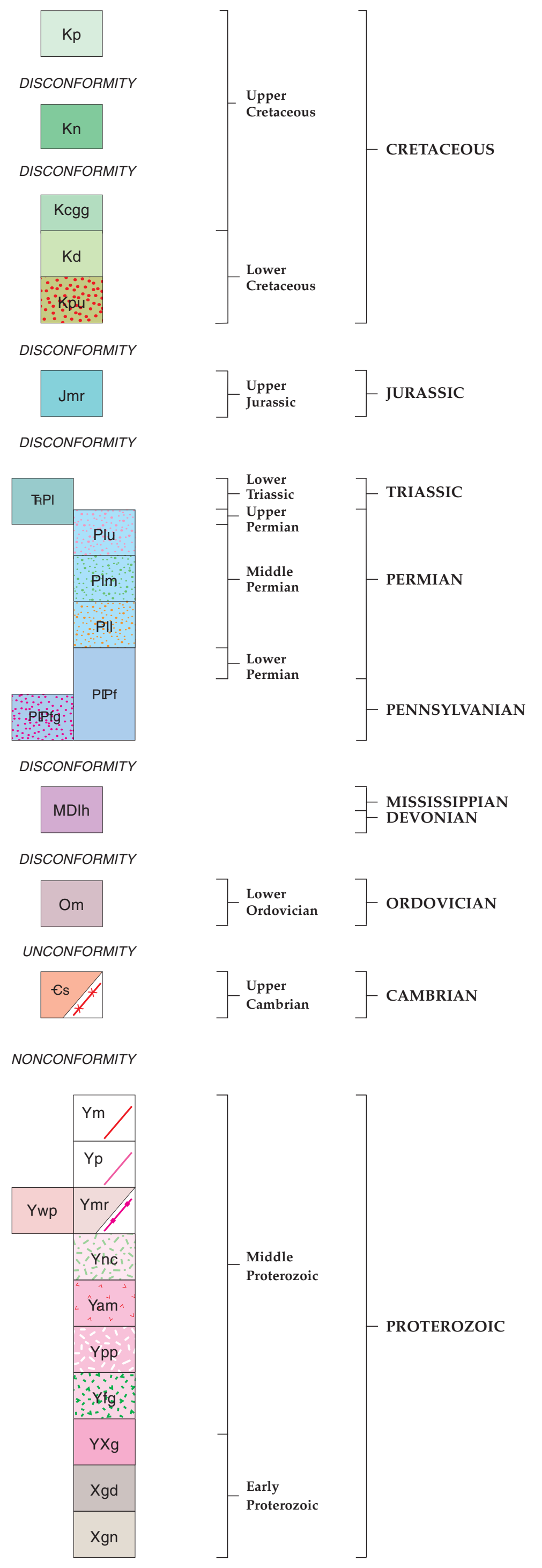
Ym	**Mafic dikes (Middle Proterozoic)**
Yp	**Pegmatite (Middle Proterozoic)**
Ymr	**Mount Rosa granite (Middle Proterozoic)**
Ywp	**Windy Point granite (Middle Proterozoic)**
Ync	**Granite of Nelson Camp (Middle Proterozoic)**
Yam	**Granite of Almagre Mountain (Middle Proterozoic)**
Ypp	**Pikes Peak Granite (Middle Proterozoic)**
Yfg	**Fayalite granite (Middle Proterozoic)**
YXg	**Granite (Early or Middle (?) Proterozoic)**
Xgd	**Granodiorite (Early Proterozoic)**
Xgn	**Migmatitic gneiss (Early Proterozoic)**

CORRELATION OF MAP UNITS

SURFICIAL DEPOSITS



BEDROCK



MAP SYMBOLS

Contact—Dashed where approximately located

Fault—Dashed where approximately located, dotted where concealed by younger deposits. Ball and bar on the actual or apparent downthrown side. Arrow shows trend and plunge of slickenside striae. Opposing arrows show relative strike-slip movement

Thrust fault—Dashed where approximately located, dotted where concealed

Anticline—Trace of axial plane

Monocline—Trace of axial plane

Syncline—Trace of axial plane

Shear zone

Strike and dip of bedding

- **Inclined—**Angle of dip shown in degrees; inclination and direction may be added to the trace of dikes
- **Overturned**

