OPEN-FILE REPORT 07-01

Geologic Map of the Olathe Quadrangle, Montrose County, Colorado

Bill Ritter Jr., Governor
State of Colorado

COLORADO
DEPARTMENT OF NATURAL RESOURCES

Harris D. Sherman, Executive Director
Department of Natural Resources

COLORADO GEOLOGICAL SURVEY

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by

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

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View from the northeastern corner of the Olathe quadrangle looking south over the Gunnison Gorge National Conservation Area. The grey to buff-colored Mancos Shale forms the badland topography visible in the foreground, and the reddish-brown Dakota Sandstone is visible in the upper left corner of the image. The San Juan Mountains are visible in the distance at left and the Uncompahgre Plateau is visible in the distance at right.

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

Bill Ritter Jr., Governor, State of Colorado
Harris D. Sherman, Executive Director, Department of Natural Resources
Vincent Matthews, State Geologist and Division Director, Colorado Geological Survey
Denver, Colorado
2007

FOREWORD

The purpose of Colorado Geological Survey Open File Report 07-01, *Geologic Map of the Olathe Quadrangle, Montrose County, Colorado* is to describe the geologic setting, mineral and ground-water resources, and geologic hazards of this 7.5-minute quadrangle located north of the City of Montrose in western Colorado. Staff geologists Matthew L. Morgan and David C. Noe, and summer volunteer geologist Stephen M. Keller, completed the field work on this project during the spring of 2006. Matt Morgan was the principal mapper and author of this report and utilized the maps and field notes generated by all three investigators. Some unit descriptions were coordinated between this area and the Montrose East quadrangle (Noe and others, 2007).

This mapping project was funded jointly by the U.S. Geological Survey through the STATEMAP component of the National Cooperative Geologic Mapping Program, which is authorized by the National Geologic Mapping Act of 1997 (award number 06HQAG0045) 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.

Vince Matthews
State Geologist and Division Director
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INTRODUCTION

The Olathe 7.5-minute quadrangle is located in Montrose County, Colorado, between the Uncompahgre and Gunnison uplifts (figures 1 and 3). The Town of Olathe (2000 CENSUS population of 1,573) is located in the northwest part of the quadrangle along State Highway 50. The Uncompahgre River runs through the western half of the quadrangle and flows northward to join the Colorado River near Grand Junction. The highest area in the quadrangle is a ridge of Dakota Sandstone in the eastern half of sec. 9 of T. 50 N., R. 9 W. (elevation 6,143 feet), and the lowest point is in the Uncompahgre River valley bottom (elevation 5,277 feet) in the northwestern part of the quadrangle.

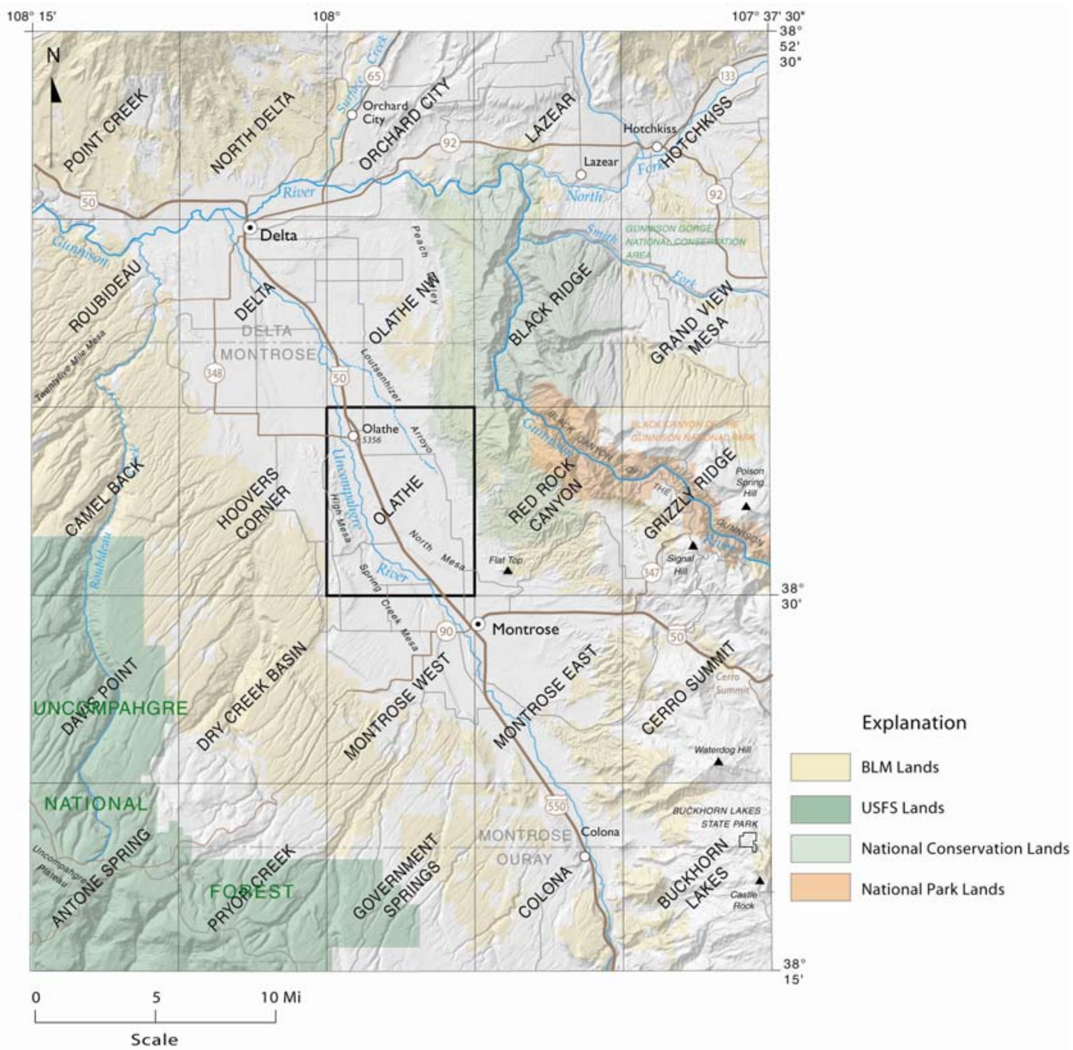


Figure 1. Location of the Olathe quadrangle (bold black outline) in relation to major geographic features.

Geologic mapping of the Olathe 7.5-minute quadrangle was undertaken by the Colorado Geological Survey (CGS) as part of the STATEMAP component of the National Cooperative Geologic Mapping Act, which is administered by the U.S. Geological Survey (USGS). Geologic maps produced by the CGS through the STATEMAP program are intended as multi-purpose maps useful for land-use planning, geotechnical engineering, geologic hazards assessment, mineral resource development, and ground-water exploration. Figure 2 shows the status of geologic maps of 7.5-minute quadrangles in the Montrose-Olathe area, including eight older maps that have been published by the USGS.

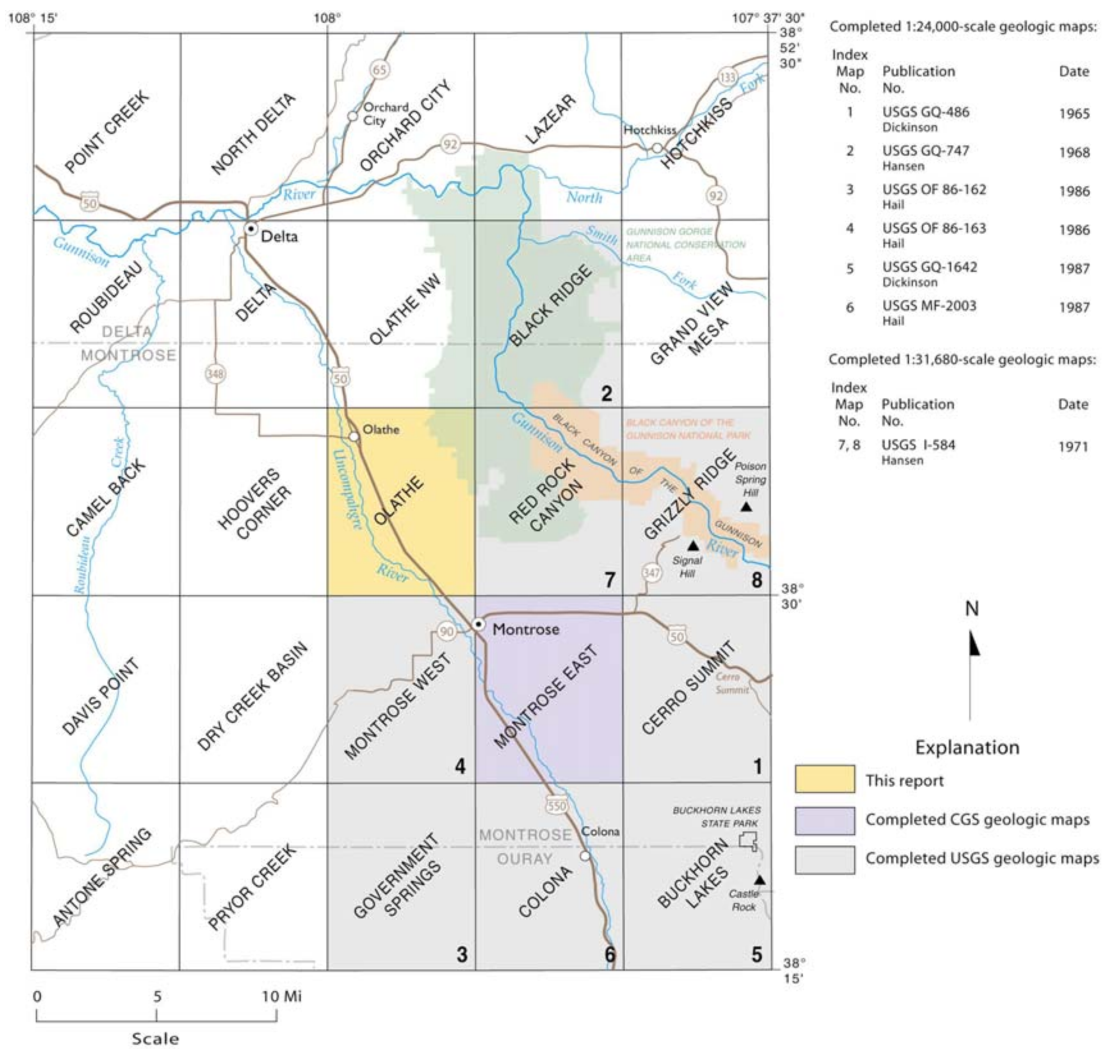


Figure 2. Index of published 1:24,000-scale geologic maps near Olathe and Montrose.

The geologic interpretations shown on the Olathe quadrangle are based on (1) CGS field investigations in April through June of 2006; (2) prior published and unpublished geologic maps and reports; (3) interpretation of black and white 1:20,000-scale Agricultural Stabilization and Conservation Service (ASCS) aerial photography flown in 1966, a 10-meter digital elevation model (DEM), a 1-meter DEM of the Peach Valley National Conservation area, and a 1-meter resolution National Agricultural Imagery Program (NAIP) digital orthophoto taken in 2005. Bedrock geology and surficial deposits were mapped in the field on aerial photographs. The photographs were scanned, georeferenced, and imported into Leica Photogrammetry Suite, where they were photogrammetrically corrected and rendered in 3D. Line work was traced directly from the scanned field photos using ERDAS Imagine Stereo Analyst for ArcView and exported as ESRI shapefiles. Universal Transverse Mercator (UTM; North American Datum 1983, Zone 13, meters) coordinates are provided for key geologic areas and photographs.

Previous Work

The Olathe quadrangle has not previously been mapped at 1:24,000-scale. Small-scale geologic mapping of the Olathe quadrangle and surrounding area was done by Tweto and others (1976) at a scale of 1:250,000. Sinnock (1978) mapped the geomorphology and landforms of the quadrangle as part of a larger, regional dissertation study, at a scale of 1:84,210. Meeks (1950) investigated the hydrogeology of surficial and bedrock units along the Uncompahgre River valley and its margins. A small portion of the eastern margin of the Olathe quadrangle that lies within the Gunnison Gorge National Conservation Area was mapped by Kellogg and others (2004) at 1:45,000-scale. Hansen (1971) mapped the Black Canyon of the Gunnison area west of the Olathe quadrangle at a scale of 1:31,680. The Black Ridge quadrangle, which lies to the northeast of the Olathe quadrangle, was mapped by Dickinson (1965). The Montrose West quadrangle, located south of the Olathe quadrangle, was mapped in reconnaissance fashion by Hail (1986). The Montrose East quadrangle (Noe and others, 2007), which lies to the southeast of the Olathe quadrangle, was mapped by CGS concurrently with this report.

Geologic Setting

A map showing major, named physiographic, geomorphic, and geologic features in the Olathe quadrangle is shown in figure 3. Few named features appear on the USGS topographic base maps. To aid in the discussions herein, we have applied informal names to designate areas or features of specific interest. These names reflect local usage where possible and are signified by quotation marks in the text.

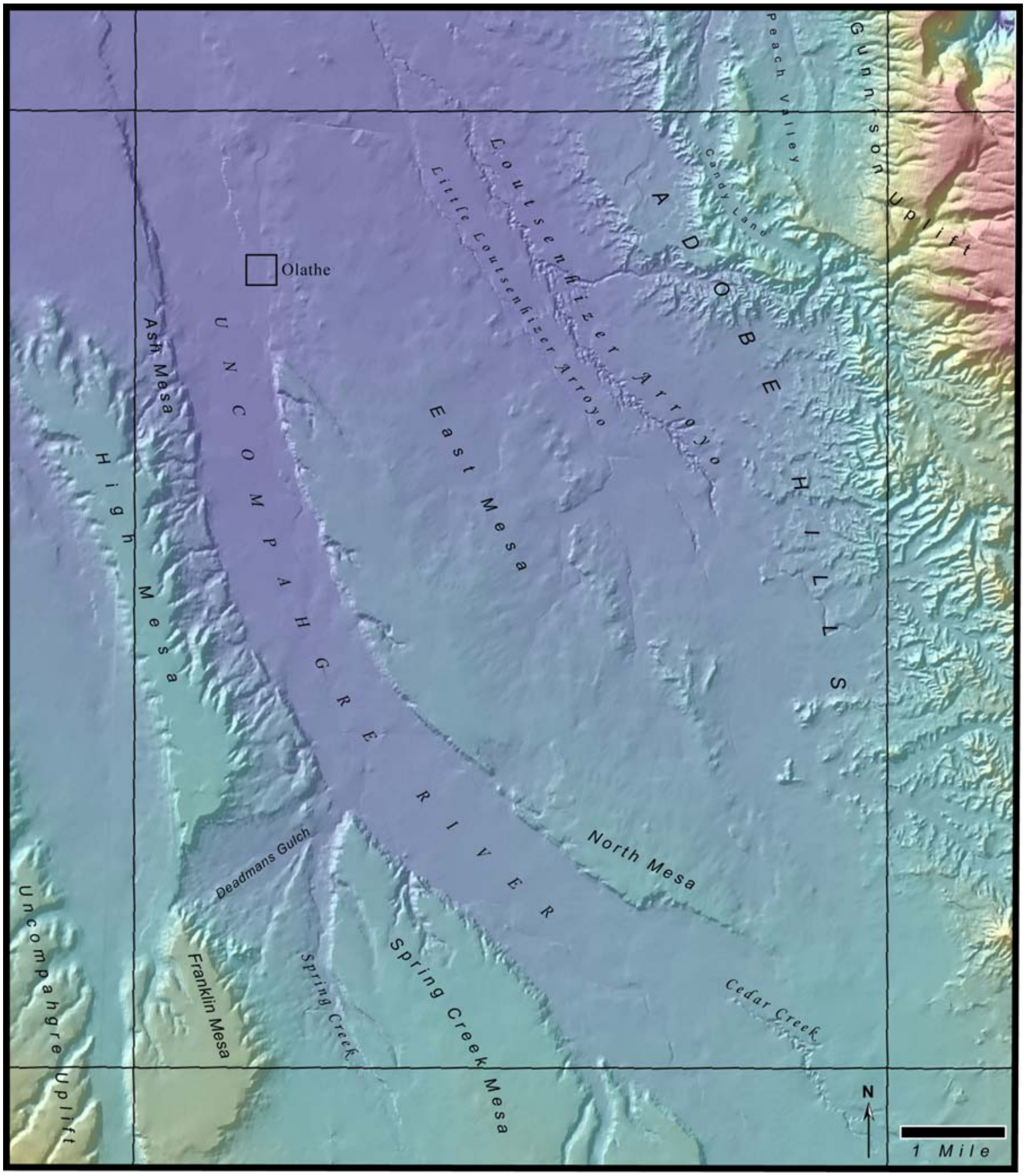


Figure 3. Hillshaded DEM of the Olathe quadrangle and surrounding region showing the location of major physiographic, geomorphic, and geologic features discussed in this text.

The Olathe quadrangle lies within the Canyonlands section of the Colorado Plateau physiographic province, an area characterized by deep canyons and monoclinal folds (Foos, 2006; Hunt, 1956). The Gunnison and Uncompahgre uplifts, which trend through the northeastern and western edges of the mapped area, respectively, are the result of vertical movement of basement blocks during the Laramide Orogeny. This movement has deformed the overlying Mesozoic rocks into gently to steeply dipping, monoclinal folds that are best exposed near Peach Valley and “Candy Lane.”

The bedrock exposed in the quadrangle records the transition from marginal marine to predominantly marine conditions during Early to Late Cretaceous time. The Mancos Shale and its various subunits were deposited within the epicontinental, Western Interior Seaway and represent muddy shallow-shelf deposits derived from deltas and shorelines that existed further to the west, in Utah (Armstrong, 1968; McGookey and others, 1972; Johnson, 2003). Within the Olathe quadrangle, the Mancos Shale typically forms badlands-style topography — the result of water and wind eroding the soft shale and carving it into gentle hills and valleys. This style of erosion is best observed in the “Adobe Hills” area on the eastern half of the quadrangle.

Several levels of Quaternary alluvial gravel deposits are found in the mapped area. Some were deposited by the modern and ancestral Uncompahgre River as it migrated over the landscape, and others originated as mud-rich debris flows derived primarily from erosion of the Mancos Shale. Due to topographic inversion, the former channels now form broad terraces and/or ridge-capping boulder-gravel veneers underlain by Mancos Shale. The topographic inversion arises from long-term incision by the Uncompahgre and Gunnison Rivers and their tributaries that commenced during the late Miocene, approximately 10 million years ago.

Three distinct levels of gravel exist along Peach Valley and “Candy Lane”; the clast compositions in these deposits are volcanic tuff, metamorphic and igneous clasts from the San Juan Mountains and Gunnison uplift, and Dakota Sandstone. Each level represents a period of aggradation and downcutting of an ancient tributary stream channel that flowed northward to the Gunnison River. This stream was captured by tributary streams during the middle to late Pleistocene, abandoning both Peach Valley and “Candy Lane”.

The Uncompahgre River, which runs through the western part of the mapped area, has five major geomorphic surfaces associated with it and continues to flow northward to the Colorado River near Grand Junction. Prominent gravel-capped mesas are the remnants of former flood plains. On the basis of terrace heights and soil characteristics, from oldest and highest to youngest and lowest these terraces and flood plains are Franklin Mesa, High Mesa, Spring Creek Mesa, North Mesa (correlative with Spring Creek Mesa), East Mesa, and Ash Mesa (correlative with East Mesa), and the modern stream valley. Modern mass-wasting deposits are common along the edges of the terraces where slope failure occurs parallel to fractures or bedding planes of the Mancos Shale.

East Mesa is a broad, gently rolling surface underlain by Mancos Shale bedrock and associated, mud-dominated alluvium. The Loutsenhizer Arroyo and its smaller counterpart, the “Little Loutsenhizer” Arroyo, separate it from the Adobe Hills. Both arroyos are deeply incised into mud-dominated alluvium that is rich in gypsum. Dissolution of the gypsum by meteoric waters and/or lowering of the water table have created many car-sized caverns and other soil piping features along the arroyo margins.

DESCRIPTION OF MAP UNITS

Geologic time divisions used in this report are shown in table 1. Numerical ages were taken from the Geological Survey of Canada (Okulitch, 2002) and the International Commission on Stratigraphy (2005). The following conventions are used for describing the surficial deposits and bedrock outcrops. Clast sizes were based on the modified Wentworth grain-size scale (Wentworth, 1922), using a chart from the American Geological Institute (Ingram, 1989). Colors of materials were determined by comparison to Munsell rock and soil color charts (Geological Society of America, 2000; GretagMacbeth, 2000). The stages of calcic soil development are based on the classification of Machette (1985).

SURFICIAL DEPOSITS

Surficial deposits shown on the map are generally more than 5 feet thick but may be thinner locally. Residuum, sheetwash, colluvium, and artificial fills of limited extent were not mapped. Contacts between surficial units may be gradational, and mapped units locally may include deposits of other types. Age divisions for the Holocene used in the Olathe quadrangle are arbitrary and informal. They 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 development. Wherever possible, we considered and adopted age assignments that have been reported by previous authors, especially Sinnock (1978), who traced stream-terrace levels along the Uncompahgre River valley and correlated them with different glacial moraines about 20 miles to the south of the mapped area, near the town of Ridgway.

TABLE 1. Geologic time chart used by the Colorado Geological Survey. Numerical ages shown in black are from the Geological Survey of Canada (Okulitch, 2002); ages shown in blue are from the International Commission on Stratigraphy (2005).

Geologic Time Chart adopted by the Colorado Geological Survey

Era	Period		Epoch		Age (Ma)
CENOZOIC	Quaternary		Holocene		0.0118
CENOZOIC	Quaternary		Pleisto-cene	upper/late	0.126
CENOZOIC	Quaternary		Pleisto-cene	middle	0.781
CENOZOIC	Quaternary		Pleisto-cene	lower/ early	1.806
CENOZOIC	Tertiary	Neogene	Pliocene		5.33 ± 0.05
CENOZOIC	Tertiary	Neogene	Miocene		22.9 ± 0.1
CENOZOIC	Tertiary	Paleogene	Oligocene		33.5 ± 0.4
CENOZOIC	Tertiary	Paleogene	Eocene		54.8 ± 0.5
CENOZOIC	Tertiary	Paleogene	Paleocene		65.0 ± 0.05
MESOZOIC	Cretaceous		Upper/Late		99.0 ± 1.0
MESOZOIC	Cretaceous		Lower/Early		144.8 ± 3.7
MESOZOIC	Jurassic		Upper/Late		156.6 ± 2.7
MESOZOIC	Jurassic		Middle		178.0 ± 1.5
MESOZOIC	Jurassic		Lower/Early		200 ± 1.0
MESOZOIC	Triassic		Upper/Late		231 ± 5
MESOZOIC	Triassic		Middle		244 ± 1
MESOZOIC	Triassic		Lower/Early		253 ± 2
PALEOZOIC	Permian		Upper/Late		258 ± 5
PALEOZOIC	Permian		Middle		229 ± 5
PALEOZOIC	Permian		Lower/Early		300 ± 3
PALEOZOIC	Carboniferous	Pennsyl-vanian	Upper/Late		306.5 ± 1.0
PALEOZOIC	Carboniferous	Pennsyl-vanian	Middle		311.7 ± 1.1
PALEOZOIC	Carboniferous	Pennsyl-vanian	Lower/Early		318.0 ± 1.3
PALEOZOIC	Carboniferous	Missis-sippian	Upper/Late		326.4 ± 1.6
PALEOZOIC	Carboniferous	Missis-sippian	Middle		345.3 ± 2.1
PALEOZOIC	Carboniferous	Missis-sippian	Lower/Early		360 ± 2
PALEOZOIC	Devonian		Upper/Late		383 ± 4
PALEOZOIC	Devonian		Middle		394 ± 2
PALEOZOIC	Devonian		Lower/Early		418 ± 2
PALEOZOIC	Silurian		Upper/Late		424 ± 1
PALEOZOIC	Silurian		Lower/Early		443 ± 4
PALEOZOIC	Ordovician		Upper/Late		460.9 ± 1.6
PALEOZOIC	Ordovician		Middle		471.8 ± 1.6
PALEOZOIC	Ordovician		Lower/Early		489 ± 1
PALEOZOIC	Cambrian		Upper/Late		499 ± 5
PALEOZOIC	Cambrian		Middle		509 ± 1
PALEOZOIC	Cambrian		Lower/Early		544 ± 1
PRECAMBRIAN	Proterozoic		Neoproterozoic		1,000 ± 50
PRECAMBRIAN	Proterozoic		Mesoproterozoic		1,600
PRECAMBRIAN	Proterozoic		Paleoproterozoic		2,500
PRECAMBRIAN	Archean		Neoarchean		2,800
PRECAMBRIAN	Archean		Mesoarchean		3,200
PRECAMBRIAN	Archean		Paleoarchean		3,600
PRECAMBRIAN	Archean		Eoarchean		not defined

HUMAN-MADE DEPOSITS

af **Artificial fill (latest Holocene)** — Riprap, engineered fill, and refuse placed during construction of roads, railroads, buildings, dams, canals, and landfills. Generally consists of unsorted silt, sand, clay, and rock fragments. This unit may also include areas of construction and quarrying operations where original deposits have been removed, replaced, or reworked. Many of the canal embankments and irrigation ditches in the quadrangle were not mapped due to their limited areal extent. The average thickness of the unit is less than 20 feet. Artificial fill may be subject to settlement, slumping, and erosion if not adequately compacted.

ALLUVIAL DEPOSITS

Clay, silt, sand, and gravel deposited in stream channels, on flood plains, and as alluvial fans and sheetwash along valley sides, in tributary drainages, and on pediment surfaces. Terrace alluvium and related deposits on pediments along these drainages were deposited mostly during periods of wetter climate that coincided with Pleistocene glaciations. The approximate terrace heights reported for each unit are the elevation differences measured between the modern creek bed and the top of the original or remnant alluvial surface adjacent to the creek. Thickness reported is the maximum exposed thickness of the unit.

Alluvial Deposits of the Uncompahgre River

The Uncompahgre River, which runs through the western half of the mapped area, has four major terrace levels in addition to the Holocene floodplain associated with the modern, incised river valley (figure 4). Most of the terraces are associated with Pleistocene glacial episodes (Sinnock, 1978). The gravel-clast compositions within these deposits consist primarily of tuffaceous and porphyritic rhyolite, andesite, metaquartzite, silica-cemented sandstone and lesser amounts of gneiss, granite, vein quartz, and limestone. These intermediate volcanics and resistant clasts are derived from the western San Juan Mountains near Ouray to the south, Cimarron Ridge to the southeast, and the Uncompahgre Plateau to the west and southwest.

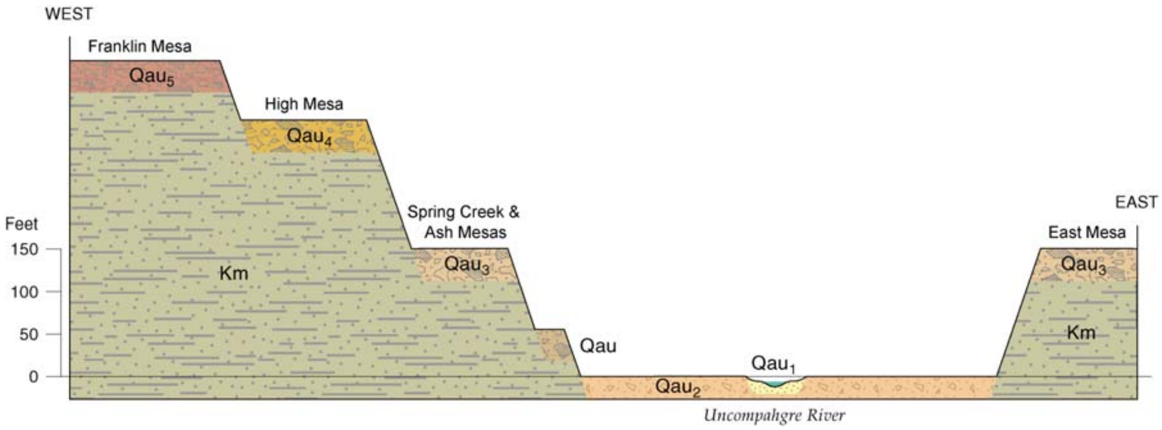


Figure 4. Diagrammatic profile of alluvial deposits associated with the Uncompahgre River. From oldest to youngest these are: Qau_5, Qau_4, Qau_3, Qau_2, and Qau_1 (the current stream channel). Qau is a local terrace remnant. See unit description for detailed information.

Qau_1 **Alluvium one of the Uncompahgre River (early to late Holocene)** — Dark-brown to dark-grayish-brown, poorly to moderately sorted, moderately consolidated clay, silt, sand, and pebble, cobble, and boulder gravel in the currently active stream channel or in low stream-terrace deposits above the current stream channel within the modern flood plain of the incised, Uncompahgre River valley. The alluvium commonly forms steep-sided walls where dissected by river erosion. Clasts are subrounded to well rounded. Soil development is absent. Many of the clasts are coated by a discontinuous rind of $CaCO_3$, indicating that they were reworked from older deposits. The deposit commonly includes organic-rich layers interbedded with clay, silt, and sand lenses. The unit may form low terraces that reach a maximum height of 8 feet above current stream level. These terraces fine upward, with localized, thin deposits of eolian or overbank sand and silt in the upper few feet. A second, younger group of lower terraces with heights of up to 4 feet have formed since 1987, when the river flows were first regulated by the Ridgway Dam, located several miles upstream. Since then, the braided flood plain has filled with sediment and the stream has mostly coalesced into a single channel. Maximum exposed thickness of the unit locally exceeds 10 feet. The unit is a potential source of commercial sand and gravel.

Qau_2 **Alluvium two of the Uncompahgre River (late Pleistocene to early Holocene)** — Reddish-brown to dark-grayish-reddish-brown, poorly to moderately sorted, moderately consolidated clay, silt, sand, and pebble, cobble, and boulder gravel in stream terrace deposits above the modern flood plain of the Uncompahgre River valley. This is the most widespread alluvium in the quadrangle and forms a broad, flat valley that is incised into by younger streams and bordered by higher mesas, many of which lie west of the river. It is the primary regolith for agriculture in the Uncompahgre River valley. The alluvium commonly forms continuous and steep-sided, cut-bank walls where it has been dissected by the modern river valley. Clasts are subrounded to well rounded. Soil development is very weak to absent and a juvenile A horizon is locally present. Many of the clasts within the deposit are coated by a discontinuous rind of $CaCO_3$, indicating they were reworked from older deposits. Agricultural practices have reworked the upper 2 feet of the deposit, making age determinations by soil properties problematic. Sinnock (1978) interpreted this terrace gravel deposit as being associated with the Pinedale glacial advance. Lenses of reworked gypsum and silt are present within the upper 2 feet of the deposit. The outer edges of the unit along the older mesas consist of mixtures of clay, silt, and sand derived from erosion of the Mancos Shale, transported colluvial material from older gravel deposits, or of alluvial mudflow deposits originating from Cedar Creek or Deadmans Gulch. The deposit includes local organic-rich layers interbedded with clay, silt, and sand lenses. The unit may form terraces that reach a maximum height of 15 feet above current stream level, with height decreasing to 10 feet downstream toward the town of Olathe. Maximum exposed thickness of the unit locally exceeds 25 feet, and deposits of greater than 120 feet have been encountered in drill holes in the adjacent Montrose West quadrangle (Dennis Lambert, Lambert & Associates, personal commun., 2006). Although the main river terrace has been abandoned, Holocene deposition has continued to occur along tributary streams. The unit generally forms a stable building surface, but there may be localized pockets of collapse-prone sediment, either within the gypsum-rich facies of the unit or along the outermost edges where fine-grained sediments predominate. Unit Qau_1 is inset into unit Qau_2 and a prominent terrace scarp separates these units. Areas along the edge of the Qau_1-Qau_2 cut bank may be prone to localized landsliding. The unit is a potential source of commercial sand and gravel.

Qau_3 **Alluvium three of the Uncompahgre River (late Pleistocene)** — Strong-brown to moderate-reddish-brown, poorly to moderately sorted, poorly to moderately consolidated silt, sand, and pebble, cobble, and boulder gravel, in stream terrace deposits above the modern flood plain of the Uncompahgre River valley. The alluvium forms a broad gravel cap on Spring Creek Mesa, Ash Mesa, and the western edge of East Mesa. Landsliding along the eastern edge of High Mesa has dissected a terrace surface that was a continuation of Ash Mesa; this dissection has left isolated, gravel capped remnants of the formerly continuous surface. Clasts are subrounded to well rounded; the dominant lithology is a bouldery, pebble-cobble gravel with a coarse sand matrix. Some boulders reach 4 feet in diameter. Soil horizons are not present on any of the studied exposures; however, the matrix of the unit reaches colors as red as 7.5YR 3/6 (moderate reddish brown). Clast bottoms are coated by a continuous rind of $CaCO_3$ and discontinuous layers of powdery $CaCO_3$ occur in thin 0.2- to 1-inch-thick zones throughout the deposit. The deposit is representative of Carbonate Stage I+ of Machette (1985). Sinnock (1978) interpreted this terrace gravel deposit as being associated with the Pinedale glacial advance. On the basis of degree of reddening of the matrix, presence of Stage I+ calcic soil, and height above modern stream level, the deposit is probably associated with one of the early Pinedale glacial stades. The unit forms terraces that may reach a maximum height of 170 feet above current stream level. The maximum exposed thickness of the unit locally exceeds 25 feet. The unit generally forms a stable building surface, although there may be localized pockets of collapse-prone sediment, and areas along the outer mesa edges may be prone to landsliding. The unit is a potential source of commercial sand and gravel.

Qau_4 **Alluvium four of the Uncompahgre River (late middle Pleistocene)** — Moderate-brown to moderate-yellowish-pink, poorly to moderately sorted, moderately consolidated silt, sand, and pebble, cobble, and boulder gravel in stream terrace deposits above the modern flood plain of the Uncompahgre River valley. The alluvium forms a broad gravel cap on High Mesa. Clasts are subrounded to well rounded and the dominant lithology is a bouldery, pebble-cobble gravel with a coarse sand matrix. Some boulders reach 5 feet in diameter. See figure 5 for typical soil profile descriptions for units Qau_4 and Qau_5. Sinnock (1978) interpreted this terrace gravel deposit as being associated with the Bull Lake glacial advance. The unit forms terraces that may reach a maximum height of 300 feet above current stream level. The maximum exposed thickness of the unit locally exceeds 25 feet. The unit generally forms a stable building surface, although there may be localized pockets of collapse-prone sediment, and areas along the outer mesa edges may be prone to landsliding. The unit is a potential source of commercial sand and gravel.

Qau_5 **Alluvium five of the Uncompahgre River (middle Pleistocene)** — Strong-brown to moderate-brown, poorly to moderately sorted, moderately consolidated silt, sand,

and pebble, cobble, and boulder gravel in stream terrace deposits above the modern flood plain of the Uncompahgre River valley. The alluvium forms a broad gravel cap on Franklin Mesa. Clasts are subrounded to well rounded and the dominant lithology is a bouldery, pebble-cobble gravel with a coarse sand matrix. Some boulders reach 5 feet in diameter. Soil development is virtually identical to Qau_4 with the exception of increased reddening and clay content of the B horizon in unit Qau_5; see figure 5 for soil profile descriptions. Sinnock (1978) interpreted this terrace gravel deposit as being associated with the Bull Lake glacial advance. The unit forms terraces that may reach a maximum height of 370 feet above current stream level. The maximum exposed thickness of the unit locally exceeds 15 feet. The unit generally forms a stable building surface, although there may be localized pockets of collapse-prone sediment, and areas along the outer mesa edges may be prone to landsliding. The unit is a potential source of commercial sand and gravel.

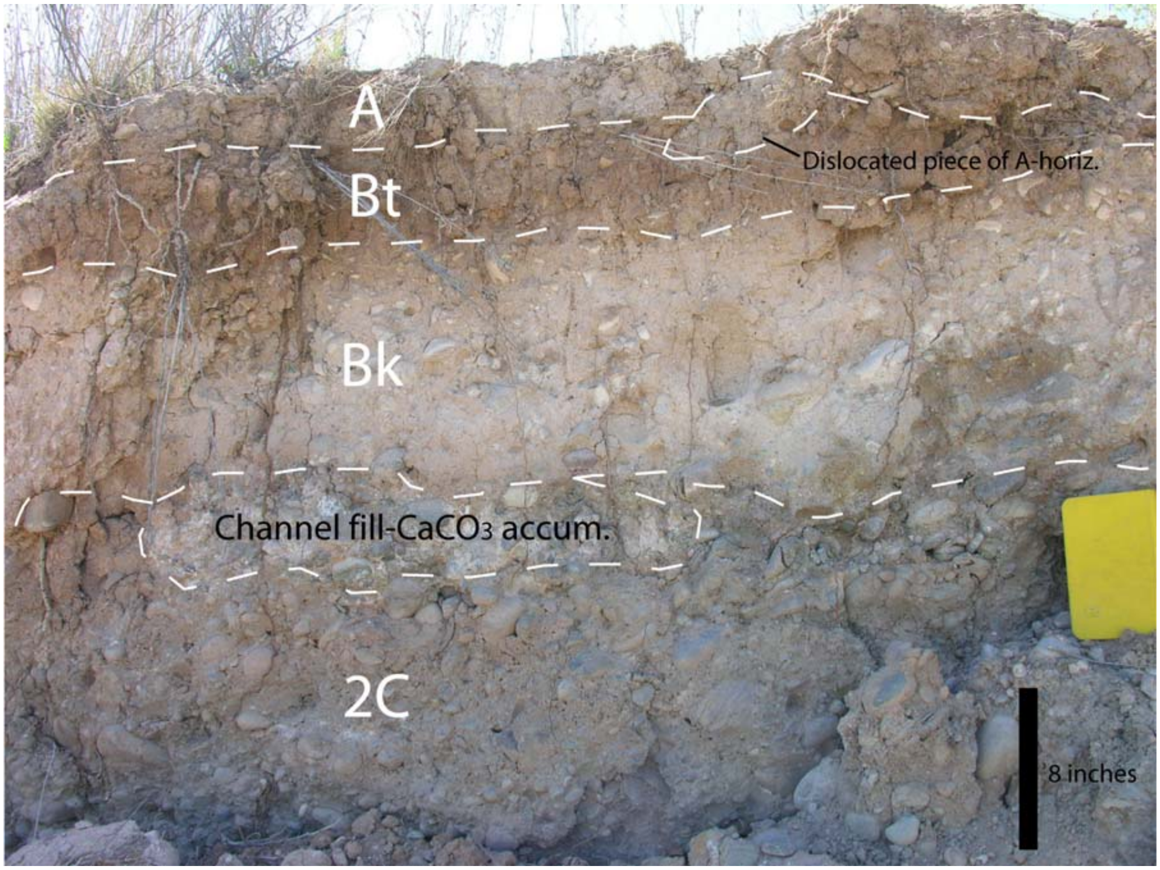


Figure 5. Photograph of the typical soil profile for units Qau_4 and Qau_5 in the Olathe quadrangle. The annotated photo outlines the different soil horizons: A horizon, 6 inches thick, 10% humified organic matter, slight accumulation of fine $CaCO_3$ (windblown), color is 10YR 4/4 (moderate yellowish brown), will form a ball when wetted due to clay content; Bt horizon, 6 inches thick, blocky structure, few clay films, forms a ball and 6-inch rope when wetted due to clay content, $CaCO_3$ coats bottoms of clasts with some accumulation in roots and cracks, color is 5YR 4/4 (moderate brown); Bk horizon, 14 inches thick, visible whitening from $CaCO_3$ accumulation, $CaCO_3$ coats undersides and occasionally the tops of clasts and fills cracks of fragmented clasts, ¼-inch $CaCO_3$ nodules common, $CaCO_3$ fills voids and is dispersed throughout the matrix, some volcanic clasts totally decomposed to grus, forms ball and 4-inch rope when wetted due to clay content, color is 5YR 7/4 (moderate yellowish pink), stage II-III calcic soil (Machette, 1985); 2C horizon, second generation parent material. The soil profile for unit Qau_5 is very similar to that of unit Qau_4 with the exception of increased reddening and clay content of the Bt horizon in the older Qau_5 deposit. UTMX: 238920.56, UTMY: 4274730.16.