Strike and dip of foliation in metamorphic rocks

- **Inclined—**Angle of dip shown in degrees

Strike and dip of fractures or joints

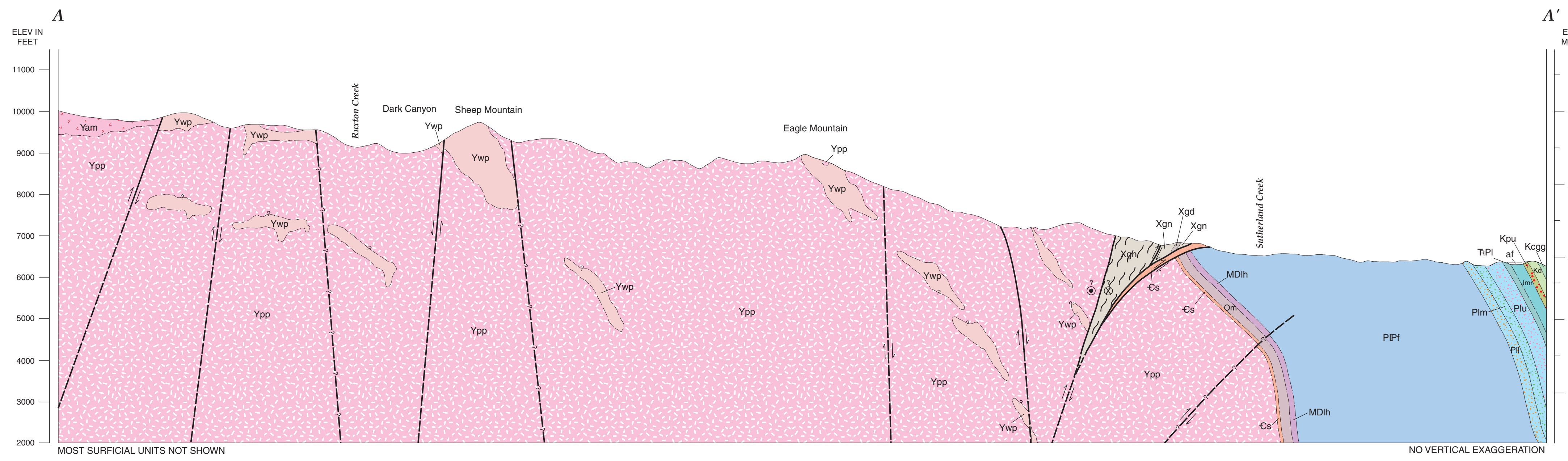
- **Inclined—**Angle of dip shown in degrees
- **Vertical**
- **Shear fracture—**Arrow shows trend and plunge of slickenside striae