Qau **Alluvium of the Uncompahgre River, undifferentiated (late? Pleistocene)** — Brown to moderate-reddish-brown, poorly to moderately sorted, poorly to moderately consolidated silt, sand, and pebble, cobble, and boulder gravel in stream terrace deposits above the modern flood plain of the Uncompahgre River valley. The alluvium forms localized, gravel-capped terraces near the Town of Olathe. These terraces could not be correlated with other surfaces in the area. Clasts are subrounded to well rounded and the dominant lithology is a bouldery, pebble-cobble gravel with a coarse sand matrix. Soil horizons were not examined due to poor exposure. The unit forms terraces that may reach a maximum height of 120 feet above current stream level. The maximum exposed thickness of the unit locally exceeds 15 feet. The unit generally forms a stable building surface, although there may be localized pockets of collapse-prone sediment, and areas along the outer mesa edges may be prone to landsliding. The unit is a potential source of commercial sand and gravel.

Alluvial Deposits of Spring Creek

Spring Creek, a tributary stream of the Uncompahgre River, contains three different alluviums that were transported from the south along the main stream channel and from Franklin Mesa to the west. The oldest of these deposits, Qas_3, contains the same clast types as the unit Qau_5; however, the Qas_3 clasts are set in a muddy matrix derived from the Mancos Shale and are locally derived via tributary streams. Due to the fan-shaped morphology of the western part of the deposit, this alluvium likely originated as mudflows from the uplands to the southwest and was planed into terraces when the mudflows reached Spring Creek. The Holocene alluviums are very similar to units Qau_1 and Qau_2, and essentially follow the modern Spring Creek flood plain. Unit Qas_2 grades into unit Qau_2 along the Uncompahgre River valley.

Qas_1 **Alluvium one of Spring Creek (early to late Holocene)** — Dark-brown to moderate-brown, poorly to moderately sorted, moderately consolidated silt, sand, and pebble, cobble, and boulder gravel in the currently active stream channel or in low stream-terrace deposits above the current stream channel within the modern flood plain of the incised, Spring Creek valley. The alluvium commonly forms steep-sided walls where dissected by river erosion. Clasts are subrounded to well rounded. Soil development is absent. Many of the clasts are coated by a discontinuous rind of $CaCO_3$, indicating that they were reworked from older deposits. The unit forms low terraces that may reach a maximum height of 3 feet above current stream level. The maximum exposed thickness of the unit locally exceeds 10 feet. The unit is a potential source of commercial sand and gravel.

Qas_2 **Alluvium two of Spring Creek (late Pleistocene to early Holocene)** — Deep-brown to dark-brown, poorly to moderately sorted, moderately consolidated silt, sand,

and pebble, cobble, and boulder gravel in stream-terrace deposits above the current stream channel within the modern flood plain of the incised, Spring Creek valley. The alluvium commonly forms steep-sided walls where dissected by river erosion. Clasts are subrounded to well rounded. A juvenile A horizon is present with color of 7.5YR 1/2 (dark brown). Many of the clasts are coated by a discontinuous rind of $CaCO_3$, indicating that they were reworked from older deposits. The unit forms terraces that may reach a maximum height of 8 feet above current stream level and grade into the Qau_2 terraces of the Uncompahgre River. The maximum exposed thickness of the unit locally exceeds 15 feet. The unit is a potential source of commercial sand and gravel.

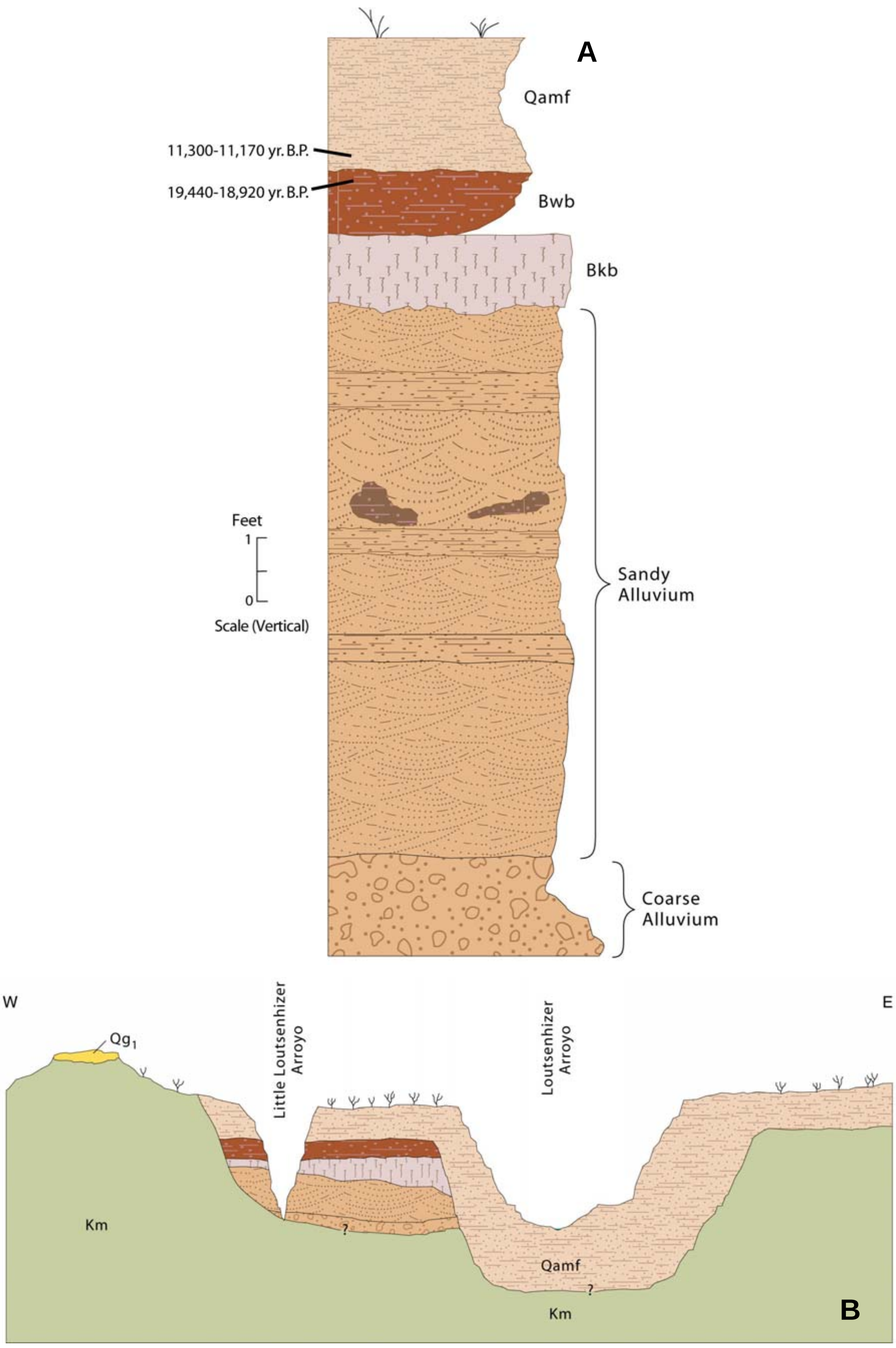
Qas_3 **Alluvium three of Spring Creek (late Pleistocene)** — Dark-brown to dark-grayish-brown, poorly to moderately sorted, poorly consolidated clay, silt, sand, and pebble, cobble, and boulder gravel in stream-terrace deposits above the current stream channel within the modern flood plain of the incised, Spring Creek valley. The alluvium forms gravel- and mud-capped terraces along the west side of Spring Creek. Clasts are subrounded to well rounded. A soil profile was not observed at any of the outcrop locations; soil development was possibly hampered due to the mobility of the muddy matrix. Many of the clasts are coated by a discontinuous rind of $CaCO_3$, indicating that they were reworked from older deposits. The unit forms terraces that may reach a maximum height of 50 feet above current stream level. The maximum exposed thickness of the unit locally exceeds 15 feet. The unit is a potential source of commercial sand and gravel.

Mudflow-Dominated Alluvium and Alluvial-Fan Deposits

The most common surficial deposits within the mapped area are associated with complex alluvial-valley-fill and alluvial-fan systems along tributary streams and in broad basins. In these systems, channelized to laterally unconstrained mudflows or mud and gravel debris flows have been the dominant depositional processes. These widespread, Holocene deposits are mudflow dominated and gravel poor, with most of the source material being derived from the Mancos Shale.

Qf **Alluvial-fan deposits (late Holocene)** — Grayish-orange-pink to grayish-orange, well sorted to locally poorly sorted, poorly consolidated, sandy silt to sandy gravel deposited in alluvial fans at the mouths of arroyos and small, ephemeral streams. The deposits have a fan-shaped morphology. Because of their fine-grained composition, they have very low surface gradients of 1° to 5°. Sediments are deposited primarily by muddy debris flows with occasional input from sheetwash and hyperconcentrated flows. The deposits consist of poorly defined silt layers, typically less than an inch to a few inches thick, which record individual mudflow depositional events. There are occasional stringers and lenses of locally reworked gravel. Deposits may locally exceed 10 feet in thickness. This map unit was assigned only to small, well developed, single alluvial fans that have prograded onto dissimilar deposits such as alluvial terraces. Alluvial fans that are in a stratigraphic continuum with more complex, mudflow-and-fan valley-fill systems were mapped as Qamf (see next entry). Areas mapped as alluvial fans are subject to future flash floods and debris flow events. The deposits may be prone to collapse, hydrocompaction, or slope failure when wetted or loaded.

Qamf **Alluvial mudflow-and-fan valley-fill deposits (early to late Holocene)** — Light-grayish-reddish-brown to pale-orange-yellow, well to occasionally poorly sorted, poorly consolidated, clayey to sandy silt deposited in valley-head and valley-side alluvial fans, tributary stream valleys, and coalescing fans in broad basins. The deposits comprise a complex system of deposits that extends for several miles along tributary stream reaches. The thickest deposits occur along Cedar Creek into the City of Montrose and contain a number of low-gradient, coalescing fans. Extensive alluvial mudflow deposits occur in the Loutsenhizer Arroyo drainage basin where there are two distinct units of differing relative age and lithology. Figure 6 explains the relationships between these deposits.



A
Qamf
11,300-11,170 yr. B.P.
19,440-18,920 yr. B.P.
Bwb
Bkb
Feet
1
0
Scale (Vertical)
Sandy Alluvium
Coarse Alluvium
W
E
Qg1
Little Loutsenhizer Arroyo
Loutsenhizer Arroyo
Km
?
Qamf
?
Km
B

Figure 6. Profile and diagrammatic cross-section of the Loutsenhizer Arroyo. (A) Generalized stratigraphic section of the deposits within the "Little Loutsenhizer" Arroyo. Calibrated C14 age dates are shown on the left side of the section. The base of the deposit consists of a coarse cobble and boulder gravel alluvium that grades into a normally graded, cross-bedded and laminar sandy alluvium. Rip-up clasts of mudstone (dark brown) are located at the base of a cross-bedded unit. The rip-ups, normal grading, and lower-angle cross beds near the top indicate an overall decrease in stream energy. Two distinct soil horizons formed on the sandy alluvium that is now buried by Qamf. The lowest buried soil horizon (Bkb) is a zone carbonate enrichment that gives it a whitened appearance. The carbonate binds grains together and fills some root holes. This is a Stage I calcic soil (Machette, 1985). The Bkb horizon is overlain by a weathered B horizon (Bwb), which is reddened due to accumulation of oxide minerals. Clay films partially coat some of the grains. The contact with the Bwb horizon and overlying Qamf is sharp and abrupt and represents distinct hiatus in deposition. The lower diagram (B) shows the relationships of these deposits. Unit Qg_1 probably covered much of this area during the late Pleistocene. It was later scoured and a new channel was cut through it and into the Mancos Shale. The coarse and sandy alluvial units were deposited in the channel and were later truncated and partially buried by alluvial mudflow deposits, Qamf. Storm events and irrigation in the area resulted in arroyo development that has cut deep (20-30 feet) steep-walled channels into these units. Scale: (A) 1 cm = 1 ft (vertical), no horizontal scale; (B) diagram is not to scale.

The depositional history within the Loutsenhizer drainage basin can be established on the basis of field relationships of the deposits (figure 6; B). During the late Pleistocene, a fluvial system of pebble, cobble, and boulder gravel (Qg1) flowed from southeast to northwest along a paleochannel of the present-day Loutsenhizer Arroyo. The northwest transport direction is substantiated by northwest clast imbrication and a high percentage of volcanic clasts derived from the San Juan Mountains. The true extent of these deposits during the late Pleistocene is unknown; however the Qg1 gravel now caps low, isolated hills of Mancos Shale that roughly parallel the current channel. Following deposition of Qg1, another alluvial system incised and deposited a fining-upward, cobble and boulder gravel and sandy alluvial unit. Trough cross-stratification and rip-up clasts are present within the middle parts of the deposit, and the deposit grades upward into thinly laminated and low-angle trough cross-stratified sandy beds. A bulk ^{14}C sample of sediment taken from the top of the Bwb horizon yielded a conventional age of 15,960±110 ^{14}C yr. B.P. (2 Sigma, 95% probability = BP 19,440-18,920) (Beta Analytic Sample #225555). This unit was deposited during the Pinedale Glaciation which ended at approximately 12,000 ^{14}C yr. B.P. A second bulk ^{14}C sample was taken 6 inches above the Bwb horizon, at the base of the Qamf deposit, that yielded a conventional age of 9,810±60 ^{14}C yr. B.P. (2 Sigma, 95% probability = BP 11,300-11,170) (Beta Analytic Sample #225554). On the basis of these age dates, it took a minimum of approximately 8000 years for the Bwb and Bkb soil horizons to form on the sandy alluvium. These soils were subsequently buried by silty alluvial mudflows (Qamf) that filled the valley during the Holocene. Recent incision from storm events, runoff, and irrigation has formed deeply incised arroyos in the Qamf deposits.

The onset of Qamf deposition roughly coincides with the tail-end of the Younger Dryas, a prolonged cold period that lasted for approximately 1,300 years from 12,700 to 11,500 yr. B.P. Increased runoff and precipitation from melting ice during the early Holocene eroded and transported mud derived from the Mancos Shale, resulting in large and extensive debris/mudflows. Much of the badlands topography that is seen today in the mapped area was created during this time.

Some of the tributary-stream systems (e.g., Loutsenhizer Arroyo and Cedar Creek; figure 3) have intermediate basins along their courses. The basin- and valley-fill sediments were deposited primarily by muddy debris flows with occasional input from sheetwash, hyperconcentrated flows, and water-flood flows. The deposits consist of poorly defined silt layers, typically less than an inch to a few inches thick, which record individual mudflow depositional events. Some layers show incipient soil development that was curtailed by burial during subsequent events.

There are occasional stringers and lenses of locally reworked gravel from older deposits on flanking, gravel-capped mesas. Modern mudflow depositional processes are actively occurring in some headwater areas. Flash flooding results in the deposition of mud fans locally containing mud-encrusted cobbles and small boulders. Near the base of the highland areas in the eastern part of the quadrangle, modern mudflows have transported boulders up to 4 feet long, depositing them as concentrated masses or boulder bars in arroyo constrictions, against trees, and in areas where the stream broadens and flattens. The downstream deposits along valley reaches and in the broad basins are nearly completely composed of mud (i.e., clayey silt).

Qamf deposits may exceed 5 feet in thickness in valley-head and valley-side areas and may exceed 25 feet in thickness along the valley reaches and in the basins. The filling of the intermediate and terminal basins has resulted in the near burial of low hills and ridges of Mancos Shale; borehole drilling may be necessary to determine bedrock depth in these areas. Many of the tributary-stream mudflow deposits and coalescing fans have been deeply dissected by stream erosion during the late Holocene, resulting in narrow arroyos that are 5 to 20 feet deep along the valley bottoms in most areas. In particular, an arroyo system along Cedar Creek has been incised to a depth of 30 feet through 28 feet of mudflow deposits and at least 2 feet of the underlying Mancos Shale. Areas mapped as Qamf may be subject to future flash floods and debris flow events, especially in non-incised valley-head and valley-side areas and within the deeply dissected modern arroyo channels. The deposits may be prone to significant collapse, hydrocompaction, or slope failure when wetted or loaded.

Mixed Debris-Flow and Alluvial Gravel Deposits

There are at least four, topographically distinct levels of older valley-fill and alluvial-fan deposits preserved as dissected, gravel-capped mesas and hilltops in the Peach Valley and "Candy Lane" areas (figure 3). These units are remnants of an ancient tributary stream system that flowed along present day Peach Valley and "Candy Lane", northward to the Gunnison River. Each gravel level represents a former channel of this paleovalley. During the late Pleistocene, stream capture by tributary streams pirated the paleoriver and its channel was abandoned.

The resistant gravels and the capping gypcrete and calcic soils have minimized erosion to the extent that the flanking hillsides of Mancos Shale were eventually eroded away and lowered by downcutting, creating repeated, topographic inversion. The resistant deposits may form flat to saddle-shaped terraces or gently rounded hilltops. In many places the surface underlying the deposit forms a pediment or defines the base of an individual paleovalley. The depositional processes of these deposits are similar in origin to the Holocene alluvial mudflow and fan (Qamf) deposits described previously. The main difference is that these older deposits contain significant gravel as a consequence of the wetter climate and higher erosion associated with Pleistocene glacial advances, whereas gravel transport has been minimized during the later, drier Holocene period. Furthermore, much of the available coarse sediment has been removed or is stranded at higher elevations, effectively cutting off the coarse sediment supply to the Qamf deposits.

The gravel clasts within these deposits are primarily silica-cemented Dakota Sandstone, tuffaceous and porphyritic rhyolite, andesite, and metaquartzite, with lesser amounts of granite, vein quartz, and andesitic and rhyolitic breccias. The sandstone clasts are derived from Dakota outcrops along the Gunnison uplift and the igneous and metamorphic clasts are derived from Cimarron Ridge to the southeast and the western San Juan Mountains near Ouray to the south. In particular, the pebble and cobble clasts may be reworked from older alluvial-gravel deposits, including the Eocene Telluride Conglomerate and the middle Pleistocene Shinn Park-Bostwick Park paleovalley system (Dickinson, 1965, 1987). Angular fragments of locally derived Dakota Sandstone colluvium cover the upper parts of the older deposits. A defining characteristic of these debris-flow deposits is the presence of concentrations of boulders, or boulder bars, that mark former debris-flow levees, snouts, and broad boulderfield deposition areas that may indicate a localized decrease in the paleovalley gradient. The boulders are commonly up to 8 feet long. Many of the largest boulders are tabular or elongate and are occasionally stacked or imbricated. Such bodies may be carried for large distances by rafting upon the dense, viscous mass of a muddy debris flow (Cruden and Varnes, 1996). The large boulders are nearly always composed of pale-red-purple to grayish-red, moderately hard, tuffaceous or brecciated rhyolite and Dakota Sandstone. The sources of the rhyolite may be the Oligocene Ute Ridge Tuff or Sapinero Mesa Tuff, from heavily eroded outcrops in the Cimarron Ridge area near Storm King point (Dickinson, 1987). These tuff units probably once covered a greater area than indicated by present exposures.

Qg_1 **Gravel deposit one (late Pleistocene to early Holocene)** — Yellowish-brown to grayish-brown, poorly sorted, moderately to poorly stratified silt, sand, and pebble, cobble, and boulder gravel. The clasts are subangular to well rounded and are predominantly Dakota Sandstone, andesite, and rhyolite with lesser amounts of quartzite and granite. The deposits are predominantly matrix-supported with the matrix typically consisting of sandy, clayey silt. Thin, discontinuous rinds of $CaCO_3$ coat the bottoms of some of the clasts; however, soil horizons or significant carbonate accumulations are not present, indicating that these clasts are probably reworked from older deposits. The unit locally exceeds 10 feet in thickness. It is correlated with unit Qau_2 alluvium of the Uncompahgre River valley by virtue of height above stream level and by soil characteristics. The unit forms flat to slightly rounded, gravel-capped terraces on the west side of the “Little Loutsenhizer” Arroyo, approximately 30-45 ft above modern stream level. See figure 6 for this unit’s relationship to the Loutsenhizer and “Little Loutsenhizer” Arroyos. This deposit generally forms a stable building surface, although there may be localized pockets of collapse-prone sediment, and areas along the terraces edges may be prone to rockfall. Because of its high silt content and an abundance of non-durable volcanic clasts, it is a marginal to fair source of commercial sand and gravel.

Qg_2 **Gravel deposit two (late Pleistocene)** — Light-yellowish-brown to grayish-red, poorly sorted, moderately to poorly stratified silt, sand, and pebble, cobble, and boulder gravel. The clasts are subangular to well rounded and are predominantly andesite and rhyolite with lesser amounts of quartzite and granite. Clasts of Dakota Sandstone make up a significant portion of clast types. The deposits are predominantly matrix-supported, with the matrix typically consisting of sandy, clayey silt. The predominant emplacement process was muddy debris flows; however some clasts originated from the surrounding high mesas as colluvium. A weak, Stage I calcic soil (Machette, 1985) is developed within the upper 1 to 3 feet and the carbonate forms filaments and surface coatings in the silt. The unit locally exceeds

15 feet in thickness. The unit forms flat to slightly rounded, gravel-capped terraces on the southwest side of “Candy Lane”, approximately 60-100 ft above modern stream level. This deposit generally forms a stable building surface, although there may be localized pockets of collapse-prone sediment, and areas along the terraces edges may be prone to rockfall. Because of its high silt content and an abundance of non-durable volcanic clasts, it is a marginal to fair source of commercial sand and gravel.

Qg_3 **Gravel deposit three (late Pleistocene)** — Interstratified clast and matrix-supported gravel, silt, and sand. The clast-supported layers are comprised of moderately sorted cobble and pebble gravel with a matrix of brownish-pink to light-grayish-brown silty coarse sand, up to 10 feet thick. The clasts are rounded to subrounded and are predominantly andesite and rhyolite with lesser amounts of quartzite and granite. Clasts of Dakota Sandstone make up a significant portion of clast types. Rounded volcanic boulders of up to 3 feet long are locally present. The basal, matrix-supported layers are up to 8 feet thick and contain rounded cobbles and pebbles plus numerous, subrounded to subangular welded tuff and brecciated rhyolite boulders of up to 3 feet long. Clast imbrication indicates a north to northwest transport direction. The matrix consists of brownish-pink, sandy to clayey silt. The middle part of the unit contains 5 to 12 feet of slightly pebbly, grayish-brown, sandy to clayey silt. The top of the unit consists of a 0.5- to 3-foot-thick, carbonate-gypsum cemented soil horizon, with abundant exposed cobbles and boulders. This local, Stage I+ (Machette, 1985) Bky horizon contains filaments of $CaCO_3$ and coarsely crystalline gypsum. The $CaCO_3$ and gypsum partially coat clasts and leave a white powder in the matrix. Fragments of Dakota Sandstone colluvium are present on the surface of the unit. The unit forms flat to slightly rounded, gravel-capped terraces and sinuous ridges and incised, fan-like surfaces along the flanks of “Candy Lane”. The tops of these surfaces are approximately 160-220 feet above modern stream level. The unit locally exceeds 25 feet in thickness. It is correlated with unit Qau_3 of the Uncompahgre River valley by virtue of height above stream level and by soil characteristics. This deposit generally forms a stable building surface, although there may be localized pockets of collapse-prone sediment, and areas along the outer mesa edges may be prone to rockfall. Because of its variable silt content and an abundance of non-durable volcanic clasts, it is a marginal to fair source of commercial sand and gravel.

Qg_4 **Gravel deposit four (middle Pleistocene)** — Interstratified clast-and matrix-supported gravel, silt, and sand. The clast-supported layers are comprised of moderately sorted cobble and pebble gravel with a matrix of brownish-pink to pale-red, silty coarse sand and are up to 40 feet thick. The clasts are rounded to subrounded and are predominantly andesite and rhyolite with lesser amounts of quartzite and granite. Clasts of Dakota Sandstone make up a significant portion of clast types. Rounded volcanic boulders of up to 2 feet long are locally present. A basal, clast-supported gravel is locally present. It consists of a 1-foot-thick, carbonate and gypsum-cemented conglomerate of blue, gray, and red, well rounded quartzite pebbles. Above this basal layer are poorly sorted, matrix-supported layers and are up to 8 feet thick; these upper layers contain rounded cobbles and pebbles plus numerous, subrounded to subangular welded tuff and brecciated rhyolite boulders of up to 4 feet long. Clast imbrication indicates a north-northwest transport direction. The matrix consists of brownish-pink, sandy to clayey silt. The middle part of the unit contains 6 to 10 feet of slightly pebbly, grayish-pink, sandy to clayey silt. The top of the unit consists of a 0.5- to 4-foot-thick, carbonate-gypsum cemented soil horizon, with abundant exposed cobbles and boulders. This widespread, Stage III-III+ (Machette, 1985) Bky horizon contains nodules of $CaCO_3$ and pendants of gypsum. The $CaCO_3$ and gypsum completely coat clasts and bind the matrix; however, $CaCO_3$ laminae were not observed. Fragments of Dakota Sandstone colluvium are present on the surface of the unit. The unit forms flat to slightly rounded, gravel-capped terraces and sinuous ridges along the flanks of Peach Valley and "Candy Lane". The top of the deposit is 250-280 feet above modern stream level. This deposit generally forms a stable building surface, although there may be localized pockets of collapse-prone sediment, and areas along the outer mesa edges may be prone to landsliding and rockfall. Because of its variable silt content and an abundance of non-durable volcanic clasts, it is a marginal to fair source of commercial sand and gravel.

Qg **Gravel deposits, undivided (Holocene)** — Yellowish-brown to gray-brown, poorly sorted, moderately to poorly stratified silt, sand, and pebble, cobble, and boulder gravel. Clast composition is predominantly tuffaceous and porphyritic rhyolite, andesite, with lesser amounts of metaquartzite, gneiss, granite, vein quartz, limestone, and silica-cemented Dakota Sandstone. Clay in the matrix is eroded from the Mancos Shale. The deposits are predominantly matrix supported with the matrix consisting of sandy, clayey silt. Soil development is absent; however, many of the clasts are coated by a discontinuous rind of $CaCO_3$, indicating they were reworked from older deposits. The unit locally exceeds 10 feet in thickness. The unit forms flat, gravel-capped surfaces on the east side of High Mesa. These gravels were deposited at the mouths of tributary streams that flow(ed) into the Uncompahgre River off High Mesa and down Spring Creek. Some colluvial input from the surrounding high mesas is likely. This deposit generally forms a stable building surface, although there may be localized pockets of collapse-prone sediment, and areas along the terraces edges may be prone to landsliding and rockfall. Because of its high silt content and an abundance of non-durable volcanic clasts, it is a marginal to fair source of commercial sand and gravel.

Undifferentiated and Undivided Alluvial Deposits

Qa **Alluvium, undifferentiated (Holocene)** — Stream-channel and flood plain deposits along valley floors of ephemeral, intermittent, and small perennial streams. Poorly to moderately sorted, weakly to well-stratified, moderately consolidated silt, sand, and pebble, cobble, and boulder gravel. Clast types are derived from the alluvial deposits of the Uncompahgre River. This unit forms small terraces that may reach a maximum height of 3 feet above modern stream level, and the deposit reaches a maximum thickness of 8 feet. Areas mapped as Qa may be prone to flooding, erosion, and sediment deposition.

Qac **Alluvium and colluvium, undivided (late Pleistocene and Holocene)** — Stream-channel and flood plain deposits along valley floors of ephemeral, intermittent, and small perennial streams, and colluvium along valley sides. Alluvium is typically composed of poorly to well-sorted, stratified, interbedded, pebbly sand, sandy silt, and sandy gravel. Colluvium may range from unsorted, clast-supported, pebble to boulder gravel in a sandy matrix to matrix-supported, gravelly, clayey sand. Clasts of Dakota Sandstone and gravels derived from alluvial deposits are the primary constituents. Some clasts of Dakota Sandstone reach lengths of 3 feet. Maximum thickness of the unit is approximately 15 feet.

MASS-WASTING DEPOSITS

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

Qc **Colluvial deposits (late Pleistocene to Holocene)** — Reworked alluvium and weathered Mancos Shale, consisting of yellowish-brown, poorly sorted, clast-supported, pebble to boulder gravel in a sandy silt matrix to matrix-supported, gravelly, clayey, sandy silt. The unit contains rounded to subrounded clasts and is weakly stratified. Clast composition is predominantly tuffaceous and porphyritic rhyolite, andesite, and lesser amounts of metaquartzite, gneiss, granite, vein quartz, limestone, and silica-cemented Dakota sandstone. Clay in the matrix is weathered Mancos Shale. The most significant deposits of colluvium occur on the west-facing slopes of East Mesa, Spring Creek Mesa, and "Candy Lane". Colluvium was deposited predominantly as rockfall; however, some originated as muddy debris flows down steep valley sides. Some colluvium deposits include localized landslide debris and may interfinger with alluvium, landslide, and alluvium-mudflow deposits. Colluvium deposits locally exceed 10 feet in thickness. Areas mapped as colluvium are susceptible to future rockfall and debris flow events.

Qls **Landslide deposits (Holocene to middle Pleistocene)** — Heterogeneous deposits consisting of unsorted and unstratified clay, silt, and sand, and cobble- and boulder-size rock fragments. Unit includes rotational and translational slides and complex slide-flow mass movements. In most places, landslides show obvious geomorphic expression that disrupts the profile of the slopes. Generally, head scarps (near-vertical detachment scars exposed at the top of and sides of the landslides) are readily recognizable; however, some scarps may be eroded or covered and not pronounced. Other common diagnostic features include hummocky topography, closed depressions, fissures, terracettes, tension cracks, and pressure ridges at the toe of the mobilized mass. The landslides typically form in weathered Mancos Shale where gypsum has lined fracture and bedding planes and caused the shale to split apart and weaken. Lubrication of fracture planes and soil piping within the Mancos Shale by irrigation and/or meteoric waters has caused many of the slope failures. Soil profiles were not developed on any of the examined deposits; however, buried soils do occur and represent multiple slope movements. The relative ages of the landslides are highly variable. Old landslide deposits are visible in the headscarps of more recent slides along Spring Creek and Franklin Mesa and their ages post-dates deposition of, and pedogenesis on, Qau_4 and Qau_5. The youngest sizeable landslide occurred in 2005 and was caused by irrigation runoff seeping into an exposed face of Mancos Shale (Blue Hill Member) along the north side of Franklin Mesa (figure 7). Most landslides in the mapped area are mixtures of alluvium from the Qau and Qg deposits and varying amounts of weathered Mancos Shale. Vegetation may be thick due to the amount of water seeping into and running off of the deposits. See the “Geologic Hazards” section for a discussion of landslides within the mapped area.

Figure 7. Translational-rotational landslide on the north side of Franklin Mesa. According to eyewitness reports, this complex slide occurred in 2005. Deposit in foreground and at top of mesa capping the landslide is Qau_5. Field of view is approximately 135 feet across. UTMX: 239266.0, UTMY: 4267403.9.

Landslide areas are subject to future movement during episodes of heavy rain or snowfall or may be reactivated by human-made disturbances such as cutting of slopes for roads, quarries, housing developments, irrigation systems, and septic systems. Poor irrigation practices may create or remobilize landslide deposits. Landslide deposits are prone to settlement when loaded or wetted. Deposits may contain expansive soils where derived from shale and mudstone formations. Thickness of landslide deposits locally exceeds 10 feet.

BEDROCK UNITS

The bedrock geology within the Olathe quadrangle is primarily Mancos Shale underlain by the Dakota Sandstone and Burro Canyon Formation. The Mancos Shale and its members were deposited within a shallow sea (Western Interior Seaway) that divided the North American Continent into two halves during the Middle to Late Cretaceous. These units are mapped on the Montrose 1° X 2° degree geologic map (Tweto and others, 1976). On the basis of field observations, we divided the Mancos Shale into distinct subunits and assigned them names typically used in the area.

The nomenclature of these stratigraphic members has been imported from the central Front Range Piedmont near Pueblo (Scott and Cobban, 1964, 1986; Scott, 1969; Cobban and Scott, 1972), the Mesa Verde area in southwestern Colorado (Leckie and others, 1997), and the Book Cliffs near Grand Junction (Hettinger and Kirschbaum, 2002).

The U.S. Geological Survey divided the Mancos Shale into lithostratigraphic units on the basis of a 550-foot core (USGS CL-1) that was extracted from the eastern side of "Candy Lane" (R. Grauch, USGS, and B. Ball, USGS, personal commun., 2006, Ball and others, 2006). Many of these units could not be identified with certainty in the field and are not used in this report. Table 2 lists collected and identified fossils with associated sample number or USGS permanent collection number. The numbers correspond to a sample location point on plate 1. Appendix 1 lists the Cretaceous fossils collected from within the Olathe quadrangle and surrounding quadrangles.

TABLE 2. Sample numbers and names of fossils identified within the Olathe quadrangle. Numbers correspond to locations shown on plate 1.

Number	Fossil Name
MM4	*Inoceramus dimidius*
MM7	*Lopha lugubris*
MM14a	*Lopha lugubris*
MM14b	*Prinocyclus bosquensis*
D14452 (USGS)	*Prinocyclus bosquensis, Scaphities witfieldi, Mytiloides incertus, Baculites sp.*
MM17	*Cremnoceramus deformis*
MM24	*Prinocyclus macombi, Lopha lugubris*
MM61	*Pycnodonte aff. kellumi*
SK34b	*Prinocyclus macombi*
SK25b,c	*Cremnoceramus crassus, Baculites sp.*
SK37c	*Mytiloides incertus?*

Mancos Shale (Upper Cretaceous)

Kms **Smoky Hill Member of the Mancos Shale** — Blackish-gray to tan, slightly calcareous to silty, marine shale. The base of the unit is moderately fossiliferous, consisting of blackish-gray, slightly calcareous shale with abundant plant debris, shell fragments, and fish scales concentrated along bedding planes. Multiple bentonite beds are located throughout the bottom half of the unit. The upper part of the unit consists of interbedded limestone and shale beds; the limestone beds are typically 12 inches thick and form flat-topped benches underlain by shale. Where exposed, they may weather to a golden color, giving the Smoky Hill a “blonde” appearance (figure 8). It has been suggested the blonde coloration arises from the presence of the sulfate mineral jarosite; however, this process of coloration is still under investigation (R. Grauch, USGS, personal commun., 2006). The most well developed weathering zone occurs immediately below the ground surface; however, multiple “blonde” zones occur lower in the section where these limestone beds are exposed to weathering. Seams of gypsum are present throughout the unit. Fossils collected within this unit include (identified by B. Cobban, USGS, personal commun., 2006): *Cremnoceramus deformis* (bivalve), *Cremnoceramus crassis* (bivalve) and an unidentified inoceremid. The exposed thickness of this unit is approximately 300 feet.