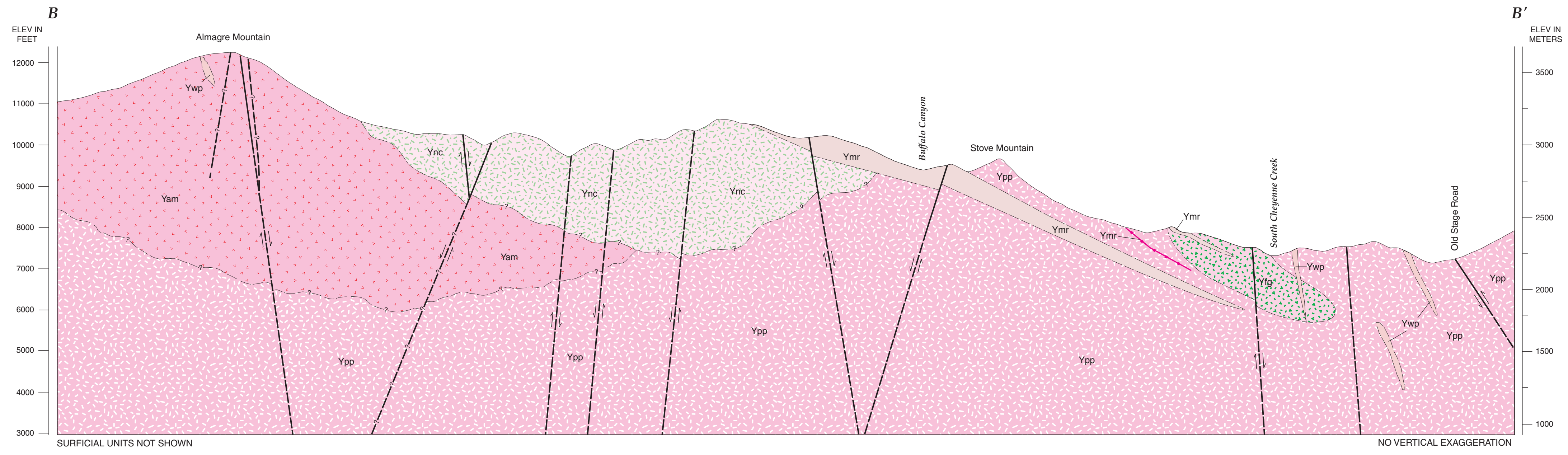
Karst feature

Soil profile location

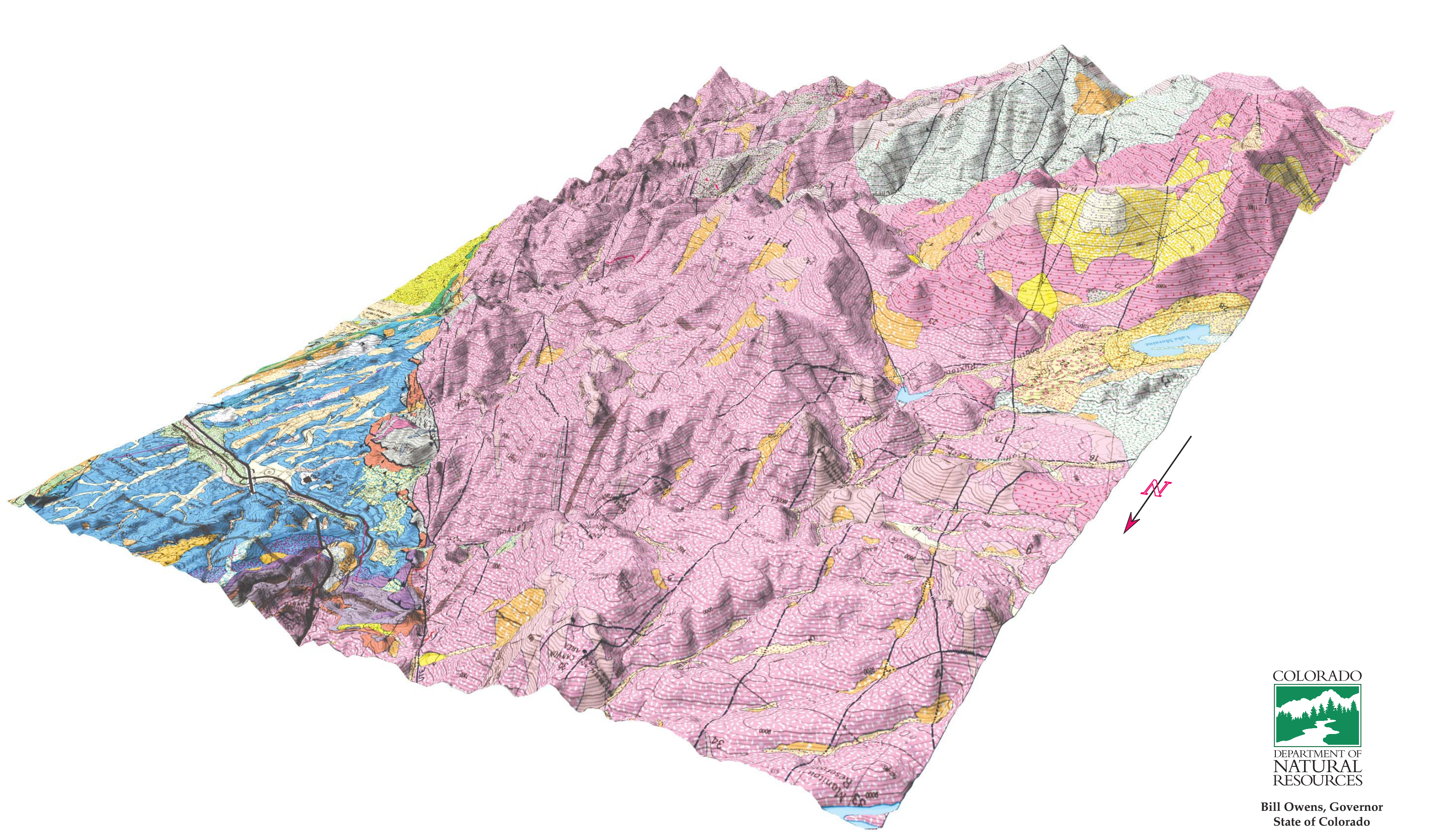
Relative movement of blocks on either side of fault with strike–slip component. "⊗" signifies 'away', "⊙" signifies 'towards'. Shown only in Cross Section A–A'

A——A' **Alignment of cross sections**





SHADED RELIEF MAP OF THE MANITOU SPRINGS QUADRANGLE WITH GEOLOGY OVERLAY; OBLIQUE VIEW LOOKING SOUTH–SOUTHEAST



Bill Owens, Governor
State of Colorado

Russell George, Executive Director,
Department of Natural Resources

Ronald W. Cattany, Director,
Division of Minerals and Geology

Vince Matthews, State Geologist
Colorado Geological Survey

GEOLOGIC MAP OF THE MANITOU SPRINGS QUADRANGLE, EL PASO AND TELLER COUNTIES, COLORADO

By John W. Keller, Christine Siddoway, Matthew L. Morgan, Erik E. Route,
Matthew T. Grizzell, Raffaello Sacerdoti, and Adair Stevenson

2003