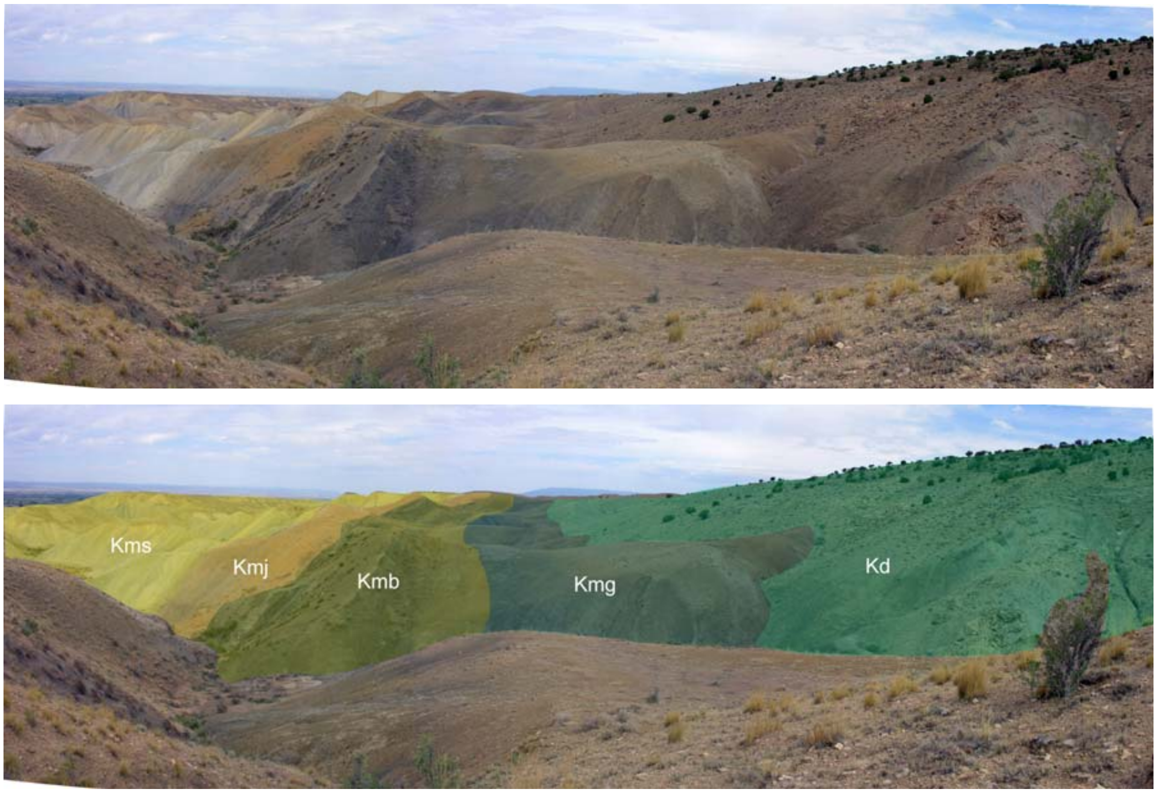


Figure 8. Photograph looking north toward Peach Valley showing the exposed bedrock units. The bottom photograph outlines with color the four members of the Mancos Shale and the Dakota Sandstone, differentiated on the basis of field observations. Kms-Smoky Hill Mbr.; Kmj-Juana Lopez and Montezuma Valley Mbrs.; Kmb-Blue Hill and Fairport Mbrs.; Kmg-Graneros and Bridge Creek Mbrs.; Kd-Dakota Sandstone. UTMX: 249509.22, 4276435.27.

Kmj **Juana Lopez and Montezuma Valley Members, undivided** — Brown to orange-brown to gray, calcarenitic, and calcareous marine shale. On the basis of field observations, the Juana Lopez is divided into two parts. The lower part is a moderately to highly fossiliferous, sandy, calcarenitic shale that exhibits low-angle cross-bedding and laminar bedding. The bedded units probably represent distal turbidite facies (D. Anderson, Colorado School of Mines and B. Ball, USGS, personal commun., 2006). The lower unit forms a distinctive orange-brown hogback near Peach Valley and orange-brown cliffs where exposed elsewhere in the mapped area. The upper unit is a gray, slightly fissile, silty, moderately calcareous shale, locally containing large concretions up to 3 feet in diameter. This part may correspond to the Montezuma Valley Member of the Mancos Shale at its type section in southwestern Colorado (as defined by Leckie and others, 1997). The contact with the overlying Smoky Hill Member is not well exposed. Fossils collected within this unit include (identified by B. Cobban, USGS, personal commun., 2006): *Prionocyclus macombi* (ammonite), *Lopha lugubris* (oyster), *Inoceramus dimidius* (bivalve), *Princoyclus bosquensis* (ammonite) (figures 9, 10, and 11), *Scaphities whitfieldi* (ammonite) (figure 11), and *Mytiloides incertus* (bivalve) (figure 9). The exposed thickness of the unit is approximately 130 feet.

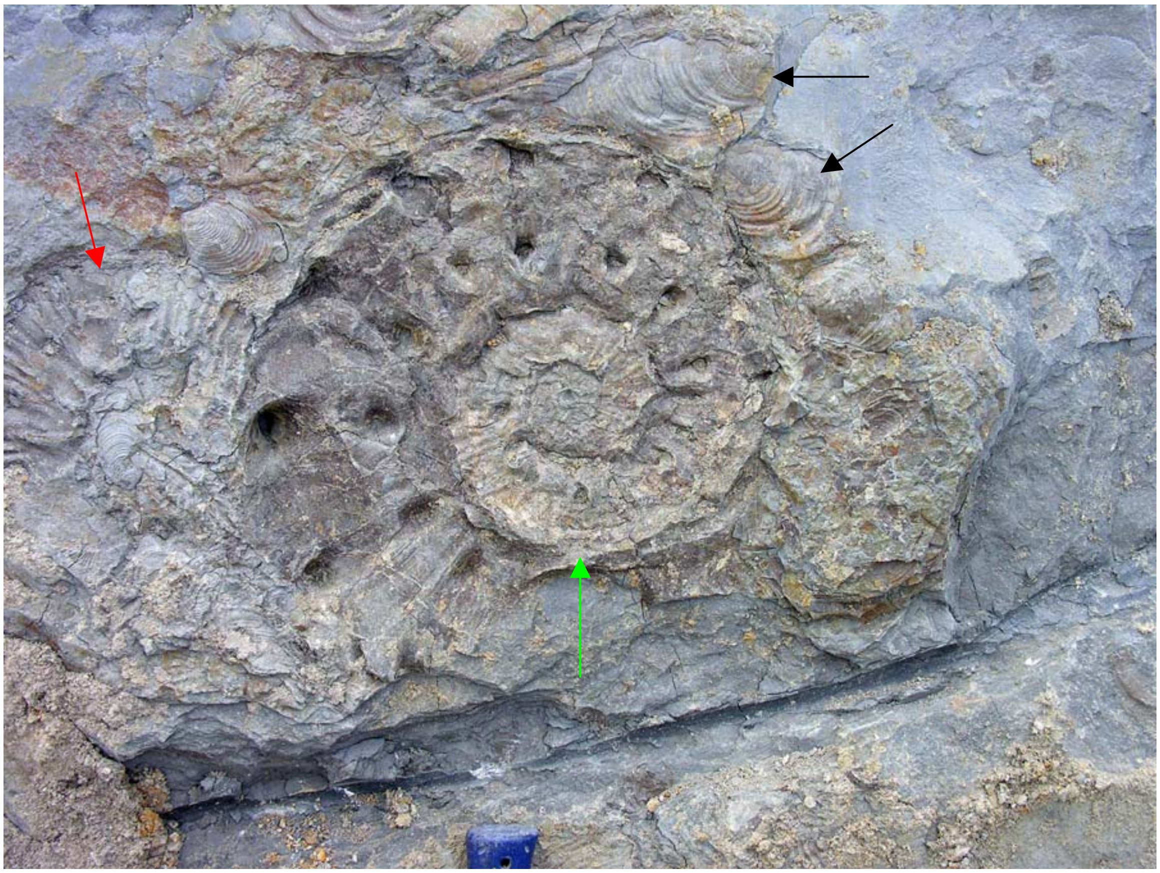


Figure 9. A large impression of *Princoyclus bosquensis* (green arrow) exposed on a block of shale from the Juana Lopez Member of the Mancos Shale from the Spring Creek pit. Specimen is approximately 9 inches across. Note the *Mytiloides incertus* (black arrows) and other *Princoyclus bosquensis* (red arrow) around the periphery. UTMX: 243276.77, UTMY: 4267429.35.

Figure 10. *Princoyclus bosquensis* within shale of the Juana Lopez Member of the Mancos Shale. Spring Creek pit locality. Width of impression is approximately 6 inches. UTMX: 243276.77, UTMY: 4267429.35.

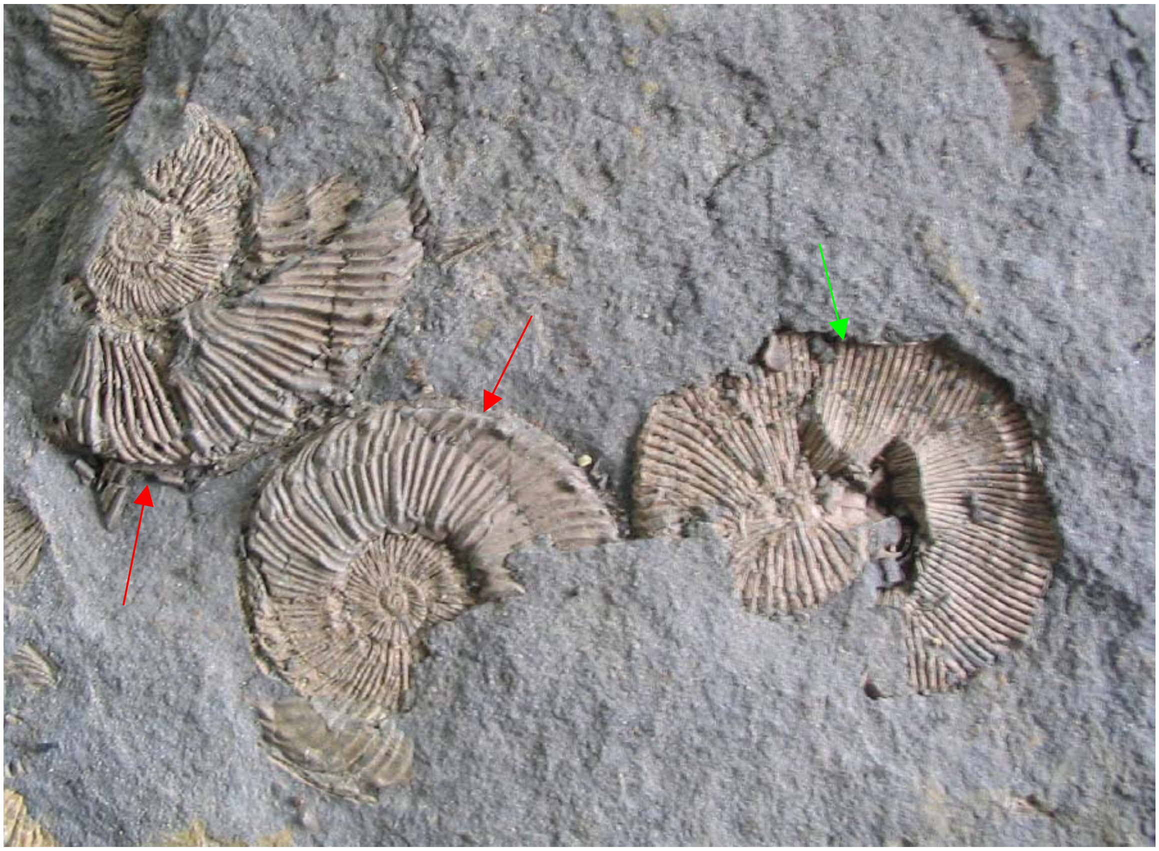


Figure 11. *Princoyclus bosquensis* (red arrows) and *Scaphities whitfieldi* (green arrow) in shale from the Juana Lopez Member of the Mancos Shale, Spring Creek pit locality. Width of photo is approximately 6 inches. UTMX: 243276.77, UTMY: 4267429.35.

Kmb **Blue Hill and Fairport Members, undivided** — Olive-green to dark-gray, glauconitic, non-fossiliferous, moderately to non-calcareous, silty, marine shale. The upper part of the unit consists of light- to dark-gray, platy, silty shale. Local seams of gypsum have caused the shale to part along bedding planes and fractures. Disc-shaped septarian concretions and calcareous sand lenses occur within the upper 20 feet of this unit. The middle part of the unit is olive-green, fissile shale with distinct bedding planes. The bedding surfaces often contain abundant glauconite grains and occasional coatings of yellow residue, presumably related to sulfide mineralization (pyrite). The glauconite and sulfide residue give the unit its overall olive-green appearance on weathered surfaces. The lower part of the unit is slightly silty, wavy-bedded, fissile shale. Glauconite and sulfide decreases to the base of the unit. Rare cone-in-cone structures are found within float derived from the Blue Hill shale. According to R. Grauch and A. Watchman (USGS, personal commun., 2006), the cone-in-cone structures are found in 2 or 3 discontinuous layers and form a rind around concretions. The Fairport Member was not specifically identified by biostratigraphy and is probably covered in the mapped area. It is mentioned here to retain consistency with the adjacent Montrose East quadrangle. The exposed thickness of the unit is approximately 170 feet.

Kmg **Graneros Member and Bridge Creek Limestone Member, undivided** — Soft, dark-gray to black to olive-green, slightly calcareous, marine shale that commonly weathers to small platy chips. Discontinuous, 8-inch-thick limestone beds occur in the middle and base of the unit and support a small hill in near the Eagle Valley Trailhead in the southeast part of “Candy Lane”. Most of the unit has distinct bedding planes that may be coated by gypsum crystals. The upper 25 feet of the unit consists of interbedded limestone, calcareous shale, and marlstone of the Bridge Creek Limestone Member. Fossils of *Pycnodote aff. kellumi* (bivalve) (identified by B. Cobban, 2006) (figure 12) were collected approximately 20 feet below the Bridge Creek Limestone Member. Glauconite and sulfide residue are locally present within the upper half of the unit. The exposed thickness of the unit in the mapped area is approximately 150 feet.

Figure 12*.* *Pycnodote aff. kellumi* collected from the Graneros Member of the Mancos Shale exposed near the Eagle Valley Trail (UTMX: 249164.50, UTMY: 4277044.50**)**, southeast part of “Candy Lane”.

Kdb **Dakota Sandstone and Burro Canyon Formation, undivided (Lower and Upper Cretaceous)** — The Burro Canyon Formation consists of low- to highangle, cross-bedded medium to fine-grained sandstone and well rounded, chert and quartz pebble conglomerate, interbedded with light-green to red mudstones. The Burro Canyon Formation was created by a vast fluvial system; Hansen (1987) suggested the chert and quartz pebbles were transported from as far away as Utah and Nevada. Thickness of the Burro Canyon Formation is approximately 25 feet in the mapped area. The overlying Dakota Sandstone is composed of well sorted, very fine- to medium-grained, light-brown to yellow-brown sandstone interbedded with gray to black siltstone and carbonaceous shale. Symmetrical ripple marks and burrows (typically *Thalassinoides*) are present on bedding planes of some sandstone beds. The paleoenvironmental setting for the Dakota Sandstone has been interpreted by Weimer (1970) as a marine regression represented by the increase in clastic sedimentation due to shifting in the distributary channels on the Cretaceous coastal plain. The approximate thickness of the Dakota Sandstone in the mapped area is 100 feet. Both formations are well exposed along the Eagle Valley Trail (UTMX: 249164.50, UTMY: 4277044.50) where many stacked channels with abundant cross-bedding are visible in the cliff faces.

Jm **Morrison Formation (Upper Jurassic) — Shown on cross-section only.**

Jw **Wanakah Formation (Middle Jurassic) — Shown on cross-section only.**

Je **Entrada Sandstone (Middle Jurassic) — Shown on cross-section only.**

Pc **Precambrian Rocks — Shown on cross-section only.**

STRUCTURAL GEOLOGY

The Gunnison uplift, which borders the northeastern edge of the mapped area, is the result of vertical movement of basement blocks during the Laramide Orogeny. The core of the uplift consists of a series of northeast-tilted basement blocks, bounded on its western side by the Red Rocks and Cimarron reverse faults (Kellogg, 2004). Neither of these faults is exposed in the mapped area. Deformation along the western margin of the Gunnison uplift created gently to steeply dipping folds that warped the overlying Cretaceous rocks. This warping occurred along block edges and resulted in a westward dipping monocline that is beautifully exposed on the east side of Peach Valley. Dips of the Mancos hogback gradually decrease from 55° at the southeast to only 5° at the north end of Peach Valley and are typically less than 5° eastward. The strike of the beds also changes from S50E to N-S in the same southeast to north direction.   The flattening of the dips and abrupt change in strike occurs near the mouth of an unnamed canyon (UTMX: 249164.51, UTMY: 4277044.53) along the Eagle Valley Trail, suggesting the canyon is a boundary between two basement blocks. Greater uplift and rotation on the southern block relative to the northern block has caused steepening in the fold limb and the change in strike.

The Montrose syncline, a gentle synclinal fold, trends roughly northwest-southeast through the northeastern part of the quadrangle. This structure may by caused by folding of the Mancos Shale over a blind fault in the subsurface or possibly the result of compression from the adjacent Uncompahgre and Gunnison uplifts. West of the Montrose syncline, the dips in the Mancos shallow to only 2° and strikes are variable.

Northeasterly tilting and rejuvenated movement along basement faults bounding the Uncompahgre uplift during the Laramide resulted in gentle folding and the shallow easterly dips of the Cretaceous rocks in the western part of the mapped area (Tweto, 1977; Stone, 1977). Strikes of the Mancos along the Uncompahgre River range from N60W east of the river to N-S on the west side. Interestingly, the axis of the Uncompahgre River has followed the general strike direction of the beds.

Some authors cite evidence for recent uplift in the Black Canyon of the Gunnison. On the basis of deposited Pleistocene terrace gravels along the Black Canyon and presence of Miocene-Pliocene gravels of Hinsdale Formation volcanics near the head of the Canyon, Hansen (1987) determined that cutting of the Black Canyon of the Gunnison commenced about 2 million years ago. He also suggested that recent uplift along faults during the Quaternary caused increased rates of downcutting within the canyon. Recent work by Karl Karlstrom and students (Sandoval and Karlstrom, 2006; Schneeflock and others, 2002) stated that knickpoint migration within the Black Canyon may also be the result of neotectonics and/or modification of drainage networks. Currently, this is a hot topic and continued research will undoubtedly yield additional clues to the origin of the Black Canyon of the Gunnison.

GEOLOGIC HAZARDS

Bedrock structure, hydrogeology, topography, surface drainage, and lithology are important controls on the development of geologically hazardous areas within the Olathe quadrangle. Landslides within the Mancos Shale affect most of the western part of the quadrangle where residential development is increasing. Mudflows and hydrocompactive and swelling soils are also impacting residential and commercial structures throughout the area. Other significant and potentially damaging hazards in the mapped area include corrosive and erodible soils and earthquakes.

Landslides

Landslides are prevalent on the slopes flanking the high, gravel-capped mesas over much of the western half of the quadrangle. The landslide debris in these areas is almost exclusively a mixture of weathered Mancos Shale and gravelly alluvium. The slope failures are mainly rotational and translational slides where failure typically occurs along a vertical or nearly vertical system of fracture planes. These fractures may become exposed from desiccation of the surface soils and/or removal of the resistant gravel cap.   Water can seep into the cracks causing dispersion of less-resistant clay layers or dissolution of gypsum within the fractures (piping). The resulting landslides typically occur along gullies or steep hillsides where runoff can accelerate and move particles out of the soil or bedrock (Selby, 1993).

Occurrence of landslides within the quadrangle is accelerated by poor agricultural practices where runoff from irrigated farmland seeps into and lubricates open fractures, resulting in slope failures. According to local residents, several human-induced landslides have occurred along the eastern margin of High Mesa and the northeast side of Franklin Mesa. These areas are highly irrigated for agriculture and runoff typically pours over the mesa sides. The oldest of these slides in recent memory dates to the early 1960s and the most recent occurred in 2005. The 2005 landslide located in sec. 16, T. 49 N., R. 10 W. (figures 7 and 13) started as a rotational landslide, where part of Franklin Mesa “peeled” away, rotated, and toppled. This created a 120-foot-wide graben where the confined debris began to flow down gradient (east), forming many 1- to 5-foot-high terracettes. Exposures along the 2005 headscarp and other, older headscarps in the area reveal many buried soil horizons that indicate multiple landslide events (figure 14).

Several other young landslides, dating back to the 1960s, are located in secs. 21 and 28, T. 50 N., R. 10 W (figure 15). These are mostly rotational landslides with headscarps reaching 40 feet in height. Composition of the deposits is exclusively weathered Mancos Shale and Quaternary gravels.

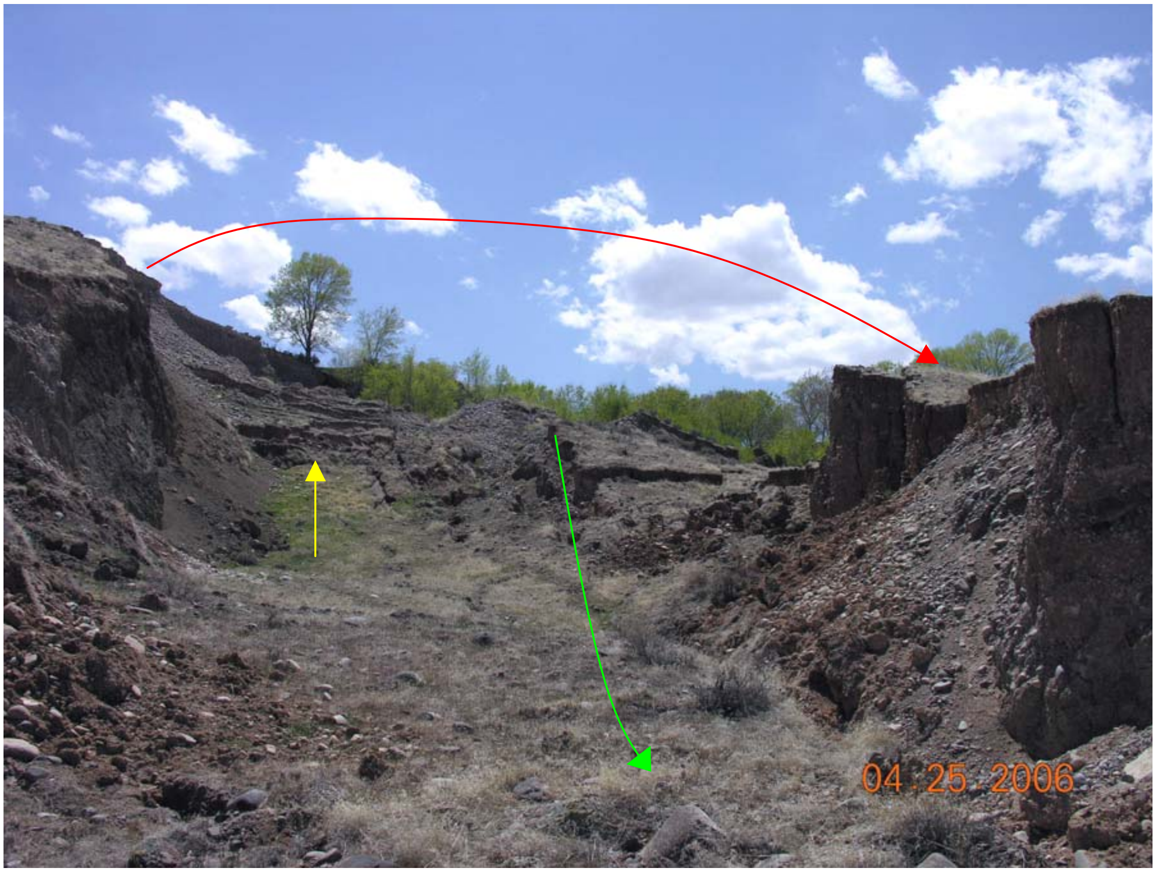


Figure 13. View looking west into the 120-foot-wide headscarp graben within the 2005 landslide. Yellow arrow points to terracettes, some reaching 5 feet in height. The debris shown by the red arrow slid from the mesa edge at the left side of the photo. Green arrow indicates the direction of debris movement within the fissure. UTMX: 239333.39, UTMY: 4267461.59.

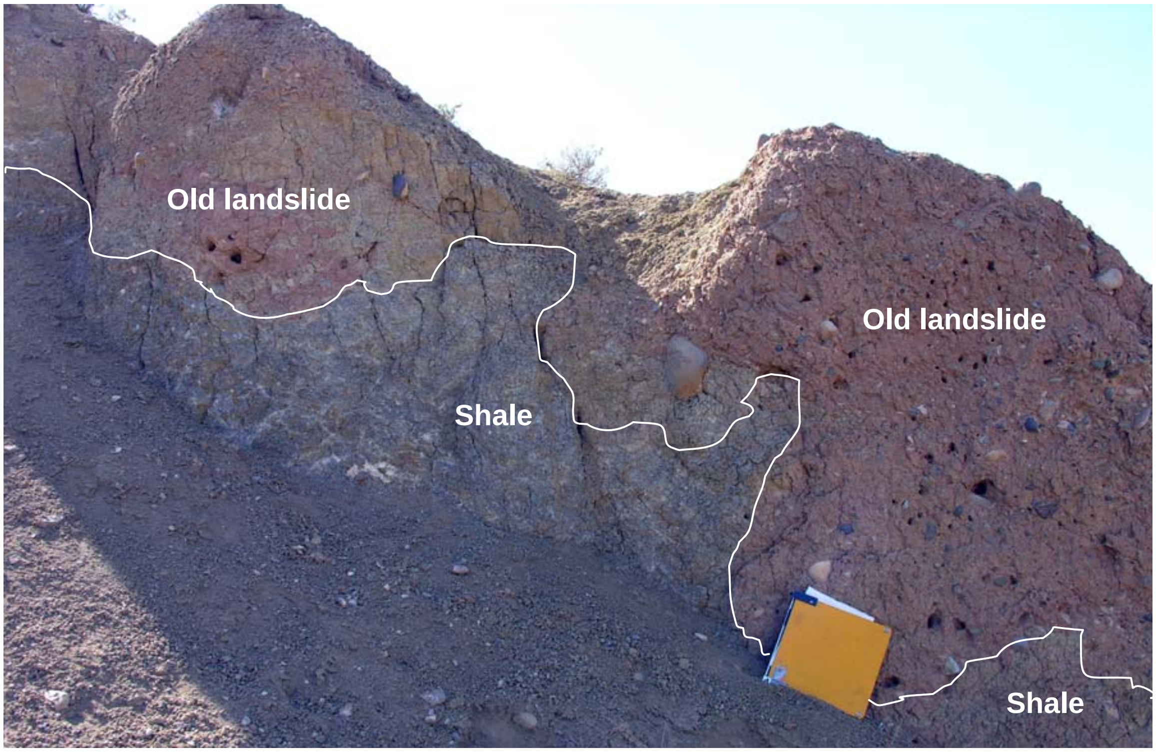


Figure 14. Older landslide deposits (pinks and yellow-browns) over highly fractured Mancos Shale (gray). Boundary between bedrock and the landslide deposit is shown by white line. UTMX: 239491.80, UTMY: 4267270.84.

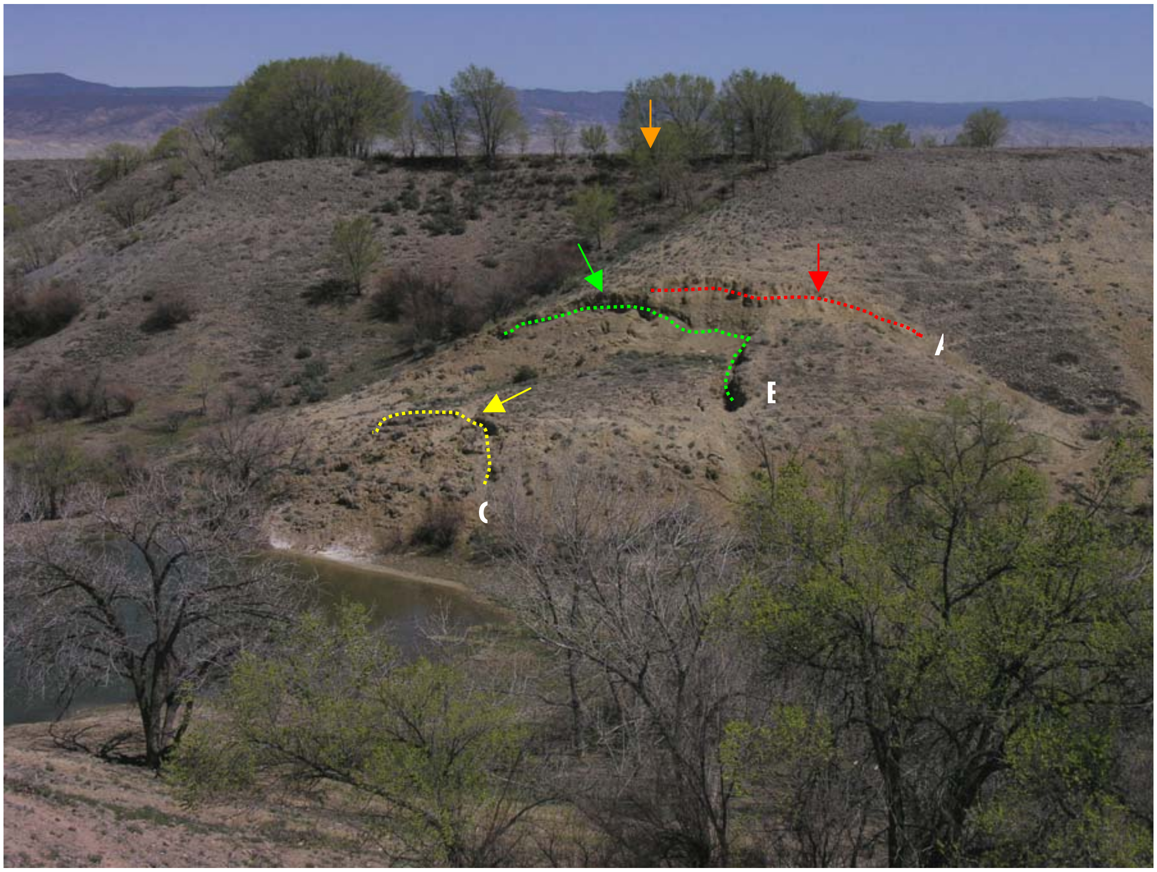


Figure 15. Photo looking west at a young rotational landslide complex on the northwest side of High Mesa. At least three different headscarps are indicated by the red, green, and yellow arrows (also labeled A, B, and C, respectively). The orange (uppermost) arrow points to an irrigated field on the flat, gravel-capped mesa surface. The landslides were probably caused by undermining of the exposed Mancos Shale by the stream at the landslide toe and by irrigation waters seeping into the shale. UTMX: 238766.77, UTMY: 4274610.71.

Muddy earthflows derived from the Mancos occur in “Candy Lane”, in the far northeastern corner of the quadrangle. These lobate flows consist of disintegrated Mancos Shale that mobilized from steep (> 50°) hillsides. The flow surfaces have a “popcorn” appearance indicative of expansive clays and contain very little (< 1%) coarse debris despite their proximity to the Qg deposits. As a result, surface support is minimal and the upper 6 inches of the deposit may collapse if walked upon.

Debris Flows (Mudflows)

Debris flows are dense, heterogeneous mixtures of mud, rock fragments, and plant materials that typically follow preexisting drainages (Varnes, 1978). As the debris flow moves down its valley, its size and power increase, and it incorporates additional materials into the flow. Once the flow reaches an area of lower gradient, the flow drops its load and the suspended sediment is deposited at the mouth of the drainage (Varnes, 1978). Debris flows can form at any point along a drainage including on the sides of valleys. They are the result of torrential rainfall or very rapid snowmelt runoff, where sediment supply is abundant and easily mobilized (Selby, 1993).

Much of the eastern half of the quadrangle consists of mud-dominated alluvium and alluvial fan deposits (Qamf). These deposits were derived mostly from the Mancos Shale and were deposited as mudflows or mud and gravel debris flows in channels or in local drainage basins. Furthermore, alluvial-fan deposits (Qf) occur over the western half of the mapped area where drainages are more confined and coarser sediment is available for transport. Small, localized debris flows occur in areas mapped as alluvium and landslides (Qls); however, these debris flows are of limited extent and are not mapped separately. Residents living within or in close proximity to these deposits and their associated drainageways should be aware of the possibility of large precipitation events triggering future debris flows that may inundate these areas with dangerous amounts of water and sediment.

Rockfall

Rockfall deposits are included in the colluvium (Qc) and landslide (Qls) units in the Olathe quadrangle. Much of the rockfall hazard occurs along the mesa edges where loose cobbles and boulders overlie unconsolidated Mancos Shale. There are isolated areas of rockfall along the steep canyon walls of the Eagle Valley Trail where blocks of Dakota Sandstone have toppled from undermining of interbedded shales and mudstones. These deposits are of limited extent and were not mapped separately. Large precipitation events and freeze-thaw processes may trigger rockfall. Areas mapped as Qc and Qls are susceptible to future rockfall events; developers and homeowners should be cautious when building in proximity to these areas.

Earthquakes

Minor seismic activity has been recorded near Montrose and Olathe. In May of 1992, the U.S. Geological Survey measured an earthquake of magnitude 2.8 approximately 5 miles southeast of Olathe, and on January 13, 1962, a magnitude 4.4 event occurred approximately 6.5 miles southwest of Montrose in the adjacent Montrose East quadrangle (Kirkham and others, 2004). Both events were felt at intensity IV (Scale I-XII) in Olathe and Montrose (Kirkham and others, 2004). The Olathe event lies along the trend of the Cimarron and Red Rocks faults, which are suspected to have middle to late Quaternary movement (Lettis and others, 1996). On October 11, 1960, the largest instrumentally recorded earthquake in Colorado measured magnitude 5.5 and occurred approximately 15 miles southeast of Montrose (Kirkham and others, 2004). This event was felt at intensity V in Olathe and damaged buildings in Montrose and nearby communities.

Additional information on faulting and earthquakes in this are is described in the CGS Colorado Earthquake Map Server (Kirkham and others, 2004) or the Colorado Late Cenozoic Fault and Fold Database and Internet Map Server (Widmann and others, 2002). Both are available for no charge on-line at *http://geosurvey.state.co.us*.

Swelling Soils

Certain parts of the Mancos Shale and surficial units derived from the Mancos Shale may undergo volumetric swelling when wetted due to the presence of smectite, an expansive clay mineral. Smectite is prevalent in marine shales of Cretaceous age in the North American mid-continent. Upon wetting, these clay minerals, which are relatively dry under natural climate conditions, draw water into their crystalline matrices and expand to accommodate the added water molecules (Noe and others, 1997). The expansion of clays results in ground heaving and potential damage to residential, private, and public buildings, paved roads, concrete flatwork, and underground utility pipes.

In the Olathe quadrangle, the Graneros and Smoky Hill Members of the Mancos Shale (Kmg and Kms) contain clay-rich zones that may be prone to swelling in near-surface bedrock. Derived soils, particularly the alluvial mudflow (Qamf) deposits, may contain pockets or zones of swelling clays. According to geologists and engineers from many of the local geotechnical companies, the detection of swelling soil conditions is best accomplished on a site-specific basis. This involves the drilling of exploratory boreholes, typically to depths of up to 20 feet, recovering samples from critical strata and depths, and testing the properties of those samples. A number of tests including Atterberg limits and swell/consolidation may be used to assess the plasticity and swell potential of the samples.

Collapsible Soils and Bedrock

Both the Mancos Shale and surficial units derived from the Mancos Shale may be prone to collapse. Where weathered Mancos Shale is near the surface, growth of gypsum crystals typically occurs along bedding planes and fractures. Increased mineralogical volume changes from the formation of gypsum in this reaction can create crystallization pressures that force or wedge apart bedding planes and fractures, causing the rock to heave. Upon further wetting, subsequent dissolution of the gypsum can create micro-pipes and subsurface voids that may cause the weathered claystone to collapse or recompress when loaded (White and Greenman, in prep.).

Surficial deposits derived from the Mancos Shale are especially prone to hydrocompaction and dispersion. In these dry deposits, the addition of water causes soil-binding agents to weaken and the loose soil skeletal fabric to collapse, which allows the soil particles to reorient into a more compact structure. This often results in ground settlement. Collapse typically occurs in matrix-supported deposits where clay- and silt-sized particles dominate the matrix. Furthermore, dissolution of gypsum within these deposits may also contribute to collapse.

Dispersion is a form of piping erosion and is a function of the mineralogy and specific soil chemistry. In the presence of fresh water, clay particles easily mobilize and begin to flow. Pseudokarst land features, such as sinkholes, pipes, soil bridges, and other subsurface voids are typical manifestations of soil dispersion in these collapse-prone units (Figure 16). Some of the voids are large enough to engulf people, cattle, and farm implements. A local resident living along the Loutsenhizer Arroyo maintains that in the 1960s a soil scientist fell into a large, snow-covered void and proceeded to walk along a subterranean cavern for several hundred feet before exiting along the arroyo bank. Soils that are susceptible to hydrocompaction and dispersion-collapse phenomena may exist in areas mapped as alluvial fans (Qf), alluvium and mudflow deposits (Qamf).

Damage such as cracking of foundations and other structural problems can be caused by ground settlement, sinkholes, subsurface voids, and heaving, usually as a result of adverse wetting and structural loading. Dry density, moisture content, and swell-consolidation tests are usually performed to determine the degree of potential hydrocompaction. Crumb tests, pinhole tests, double hydrometer tests, and measurement of soluble salts and calculation of the Sodium Absorption Ratio (SAR) are more specialized tests to determine the potential of soil dispersion (White and Greenman, in prep.). Because of the frequency of subsurface voids and potential for long-term settlement, residents should be cautious when building upon or traversing the units mapped as Qamf.

Some of the bedrock zones and soil deposits may have both collapse and swelling properties. The actual reaction of the bedrock to introduced water may depend on its clay mineralogy, the natural moisture content, the presence and abundance of gypsum, and applied external load (weight of a structure). The reaction of the soil to wetting may depend on its porosity and internal skeletal fabric, in addition to clay mineralology, moisture contents, and applied load. Instances occur where certain soil deposits and weathered bedrock may slightly swell upon wetting but quickly settle or collapse upon incremental loading. Such conditions need to be assessed by professional engineering geologists or geotechnical engineers and taken in account during the design of structure foundations, concrete slabs, and road pavements.

Figure 16. A sinkhole within Qamf deposits along the Loutsenhizer Arroyo. The sinkhole is approximately 40 feet long, 25 feet wide and 15 feet deep. It formed due to collapse of a soil bridge into a subterranean void. Red arrow points to an intact soil bridge overlying a void space. UTMX: 244452.97, UTMY: 4277454.92.

Erodible Soils

Wind and water runoff are the biggest causes of erosion; however, these are amplified by development and grazing of vegetated lands where the soil is exposed and easily eroded. Exposed bedrock of the Mancos Shale and its surficial derivatives are susceptible to moderately high erosion, especially where vegetation is naturally absent or has been removed (NRCS, 2006) and where slopes are at least moderately steep. Soils with a high silt fraction are the easiest to erode and produce high rates of runoff. The National Resource Conservation Service (NRCS) estimates that 86 tons per acre per year of soil erosion is possible from the Mancos Shale and silty surficial units. The least susceptible areas of erosion correspond to the gravel-capped mesas and Dakota Sandstone.

There is a close correlation between wind erosion and the texture of the surface layer, the size and durability of surface clods, rock fragments, humus, and amount of $CaCO_3$

in the soil. Wind velocity, soil moisture and frozen soil layers also influence wind erosion. The estimates for erosion are based primarily on percentage of silt, sand, and organic matter and on soil structure and saturated hydraulic conductivity (NRCS, 2006).

Wind erosion may adversely affect the respiratory functions of humans and livestock by reducing air quality by increasing airborne dust. Furthermore, soil erosion increases the risk of pollution to surface and ground waters due to the use of pesticides from agricultural and residential treatment of vegetation.

Some local residents report suffering from intermittent bouts of shaking, insomnia, headaches, numbness, chest tightness, and high blood pressure. These adverse health effects may be caused by selenium poisoning or selenosis (MedicineNet.com, 2006). The selenium is found in the Mancos Shale and soils derived from the Mancos Shale. It is commonly inhaled by humans and livestock during and following wind storm events. Precipitation brings the selenium and other salts to the surface; crusts may form on the surface soils when dry.

Corrosive Soils

The Mancos Shale and sediments derived from the Mancos Shale typically have high salt and sulfate content and should be considered a potentially corrosive soil. Corrosive soils may damage typical concrete and buried metal. According to a local resident, a one-inch-thick steel pipe was nearly dissolved after only one year of burial two feet below the ground. Residents should frequently examine any pipes or storage tanks (i.e. propane) that are exposed to these soils for signs of corrosion. The use of PVC pipes and plastic tanks, cathodic protection, or corrosion-resistant coatings is highly recommended in these areas. Most geotechnical consultants in the Olathe area specify special corrosion-resistant concrete mixes for foundations and slab-on-grades, as well as protective coatings for buried metalworks.

MINERAL RESOURCES

Sand and gravel are presently the most economically significant mineral resources in the Olathe quadrangle. Six active aggregate mines are located in the mapped area; the most productive is the Spring Creek Pit, which produces 100,000 tons of aggregate per year (Guilinger and Keller, 2004). From the 1940s through the 1980s, several oil and gas wells were drilled and subsequently abandoned. No production information is listed for these wells (Colorado Oil and Gas Conservation Commission website at http://oil-gas.state.co.us).

According to local residents, clay from the Mancos Shale was used to produce “adobe” bricks for building stone. Many of these turn-of-the-century structures are still standing today throughout the area.

Potential exists for the development of additional sand and gravel operations in the significant alluvial deposits in the mapped area and shale outcrops may provide clay for brick production. Figure 17 shows the locations of the currently active gravel pits and inactive oil and gas wells within the quadrangle.

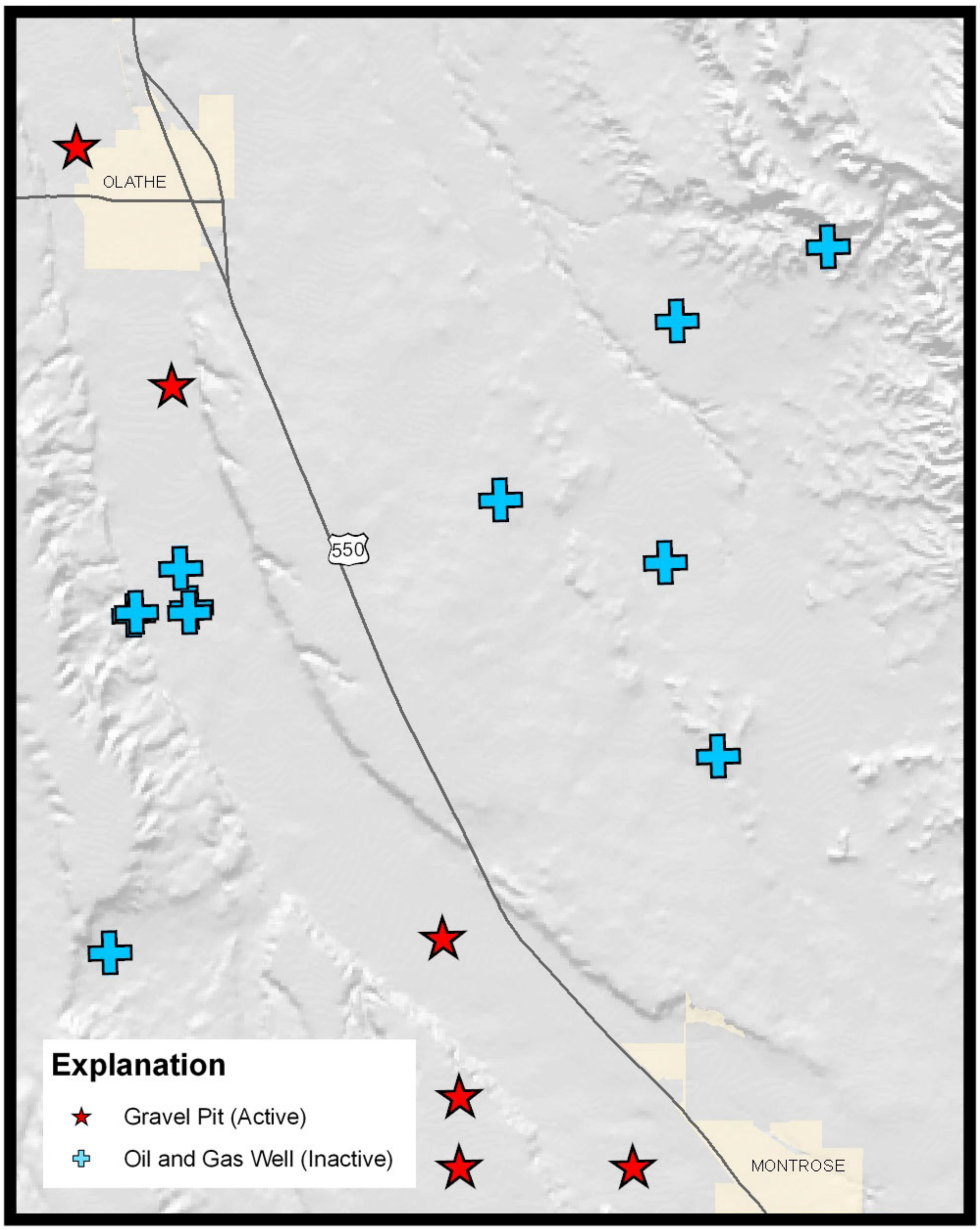


Figure 17. Location of active gravel pits and inactive oil and gas wells in the Olathe quadrangle.

Construction Aggregates (crushed rock and sand and gravel)

Six sand and gravel operations are currently active in the quadrangle. Thirteen other sand and gravel pits were once active; however, these have ceased operation and are in various stages of reclamation (Keller and others, 2002). In addition to sand and gravel, crushed stone may also be produced from these operations. Production comes from the Quaternary alluvium deposited by the Uncompahgre River and its tributaries.

The largest producing operation in the quadrangle is the Spring Creek Pit located in sec. 13, T. 49 N., R. 10 W. Annual production has topped 100,000 tons of sand and gravel (Guilinger and Keller, 2004). The mine is owned by Oldcastle SW Group and operated by United Companies of Mesa County of Grand Junction, Colorado.

Oil and Gas

From 1928 through 1984, 14 oil and gas wells were drilled and subsequently abandoned within the mapped area (COGCC website at http://oil-gas.state.co.us/ and G. Young, CGS, personal commun., 2007). The “Eisaguirre #2” well, located in the SE NE sec. 17, T. 50 N., R. 9 W., was drilled into the western edge of Montrose syncline to a depth of 500 feet where Mancos Shale was encountered. A series of wells followed a northwest-southeast trend along the Loutsenhizer Arroyo. The Mancos in this area dips to the north between 2° and 4° degrees and strikes roughly east-west, possibly indicating the presence of a broad, north-plunging anticline. The location of the wells along the crest of the anticline suggests a structural trap may have been the target. The deepest well with log information was the Uncompahgre Oil and Gas “Olathe #1” (SE SE SW sec. 27, T. 50 N., R.10 W.) encountered Chinle Formation at a depth of approximately 2000 feet (Figure 18). No production information is listed for any of the wells so it is doubtful they were successful, and thus it is unlikely that the area will yield any future production. Additional information on oil and gas production may be obtained from the Colorado Oil and Gas Conservation Commission.

Figure 18. An old photograph probably showing the Uncompahgre Oil and Gas “Olathe #1” well. The photo was likely taken in 1928-1929, soon after the well was drilled. View is looking to the northeast. Photo from the collection of Vince Matthews.

GROUND-WATER RESOURCES

The primary source of domestic drinking water within the Olathe quadrangle comes from the Gunnison River (M. Catlin, Uncompahgre Valley Water Users Association, personal commun., 2006). The water is transported to the local communities via the 5.8 mile-long Gunnison Tunnel and is stored in the Taylor Park Reservoir located approximately 60 miles east of Olathe in the Sawatch Range. A complex system of canals and diversion dams makes the water available for agricultural use. Other important sources of domestic drinking water are from alluvial and bedrock wells. Depending on location, ground water can be found in two hydrogeologic units: (1) consolidated bedrock aquifers found in the Dakota Sandstone, or (2) Quaternary alluvium. The following sections describe each of these hydrogeologic units and provide information about general hydrogeologic characteristics of the units gathered from available literature. The scope of this discussion is limited to providing a general description of the ground-water resources that might be available within the quadrangle; further details, such as specifics about water quality, surface water, and current water level data can be obtained from available literature. Additional information on ground water in Colorado is in the CGS Ground Water Atlas of Colorado (Topper and others, 2003).

Alluvial Aquifers

A majority of the ground-water for domestic use comes from the Quaternary alluvial and alluvial terrace deposits associated with the Uncompahgre River valley. This alluvial aquifer is part of the Gunnison River basin, which extends west from the Continental Divide to Grand Junction and south to Telluride (Topper and others, 2003). Much of the alluvium is in direct hydraulic connection with the river and forms an unconfined aquifer where saturated with ground water. The areal extent of the alluvial aquifer roughly coincides with the areal extent of the alluvium; however, the alluvium is not always saturated with ground water and the presence of alluvium at the surface does not imply the presence of an aquifer at depth.

On the basis of records obtained from the Colorado Department of Water Resources (DWR), water levels in wells completed in the alluvial aquifer generally lie between the surface and approximately 35 feet below the surface. The areal extent of the alluvial aquifer, therefore, would be expected to be somewhat smaller than that of the alluvium. Well depths drilled into the alluvium range from 11 to 65 feet and depths are greatest at the northern and southern ends of the valley. Well yields vary from 0 to 110 gallons per minute (GPM) but are typically 30 GPM and do not significantly fluctuate by location.

Recharge of the alluvial aquifer occurs via natural precipitation, infiltration from the surface water canal system (Meeks, 1950), and from the Uncompahgre River and its tributaries (Topper and others, 2003). The alluvial water can be high in $CaCO_3$, resulting in hard water and requiring the use of a water softener (Meeks, 1950). Due to the possibility of natural and human contamination from surface waters and the introduction of salts from bedrock units, it is recommended that residents using alluvial water for domestic purposes complete a water quality test. According to Apodaca and Bails (2000) water-quality data for the Uncompahgre River alluvial aquifer is as follows:

Total Dissolved Solids (TDS), mg/L	Hardness, mg/L	Radon-222, pCi/L	Iron, µg/L
168-397 (279)	94-290 (195)	577-1928 (1033)	<3.0-7439 (1503)

Bedrock Aquifers

The Dakota Sandstone is the primary bedrock aquifer in the mapped area for both domestic and livestock uses where ground-water from alluvial aquifers is not feasible. Regionally, sandstone bodies in the lower part of Mancos Shale are also used for domestic water, but to a limited extent (Meeks, 1950). West of the mapped area, in Shavano Valley, the Morrison Formation is a common domestic water target. No water wells in the Olathe quadrangle produce from either the Mancos Shale or the Morrison Formation.

The Dakota Sandstone generally consists of well sorted, very fine- to medium-grained, light-brown to yellow-brown sandstone interbedded with gray to black siltstone and carbonaceous shale. The porosity of the sandstone beds is highly variable and is not published for the Olathe area. On the basis of surface outcrops and well logs, the potential thickness of the Dakota Sandstone aquifer ranges from about 100 to 180 feet in the mapped area (Meeks, 1950). The aquifer may be confined to partially confined, and artesian wells occur in some locations.

Water-level data for the Dakota aquifer can be obtained from the Division of Water Resources (DWR) well permit files. Well-completion reports and pump-installation reports for wells often list the water levels that existed when the wells were completed. These data are one-time measurements and thus, the reported water level is not necessarily representative of current conditions in the well. Water levels in the Dakota aquifer can be expected to vary considerably depending on location and elevation; values listed in the DWR permit database are between 245 and 1,090 feet below the surface. Well yields from the Dakota aquifer within the quadrangle typically range from 1 to 30 GPM and average 12 GPM. Ground water from the Dakota Sandstone aquifer is considered “tributary” and directly connected to surface water (Hobbs, 2003). Thus, this groundwater is subject to the State of Colorado surface water appropriations system.

According to Meeks (1950) water from the Dakota aquifer tends to contain sodium bicarbonate that can impart a distinctive taste to the water. The quality of the water decreases from west to east and is typically better near the recharge zone on the east flank of the Uncompahgre uplift (Meeks, 1950). In general, water quality of the Dakota aquifer in the area is adequate for domestic use with total dissolved solids (TDS) values ranging from approximately 210 to 4,200 mg/L and averaging 1,845 mg/L (Meeks, 1950).

REFERENCES CITED

Apodaca, L.E., and Bails, J.B., 2000, Water quality in the alluvial aquifers of the Southern Rocky Mountains physiographic province, upper Colorado River basin, water years 1972-92: U.S. Geological Survey Water-Resources Investigations Report 97-4240.

Armstrong, R.L., 1968, Sevier orogenic belt in Nevada and Utah: GSA Bulletin, v. 79, p. 429-458.

Ball, B.A. Cobban, W.A., Grauch, R.I., McKinney, K.C., Livo, K.E., Sawyer, D.A., and Merewether, E.A., 2006, A new core of the Mancos Shale (USGSCL-1), Gunnison Gorge National Conservation Area, Montrose County, Colorado: *in* Larson, N.L. and Landman, N.H., eds, A symposium on the paleontology, geology and stratigraphy of the Late Cretaceous Western Interior seaway, black Hills Museum of Natural History, Hill city, SD, p. 13-14.

Cobban, W.A., and Scott, G.R., 1972, Stratigraphy and ammonite fauna of the Graneros Shale and Greenhorn Limestone near Pueblo, Colorado: U.S. Geological Survey Professional Paper 645, 101 p.

Cruden, D.M., and Varnes, D.J., 1996, Landslide types and processes, in Turner, A.K., and Schuster, R.L. (Editors), Landslides – investigation and mitigation: Transportation Research Board Special Report 247, National Academy Press, Washington, D.C., p. 36-75.

Dickinson, R.G., 1965, Geologic map of the Cerro Summit quadrangle, Montrose County, Colorado: U.S. Geological Survey, Geologic Quadrangle Map GQ-486, scale 1:24000.

Dickinson, R.G., 1987, Geologic map of the Buckhorn Lakes quadrangle, Montrose County, Colorado: U.S. Geological Survey, Geologic Quadrangle Map GQ-1642, scale 1:24,000.

Foos, Anabelle, 2006, Geology field trip guide to the Colorado Plateau: National Park Service on-line guidebook, http://www2.nature.nps.gov/geology/education/foos/plateau.pdf.

Geological Society of America, 2000, Munsell Soil Color Chart, MC-01.

GretagMacbeth, 2000, Munsell® soil color charts, year 2000 revised washable edition: New Windsor, NY, GretagMacbeth, LLC.

Guilinger, J.R., and Keller, J.W., 2004, Directory of active and permitted mines in Colorado – 2002: Colorado Geological Survey Information Series 68.

Hail, W.J., 1986, Geologic reconnaissance map of the Government Springs quadrangle, Montrose and Ouray Counties, Colorado: U.S. Geological Survey, Open-File Report OF-86-162, scale 1:24000.

Hail, W.J., 1986, Geologic reconnaissance map of the Montrose West quadrangle, Montrose County, Colorado: U.S. Geological Survey Open-File Report OF-86-163, scale 1:24000.

Hail, W.J., 1987, Geologic map of the Colona quadrangle, Montrose and Ouray Counties, Colorado: U.S. Geological Survey, Miscellaneous Field Studies Map MF-2003, scale 1:24000.

Hansen, W.R., 1968, Geologic map of the Black Ridge quadrangle, Delta and Montrose Counties, Colorado: U.S. Geological Survey, Geologic Quadrangle Map GQ-747, scale 1:24000.

Hansen, W.R., 1971, Geologic map of the Black Canyon of the Gunnison River and vicinity, western Colorado: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-584, scale 1:31680.

Hansen, W.R, 1987, The Black Canyon of the Gunnison – in depth: Tucson, Arizona, Southwest Parks and Monuments Association, 58 p.

Hettinger, R.D., and Kirschbaum, M.A., 2002, Stratigraphy of the Upper Cretaceous Mancos Shale (upper part) and Mesaverde Group in the southern part of the Piceance and Unita Basins, Colorado and Utah: U.S. Geological Survey Geologic Investigations Series I-2764, 21 p., 2 plates.

Hobbs, Jr., Gregory, 2003, Citizen's Guide to Colorado Water Law: Colorado Foundation for Water Education, 33 p.

Hunt, C.B., 1956, Cenozoic geology of the Colorado Plateau: U.S. Geological Survey Professional Paper 279, 99 p.

Ingram, R.L., 1989, Grain-size scales used by American geologists – modified Wentworth scale, *in* Dutro, J.T., Jr., Dietrich, R.V., and Foose, R.M. (Compilers), AGI data sheets, 3rd Edition: Alexandria, VA, American Geological Institute, Sheet 17.1.

International Commission on Stratigraphy, 2005, International stratigraphic chart: downloaded January 2006 from the International Commission on Stratigraphy website, www.stratigraphy.org/chus.pdf.

Johnson, R.C., 2003, Depositional framework of the Upper Cretaceous Mancos Shale and the lower part of the Upper Cretaceous Mesaverde Group, western Colorado and eastern Utah: U.S. Geological Survey Digital Data Series DDS-69-B, 24 p., 1 plate.

Keller, J.W., Phillips, R.C., Morgan, K., 2002, Digital inventory of industrial mineral mines and mine permit locations in Colorado: Colorado Geological Survey Information Series 62, CD-Rom.

Kellogg, K.S., Hansen, W.R., Tucker, K.S., and Van Sistine, D.P., 2004, Geology of the Gunnison Gorge National Conservation Area, Delta and Montrose Counties, Colorado: U.S. Geological Survey, Fact Sheet FS-2004-3050, scale 1:45000.

Kirkham, R.M., Rogers, W.P., Powell, L., Morgan, M.L., Matthews, V., and Pattyn, G.R., 2004, Colorado Earthquake Map Server: Colorado Geological Survey Bulletin 52b, http://geosurvey.state.co.us/pubs/eq/.

Leckie, R.M., Kirkland, J.I., and Elder, W.P., 1997, Stratigraphic framework and correlation of a principal reference section of the Mancos Shale (Upper Cretaceous), Mesa Verde, Colorado: New Mexico Geological Society Guidebook 48, p. 163-216.

Lettis, W., Noller, J., Wong, I., Ake, J., Vetter, U., and LaForge, R., 1996, Draft report, Seismotectonic evaluation of Colorado River storage project-Crystal, Morrow Point, Blue Mesa dams, Smith Fork project-Crawford dam, west-central Colorado: unpublished draft report prepared by William Lettis & Associates, Inc., Woodward-Clyde Federal Services, and Seismotectonics and Geophysical Group of the U.S. Bureau of Reclamation in Denver, Colorado, 177 p.

Machette, M.N., 1985, Calcic soils of the southwestern United States: Geological Society of America Special Paper 203, p. 1-21.

McGookey; D.P., Haun, J.D.; Hale, L.A.; Goodell, H.A.; McCubbin, D.G.; Wreimer, R.J.; Wulf, G.R.; and Cobban, W.A., 1972, Cretaceous system, *in* Mallory, W.W.; Nolte, C.J.; Jensen, F.S.; and Griffith, E.G. (eds.), Geologic atlas of the Rocky Mountain region: Denver, Rocky Mountain Association of Geologists, p. 190-228.

MedicineNet.com, 2006, Definition of Selenosis: http://www.medterms.com/script/main/art.asp?articlekey=39069, accessed November 1, 2006.

Meeks, T.O., 1950, Reconnaissance of ground-water conditions in the Uncompahgre Valley, Colorado: U.S. Department of Agriculture, Soil Conservation Service Regional Bulletin 112, Geological Series 3, 21 p.

Merewether, E.A., Sawyer, D.A., and Cobban, W.A., 2006, Molluscan fossils and stratigraphic descriptions from the Upper Cretaceous Mancos Shale, west-central Colorado: U.S. Geological Survey Open-File Report 2006-1326.

National Resources Conservation Service, 2006, On-line soil survey data for Montrose County: http://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx.

Noe, D.C., Jochim, C.L., and Rogers, W.P., 1997, A guide to swelling soils for Colorado homebuyers and homeowners: Colorado Geological Survey Special Publication 43.

Noe, D.C., Morgan, M.L., and Keller, S.M., 2007, Geologic map of the Montrose East quadrangle, Montrose County, Colorado: Colorado Geological Survey Open-File Report OF-07-2, scale 1:24000.

Okulitch, A.V., 2002, Geological time chart: Geological Survey of Canada Open File 3040 (National Earth Science Series, Geological Atlas) - revision.

Sandoval, M.M. and Karlstrom, Karl, 2006, Incision history of the Black Canyon of the Gunnison — Update and summary of available constraints: Geological Society of America Abstracts with Programs, v. 38, no. 6, p. 11.

Schneeflock, Fletcher, Meyer, Grant, Karlstrom, Karl, and Wagner, Stacy, 2002, Quaternary drainage development and incision history in the Black Canyon of the Gunnison area, Colorado: Geological Society of America Abstracts with Programs, http://gsa.confex.com/gsa/2002AM/finalprogram/abstract_40865.htm.

Scott, G.R., 1969, Geologic map of the southwest and southeast Pueblo quadrangles, Colorado: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-597, scale 1:24,000.

Scott, G.R., and Cobban, W.A., 1964, Stratigraphy of the Niobrara Formation at Pueblo, Colorado: U.S. Geological Survey Professional Paper 454-L, 27 p.

Scott, G.R., and Cobban, W.A., 1986, Geologic and stratigraphic map of the Pierre Shale in the Canyon City-Florence basin and Twelvemile Park area, south-central Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-937, scale 1:100,000.

Selby, M.J., 1993, Hillslope materials and processes: Oxford, Oxford University Press, 451 p.

Sinnock, S., 1978, Geomorphology of the Uncompahgre Plateau and Grand Valley, western Colorado, USA: Ph.D. Dissertation, Purdue University, West Lafayette, IN, 201 p., 2 map plates, scale 1:84,210.

Stone, D.S., 1977, Tectonic history of the Uncompahgre Uplift: Rocky Mountain Association of Geologists 1977 Symposium, p.11-21.

Topper, R., Spray, K.L., Bellis, W.H., Hamilton, J.L., and Barkmann, P.E., 2003, Ground water atlas of Colorado: Colorado Geological Survey Special Publication 53, 210 p.

Tuttle, M.L.W., Grauch, R.I., and Stillings, L.L., 2005, Salt and selenium in Mancos Shale terrane on the Gunnison Gorge National Conservation Area, western Colorado, USA: Geological Society of America Abstracts with Programs, vol. 37, no. 6, p. 45.

Tweto, Ogden, 1977, Tectonic history of west-central Colorado: Rocky Mountain Association of Geologists 1977 Symposium, p.11-21.

Tweto, Ogden, Steven, T.A., Hail, W.J., and Moench, R.H., 1976, Preliminary geologic map of the Montrose 1 degree x 2 degrees quadrangle, northwestern Colorado: U.S. Geological Survey, Miscellaneous Field Studies Map MF-761, scale 1:250000.

Varnes, D.J., 1978, Slope movement types and processes, *in* Schuster, R. L., and Krizek, R. J., eds, Landslides – analysis and control: Washington D.C., TRB, National Research Council, p. 11-33.

Weimer, R.J., 1970, Dakota Group (Cretaceous) stratigraphy, southern Front Range, South and Middle Parks, Colorado: The Mountain Geologist, v. 7, no. 3, p. 157-184.

Wentworth, C.K., 1922, A scale of grade and class terms for clastic sediments: Journal of Geology, v. 30, p. 377-392.

White, J.L., and Greenman, C., in prep, Collapsible Soils in Colorado: Colorado Geological Survey Engineering Geology Bulletin.

Whittig, L.D., Deyo, A.E., and Tanji, K.K., 1982, Evaporite mineral species in Mancos Shale and salt efflorescence, Upper Colorado River Basin: Soil Society of America Journal, v. 46, no. 3, p. 645-651.

Widmann, B.L., Kirkham, R.M., Morgan, M.L., and Rogers, W.P., with contributions by Crone, A.J., Personius, S.F., and Kelson, K.I., and GIS and Web design by Morgan, K.S., Pattyn, G.R., and Phillips, R.C., 2002, Colorado Late Cenozoic fault and fold database and

Internet map server: Colorado Geological Survey Information Series 60a, http://geosurvey.state.co.us/pubs/ceno/.

Appendix 1. List of Cretaceous fossils collected within the Olathe quadrangle and surrounding quadrangles.

Cretaceous Fossils Collected from the Olathe Quadrangle and Surrounding Quadrangles

CGS Locality Number	USGS Mesozoic Locality Number	Fossils Identified by Wm. Cobban, USGS	Mollusc or Ammonite Guide Fossil Zone	Age	Formation or Mancos Shale Member	Quadrangle	County	State	Land Survey System Location	UTM83-X	UTM83-Y	Collected by	Date
DN045	D14525	*Baculites sp. (B. haresi?);* trace fossils	*C. balticus; Scaphites hippocrepis*	Lower Campanian	Prairie Canyon Mbr	Montrose East	Montrose	CO	se nw sw 9-48N-8W	259155	4256619	David C. Noe	05/19/06
DN072	D14529	*Cataceramus balticus*	*C. balticus; Scaphites hippocrepis*	Lower Campanian	Prairie Canyon Mbr	Montrose East	Montrose	CO	ne nw sw 29-49N-8W	255891	4262927	David C. Noe	05/25/06
DN064	D14530	*Baculites aquilaensis*	*C. balticus; Scaphites hippocrepis*	Lower Campanian	Prairie Canyon Mbr	Montrose East	Montrose	CO	se sw sw 21-49N-8W	257684	4263698	David C. Noe	05/25/06
DN066	D14531	*Baculites sp., Cataceramus balticus*	*C. balticus; Scaphites hippocrepis*	Lower Campanian	Prairie Canyon Mbr	Montrose East	Montrose	CO	sw se se 21-49N-8W	258478	4263760	David C. Noe	05/23/06
DN085	D14532	*Baculites aquilaensis; Ichthyodectes* scales	*C. balticus; Scaphites hippocrepis*	Lower Campanian	Prairie Canyon Mbr	Montrose East	Montrose	CO	n nw se 22-49N-8W	259930	4254357	David C. Noe	06/06/06
DN015	D14520	*"Inoceramus" sp.; Pseudoperna congesta*	(can't tell)	Coniacian or Santonian	Smoky Hill Mbr	Montrose East	Montrose	CO	sw nw nw 14-48N-9W	252555	4256167	David C. Noe	04/26/06
DN105	D14521	*"Inoceramus" sp.; Pseudoperna congesta;* trace fossils	(can't tell)	Coniacian or Santonian	Smoky Hill Mbr	Montrose East	Montrose	CO	nw nw sw 13-48N-9W	254138	4255410	David C. Noe	11/06/06
DN106	D14522	*"Inoceramus" sp.; Pseudoperna congesta;* fish scales	(can't tell)	Coniacian or Santonian	Smoky Hill Mbr	Montrose East	Montrose	CO	s nw sw 13-48N-9W	254265	4255165	David C. Noe	11/07/06
DN024	D14523	*"Inoceramus" sp.; Pseudoperna congesta;* fish scales	(can't tell)	Coniacian or Santonian	Smoky Hill Mbr	Montrose East	Montrose	CO	sw ne ne 31-48N-8W	256772	4251090	David C. Noe	05/02/06
DN027	D14524	*"Inoceramus" sp.; Pseudoperna congesta*	(can't tell)	Coniacian or Santonian	Smoky Hill Mbr	Montrose East	Montrose	CO	se se ne 29-48N-8W	258706	4252337	David C. Noe	11/07/06
DN044	D14526	*"Inoceramus" sp.; Pseudoperna congesta*	(can't tell)	Coniacian or Santonian	Smoky Hill Mbr	Montrose East	Montrose	CO	sw se se 8-48N-8W	258591	4256295	David C. Noe	05/17/06
DN082	D14527	*Magadiceramus subquadratus crenulatus; Pseudoperna congesta*	*M. subquadratus crenulatus*	Upper Coniacian	Smoky Hill Mbr	Montrose East	Montrose	CO	ne se nw 7-48N-8W	256399	4257370	David C. Noe	06/05/06
DN084	D14528	*"Inoceramus" platinus; Psuedoperna congesta*	(can't tell)	Middle to Upper Coniacian	Smoky Hill Mbr	Montrose East	Montrose	CO	se se se 1-48N-9W	255546	4258093	David C. Noe	06/05/06
SK25b,c	—	*Cremnoceramus crassus crassus*	*C. crassus crassus*	upper Lower Coniacian	Smoky Hill Mbr	Olathe	Montrose	CO	se se 33-50N-10W	239665	4271084	Stephen M. Keller	05/11/06
MM17	—	*Cremnoceramus deformis deformis*	*C. deformis deformis*	late Lower Coniacian	Smoky Hill Mbr	Olathe	Montrose	CO	s se 1-49N-10W	244270	4269055	Matthew L. Morgan	05/03/06
DN010	D14518	*Mytiloides incertus*	*M. incertus; Scaphites negricollensis*	Upper Turonian	Montezuma Valley Mbr	Montrose East	Montrose	CO	c s 4-48N-9W	250099	4258545	David C. Noe	04/20/06
SK37c	—	*Mytiloides incertus?*	*M. incertus; Scaphites whitfieldi*	Upper Turonian	Juana Lopez Mbr	Olathe	Montrose	CO	s sw 2-49N-10W	241600	4269122	Stephen M. Keller	05/14/06
MM15	D14452	*Prinocyclus bosquensis; S.whitfieldi; Mytiloides incertues; Baculites sp.*	*M. incertus; Scaphites whitfieldi*	Upper Turonian	Juana Lopez Mbr	Olathe	Montrose	CO	n nw 13-49N-10W	243267	4267423	Matthew L. Morgan	05/02/06
MM14	—	*Prinocyclus bosquensis; Lopha lugubris*	*M. incertus; I. dimidius; Scaphites whitfieldi*	Middle? to Upper Turonian	Juana Lopez Mbr	Olathe	Montrose	CO	sw sw 2-49N-10W	241573	4269168	Matthew L. Morgan	04/27/06
—	D3842	*Inoceramus perplexus; Prionocyclus macombi; Ostrea lugubris*	*I. Perplexus; I. dimidius; P. macombi*	Middle to Upper Turonian	Juana Lopez Mbr	Montrose East	Montrose	CO	n nw ne 27-48N-9W	251642	4252546	R.G. Dickinson	1962
MM24	—	*Prionocyclus macombi; Lopha lugubris*	*I. dimidius; P. macombi*	Middle Turonian	Juana Lopez Mbr	Olathe	Montrose	CO	ne nw 9-50N-9W	248521	4278337	Matthew L. Morgan	5/13/2006
SK34b	—	*Princyclus macombi*	*I. dimidius; P. macombi*	Middle Turonian	Juana Lopez Mbr	Olathe	Montrose	CO	nw nw nw 10-49N-10W	239908	4269109	Stephen M. Keller	5/12/2006
K138	D14513	*Prionocyclus macombi; Lopha lugubris*	*I. dimidius; P. macombi*	Middle Turonian	Juana Lopez Mbr	Montrose East	Montrose	CO	se ne se 27-48N-9W	252175	4252052	Stephen M. Keller	05/23/06
K142	D14514	*Inoceramus dimidius; Prionocyclus macombi*	*I. dimidius; P. macombi*	Middle Turonian	Juana Lopez Mbr	Montrose East	Montrose	CO	e se nw 27-48N-9W	251496	4252598	Stephen M. Keller	05/23/06
K141	D14515	*Prionocyclus macombi; Lopha lugubris*	*I. dimidius; P. macombi*	Middle Turonian	Juana Lopez Mbr	Montrose East	Montrose	CO	s se sw 22-48N-9W	251303	4253215	Stephen M. Keller	05/23/06
MM7	—	*Lopha lugubris*	*I. dimidius; P. macombi*	Middle Turonian	Juana Lopez Mbr	Olathe	Montrose	CO	ne sw 21-50N-10W	239194	4274887	Matthew L. Morgan	04/24/06
DN005	D14516	*Inoceramus dimidius*	*I. dimidius; P. macombi*	Middle Turonian	Juana Lopez Mbr	Montrose East	Montrose	CO	e se ne 5-48N-9W	249160	4259797	David C. Noe	04/19/06
DN008	D14517	*Inoceramus dimidius*	*I. dimidius; P. macombi*	Middle Turonian	Juana Lopez Mbr	Montrose East	Montrose	CO	c ne ne 9-48N-9W	250698	4257871	David C. Noe	04/20/06
MM4	—	*Inoceramus dimidius*	*I. dimidius; P. macombi*	Middle Turonian	Juana Lopez Mbr	Olathe	Montrose	CO	se ne 27-50N-10W	241272	4273254	Matthew L. Morgan	04/18/06
—	D11894	*Inoceramus dimidius*	*I. dimidius; P. macombi*	Middle Turonian	Juana Lopez Mbr	Olathe NW	Montrose	CO	se 33-15S-94W	247804	4287489	E.A. Merewether and W.A. Cobban	1982
—	D11893	*Inoceramus dimidius; Lopha lugubris*	*I. dimidius; P. macombi*	Middle Turonian	Juana Lopez Mbr	Olathe NW	Montrose	CO	sw 34-15S-94W	248244	4287348	E.A. Merewether and W.A. Cobban	1982
—	D14150	*Incoceramus dimidius; Lopha lugubris*	*I. dimidius; P. macombi*	Middle Turonian	Juana Lopez Mbr	Red Rock Canyon	Montrose	CO	se sw 29-50N-8W	256252	4272066	E.A. Merewether and D.A. Sawyer	6/25/1905

Compiled by David C. Noe and Matthew L. Morgan, Colorado Geological Survey

Version of 1/17/2007

Cretaceous Fossils Collected from the Olathe Quadrangle and Surrounding Quadrangles

CGS Locality Number	USGS Mesozoic Locality Number	Fossils Identified by Wm. Cobban, USGS	Mollusc or Ammonite Guide Fossil Zone	Age	Formation or Mancos Shale Member	Quadrangle	County	State	Land Survey System Location	UTM83-X	UTM83-Y	Collected by	Date
DN011	D14519	*Baculites sp.; Inoceramus dimidius?*	*I. dimidius; P. macombi*	Middle Turonian	Juana Lopez Mbr	Montrose East	Montrose	CO	e ne sw 4-48N-9W	249975	4259193	David C. Noe	05/20/06
DN006	D14535	*Inoceramus dimidius; Prionocyclus macombi*	*I. dimidius; P. macombi*	Middle Turonian	Juana Lopez Mbr	Montrose West	Montrose	CO	nw ne se 5-48N-9W	248940	4259326	David C. Noe	04/19/06
—	D3841	*Inoceramus dimidius; Ostrea lugubris*	*I. dimidius; P. macombi*	Middle Turonian	Juana Lopez Mbr	Montrose West	Montrose	CO	sw ne 5-48N-9W	248520	4259747	R.G. Dickinson	1962
—	D11892	*Inoceramus dimidius; Prinocyclus macombi*	*I. dimidius; P. macombi*	Middle Turonian	Blue Hill Mbr	Olathe NW	Montrose	CO	sw 34-15S-94W	248244	4287348	E.A. Merewether and W.A. Cobban	1982
—	D11891	*Prinocyclus hyatti*	*I. howelli; P. hyatti*	Middle Turonian	Blue Hill Mbr	Olathe NW	Montrose	CO	sw 34-15S-94W	248244	4287348	E.A. Merewether and W.A. Cobban	1982
—	D11890	*Inoceramus dimidius; Lopha lugubris*	*I. dimidius*	Middle Turonian	Blue Hill Mbr	Olathe NW	Montrose	CO	sw 34-15S-94W	248244	4287348	E.A. Merewether and W.A. Cobban	1982
—	D11889	*Pycnodonte newberryi*	*Mylitoides hattini; Nigericeras scotti*	Upper Cenomanian to Lower Turonian	Bridge Creek Mbr	Olathe NW	Montrose	CO	se 34-15S-94W	249310	4287348	E.A. Merewether and W.A. Cobban	1982
—	D14168	*Pycnodonte newberryi*	*Mylitoides hattini; Nigericeras scotti*	Upper Cenomanian to Lower Turonian	Bridge Creek Mbr	Olathe	Montrose	CO	sw se 9-50N-9W	249124	4277052	E.A. Merewether and D.A. Sawyer	2003
—	D14164	*Pycnodonte aff kellumi*	*pre I. Pictus?*	Upper Cenomanian	Graneros Mbr	Montrose West	Montrose	CO	nw nw 20-48N-9W	247739	4254694	???	???
MM61	—	*Pycnodonte aff kellumi*	*pre I. Pictus?*	Upper Cenomanian	Graneros Mbr	Olathe	Montrose	CO	sw se 9-50N-9W	248999	4276983	Matthew L. Morgan and David C. Noe	11/18/2006
—	D11888	*Johnsonites sulcatus; Borissiakoceras compressum; Inoceramus macconnelli*	*I. macconnelli*	lower Middle Cenomanian	Graneros Mbr	Olathe NW	Montrose	CO	se 34-15S-94W	249310	4287348	E.A. Merewether and W.A. Cobban	1982
—	26946		*Plesiacanthoceras wyominensis*	Middle Cenomanian	Dakota Sandstone	Montrose West	Montrose	CO	19-48N-9W	???	???	???	???

Sources of information for fossils collected previous to this study include Dickinson (1965) and Merewether and others (2006)
Note by Wm. Cobban: Pieces of large inoceremids are referred to as " *Inoceramus* " and may be either *Megadiceramus* , *Volviceramus* , or *Platyceramus*